**The Dissertation Committee for Patricia Ann Bobeck Certifies that this is the approved version of the following dissertation:**

# JEAN-BAPTISTE PARAMELLE: METHOD, RESULTS, AND CONTRIBUTION TO HYDROGEOLOGY

**Committee:**

John M. Sharp, Jr., Supervisor

Marc Hesse

Charles Kerans

Kenneth Taylor

Michel Bakalowicz

# JEAN-BAPTISTE PARAMELLE: METHOD, RESULTS, AND CONTRIBUTION TO HYDROGEOLOGY

**by**

**Patricia Ann Bobeck, B.A., A.M., M.A.**

**Dissertation**

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

**Doctor of Philosophy**

**The University of Texas at Austin**

**May 2017**

# Acknowledgements

I owe more appreciation than I can list here. First, I thank Dr. Jack Sharp for welcoming me back to graduate studies and for his enthusiastic support for this project and French hydrogeology. Jack generously provided important feedback throughout the years of course work and encouragement and sound guidance during the dissertation process. He has offered abundant suggestions and insight for research directions and cheerful encouragement over the years of this project. Jack also provided generous financial support for coursework, fieldwork, and conference attendance.

I thank Kenneth Taylor of the University of Oklahoma for his attentive readings of the translation and for suggestions for improving the text. Ken also suggested topics to research and address in the translator's notes that accompany the translation and made significant contributions to the appendices. Ken also shared from his wealth of knowledge information on French scientists and naturalists of the 18th and 19th centuries and their contributions to the development of the scientific method. His contributions added greatly to my understanding of intellectual and scientific world Paramelle inhabited. Ken also put me in touch with Jean Margat of the Bureau de Recherches Géologiques et Minières (BRGM) in Orléans, France. Mr. Margat provided a folder of historical hydrogeological documents and interesting insight on the history of hydrogeology in France.

Michel Bakalowicz of the University of Montpellier, France, has been an enthusiastic supporter of this project since our first meeting in 2013 when we talked at length about Paramelle, the historical background of his work, E.A. Martel, and the history of dowsing. Michel suggested contacts in the Dept. of Lot (André Tarrisse and Cyril Delporte) who showed me the limestone plateaus where Paramelle walked almost two

centuries ago looking for water. Michel also introduced me to his colleague Sévérin Pistre, professor of hydrogeology at the University of Montpellier. Michel also conducted extensive research on authors who have cited Paramelle in their work and provided this information for use in the dissertation. Michel has helped me immensely by alluding to socio-cultural background that I did not have, for example, an understanding of the gulf between Paramelle, the provincial priest, and the members of academies and elite engineering corps such as Henry Darcy. Michel helped me understand obscure passages of Paramelle's book and reviewed my figures illustrating Paramelle's concepts.

Andre Tarrisse, former hydrogeologist of the Department of Lot, and Cyril Delporte, current hydrogeologist of the Department of Lot, introduced me to the northern part of the department where we visited the parishes Paramelle served when he was beginning his water search. André began working in the department of Lot in the 1970s when Paramelle's methods were still used to find groundwater. He invited me on numerous excursions to see the locations Paramelle describes in his book. André also found descendants of Paramelle and facilitated a meeting with them. André spent several days in the field in Lot with Jack Sharp and me. In addition, André introduced me to Jean Taisne, the speleologist who transcribed Paramelle's 1827 handwritten memoir for publication by the Spéléo-Club of Paris. Mr. Taisne is the author of several articles on Paramelle.

André introduced me to other Paramelle enthusiasts in France. The first of these was Daniel Clément and his wife Agnes, who invited me to the paradise of Moloy to explore the water supply system made possible by Paramelle's discovery of water in 1849. Through Daniel, I met Gérald Naigeon of Gevrey-Chambertin who gave me a tour of the Source Lavaux, a water system built to exploit another of Paramelle's discoveries; this one is still providing water to residents of Gevrey.

J.P. Nicot and Gregory Frébourg, French geologists at the University of Texas Bureau of Economic Geology, read the translation and helped with numerous words and expressions not found in dictionaries or online.

Archivists in the Archives départementales of 39 departments made it possible for me to look through stacks of records relating to Paramelle's visits to their departments. They were extremely generous with their time and expertise and they made it possible to document Paramelle's travel and work. The archives contain lists of individuals who were willing to pay for Paramelle's services, notices of Paramelle's visits, and newspaper articles recounting his successes and the competition between departments for his services. The archivists cheerfully explained the French archives system and offered suggestions on finding additional information. And they cheerfully put up with my less-than-perfect French, perhaps because they were mildly amused that I had traveled from Texas to research a 19th century country priest. Many of the archivists remained in contact with me after finding additional materials after my visit. Two archivists stand out for their helpfulness. Anne-Laurence Hostin, archivist in Privas, Ardèche, a computer whiz, found a database of about 90 regional newspaper articles on Paramelle. It was by far the largest cache of newspaper articles I found. Annie Massot, archivist in Digne-les-Bains, Basses-Alpes, invited me on a 4-hour geologic field trip around Digne-les-Bains after we finished our work at the Archives on a Friday afternoon.

The Jackson School of Geosciences of University of Texas provided material support from two funds, the Ronald K. DeFord and the W. R. Muehlberger scholarships to defray field costs. Gifts from these two funds were especially dear to me since I had known both of these men in the 1970s and 1980s during my undergraduate and master's degree years at UT.

Mark Helper, ever helpful and cheerful, introduced me to the geologic use of ArcGIS in 2012 and generously offered valuable ArcGIS help on this dissertation project on multiple occasions.

Vincent Clause also generously gave his time to help me organize the ArcGIS portion of this research.

Dennis Trombatore, librarian of the Walter Geology Library, made this dissertation possible by housing an incredible wealth of resources right here on campus and sharing his vast knowledge of library arts to help me track down obscure titles, and by ordering geologic maps. The Walter Library is truly a treasure.

Edwin Robert, Latin-English translator, contributed English translations of Paramelle's citations of the ancients.

On the personal side, I am most grateful to my son Dennis who helped me in more ways than I can count during the years of this PhD process.

# JEAN-BAPTISTE PARAMELLE: METHOD, RESULTS, AND CONTRIBUTION TO HYDROGEOLOGY

**Patricia Ann Bobeck, Ph.D.**

The University of Texas at Austin, 2017

Supervisor: John M. Sharp, Jr.

This study consists of three parts: a translation of Paramelle's 1856 *The Art of Finding Springs*; a synthesis of Paramelle's method, as set out in the book; and an application of his observational method to two karst areas of Texas. Paramelle's book is a compilation of the observations and experiences gained during 40 years of exploring for water in 40 of France's departments. Paramelle's observational method was a scientific advance over water finding methods used in the early $19^{th}$ century. The breadth and details of Paramelle's observations are summarized in the second part. Paramelle found shallow water in karst areas by locating the thalweg, the location of focused groundwater flow, and he maintained that beneath every surface thalweg was an underground thalweg. Shallow water could be found in small valleys where the thalweg was easily visible on the surface. Water is abundant where a thalweg joins a stream. He calculated the amount of groundwater present by the size of the recharge area, an area of permeable rock overlying an impermeable layer. He observed the swallet-resurgence connection, the disappearance of a stream into the streambed and its reappearance downstream. Paramelle noted that aligned sinkholes overlay underground conduits and caverns. In part three, Paramelle's observations are applied to two karst areas of Texas, New Braunfels and the Stockton

Plateau. In the New Braunfels area, wells located within 200 m of subsidence areas (coalesced sinkholes) have higher yields than wells located farther from these features. On the Stockton Plateau, the presence of springs in recesses confirms Paramelle's observations that shallow water is present in small valleys, at permeability contrasts, and downgradient of recharge areas of sufficient size. Paramelle's scientific observation of rock units and water occurrence provided water for many towns and farms in the $19^{th}$ century and greatly promoted the use and popularity of groundwater in France. His success in using the observational method is a reminder of the importance of paying attention to observations, especially when they do not support established theories.

## Table of Contents

## List of Tables

# List of Figures

# Chapter 1. Introduction

Jean-Baptiste Paramelle was a 19th century "water finder" or "hydroscope" according to the terminology of the day. Today we would call him a hydrogeologist, in fact a karst hydrogeologist because he developed his water finding methods on limestone plateaus.

Chapter 2 of this dissertation is an English translation of Paramelle's 1856 publication *The Art of Finding Springs*, written after Paramelle had retired from the rigors of a 31-year career searching for groundwater. For Paramelle, "springs" means groundwater. The 32-chapter book, which is a how-to manual for finding shallow groundwater, was a best-seller when originally published. Paramelle's observations remained the basis for finding groundwater well into the 20th century.

Chapter 3 is a synthesis of Paramelle's observational method for finding water and how he developed it. To find water Paramelle had no alternative to the observational method because he had no other tools. He was a patient observer, spending nine years walking the limestone plateaus while figuring out where the water was and at what depth. He spent the remainder of his career accumulating additional observations as he traveled across France searching for groundwater, in the lineage that includes engineer Terzaghi who in the 20th century developed an observational method to help engineers prevent engineering failures by bridging the gap between calculations and field observations.

Chapter 4 is an application of Paramelle's observational method to two karst areas in Texas. I wanted to determine if Paramelle's ideas could be used to find productive water wells, particularly in proximity to subsidence areas. I used GIS to examine two areas, New Braunfels and the Stockton Plateau. In the New Braunfels area, I found that wells closer to subsidence areas (within 200 m) have higher average mean yields than wells located farther away. On the Stockton Plateau, I did not find any wells whose 200-m buffers intersected subsidence areas. I then looked at shallow groundwater, in the form of springs, to see if Paramelle's observations pertained to them. I found that the springs generally illustrate Paramelle's observations on favorable locations for digging for groundwater.

Chapter 5 is a summary and conclusion focusing on Paramelle's accomplishments, his impact on the fields of geology, hydrogeology, speleology, and karst, and the personality traits that led to his success.

### 1.1. DEVELOPMENT OF THE RESEARCH PROPOSAL INTO THE DISSERTATION

My research proposal consisted of five projects, which were:

1. Translate *The Art of Finding Springs* into English,

2. Compile the elements of Paramelle's method into a succinct and modern summary,

3. Analyze Paramelle's method by examining the geology and hydrogeology of sites where he discovered water,

4. Determine Paramelle's place in the history of hydrogeology studying the ideas he incorporated into his method and evaluating his impact on later hydrogeology,

5. Compare Paramelle's theories to modern methods by applying them to karst in the United States to see if his insights contribute to finding groundwater.

Because of the Jackson School of Geoscience's preference for a dissertation with three substantive chapters and an introduction and conclusion, I revised my five projects into three chapters, as follows.

Project 1, the translation, is Chapter 2 of the dissertation. Project 2, Paramelle's observational method, is the subject of Chapter 3. Project 5, the application of Paramelle's method to a site in the US, is the subject of Chapter 4.

I conducted significant research on Project 3, locating places where Paramelle found water, mostly by using departmental archives in France. This project is discussed below under Contacts in France.

Project 4, Paramelle's sources of information and later authors who refer to him, does not have a chapter in the three-chapter format of this dissertation. The sources of information are not always easy to determine. Paramelle wrote from the perspective of his period in history, using the common "received wisdom" of the first half of the $19^{th}$ century. In some cases he cites references but in many cases he does not. A thorough study of Paramelle's "received wisdom" is beyond the scope of this study. I have focused on enumerating and describing Paramelle's insights and observations. For a list of contemporary authors who refer to Paramelle, I began with the names cited in Paramelle's *The Art of Finding Springs*. I added to the list as I ran across references to Paramelle in my research.

Authors Paramelle cited in his 1827 Memoire are listed in Appendix A. Authors Paramelle cited in *The Art of Finding Springs* are listed in Appendix B. Authors who cite Paramelle are listed in Appendix C. Both Michel Bakalowicz and Kenneth Taylor contributed substantially to the appendices.

### 1.2. CHOICE OF PARAMELLE AS A DISSERTATION TOPIC

I first encountered Jean-Baptiste Paramelle while translating Henry Darcy's *Public Fountains of the City of Dijon* in the early 2000s. Darcy's book was published in 1856, the same year as Paramelle's. In the preface to his book, Darcy speaks of Paramelle as "an ingenious springs seeker." In Chapter 3, where Darcy discusses the spring he diverted to provide Dijon's water, in a section on ancient and modern springs seekers, he includes a report written by his staff geologist to document a field excursion with Paramelle, which probably occurred sometime in the 1840s. And, in the famous Appendix D where Darcy describes his pipe experiments, he devotes several more pages to a review of Paramelle's newly published book. It is thus clear that Paramelle was a major figure in the water community in France in the middle of the 19th century and that Darcy had high praise for Paramelle's success in finding water (Darcy, 1856).

At the IAH International Symposium Darcy 2006 in Dijon, Philippe Renard of the Université of Neuchâtel enthusiastically thanked me for making Darcy's book accessible to English-speaking readers. He then told me how Paramelle had popularized the use of groundwater throughout France in the 19$^{th}$ century and encouraged me to make a contribution to the English-speaking geologic community equivalent to the Darcy translation by translating Paramelle's *Art of Finding Springs* into English.

The opportunity to conduct research on Paramelle came up in 2011 when I applied to and was accepted into the UT Jackson School. During my PhD work I wanted to use my foreign language expertise in conjunction with geologic knowledge to create a unique contribution to the field of geology. Paramelle was an obvious choice.

### 1.3. Research in France

Paramelle began his scientific career with a subsidy from the authorities of the Department of Lot to defray expenses for finding water for its residents. As his successes became known, other departments requested his services. Most of these interdepartmental contacts were made through prefects, the appointed official who presides over departments. To find records of Paramelle's discoveries, French archivists recommended I conduct research in departmental archives, patrimonial libraries, municipal libraries, and libraries of historical societies, in addition to the Bibliothèque Nationale and its on-line database Gallica.

Most of the Paramelle records in departmental and municipal libraries are bundles of documents that are not viewable on-line. During the summers of 2014 and 2015, I visited departmental archives in the departments where Paramelle had worked to photograph records of his visits and discoveries. I visited primarily departmental archives because they were most likely to contain the prefect's records. I visited patrimonial and municipal libraries if they were located near the departmental archives and open during the hours I was there. Through this process, I photographed large files of a variety of documents: lists of citizens (subscribers) who requested Paramelle's services; handwritten town council deliberations; correspondence between officials and Paramelle; newspaper accounts of Paramelle's visits, explorations, and discoveries; speeches about Paramelle; examples of Paramelle's informational brochures and receipts issued to clients. Some departmental archives had hundreds of documents; some had none. Images of these documents are not included in this dissertation; the material is voluminous and is not yet completely inventoried. Appendix D is a summary of this research.

During the summer of 2013, I visited the Department of Lot, France, for the first time. Michel Bakalowicz introduced me to André Tarrisse, a hydrogeologist who had worked in the Department of Lot since the 1970s. André showed me the karst plateau where Paramelle began his search for water and lived most of his life. Along with Cyril Delporte, current hydrogeologist in the Department, we visited many of the locations described in Paramelle's book. André also introduced me to Jean Taisne, a speleologist who had transcribed Paramelle's handwritten 1827 (Taisne and Choppy, 1987) report to the government of the Department of Lot, which summarized Paramelle's first research on finding water on the Causses du Quercy and served as the foundation for *The Art of Finding Springs*. Mr. Taisne has also conducted research and written articles on Paramelle's life and geologic contributions (Taisne, 1986; Taisne and Choppy, 1987).

### 1.4. PARAMELLE'S BUSINESS MODEL

At the beginning of his career, Paramelle expanded his fieldwork outside the Department of Lot as a result of requests from neighboring departments, likely through prefects. From 1832 to 1853, he conducted fieldwork from March 1 through July 1, and from September 1 through December 1. He organized his work by department, giving priority to the department that had compiled the greatest number of requests in advance. The prefect usually organized the registration of subscribers by sending notices to mayors with instructions on how to compile subscriber lists; many of these lists are archived in the Departments. Paramelle actively encouraged competition among the departments; his correspondence with prefects states which department has the greatest number of subscribers, and how that prefect's department ranks in his list. He explored a department only once, and did not add subscribers once he was in the department. He maintained a strict routine during his fieldwork. If he did not complete his exploration in a department at the end of his field season, he returned to that department at the beginning of the next field season to complete the department before moving on to the next department on the list.

When Paramelle arrived at a site, he conducted a geologic examination to determine if groundwater was present. If so, he indicated its depth and volume. If the landowner thought the water was too far from his house, too deep, too meager, or if he wasn't actually the owner of that parcel of land, Paramelle would go no further and the landowner did not pay him. If the landowner was interested in the water and asked for Paramelle's indication, Paramelle would indicate the location to excavate, provide a written receipt listing the location, depth and volume, and collect payment. If within one year of Paramelle's indication, the landowner did not find water at this location or depth and in the volume Paramelle claimed, Paramelle refunded his money. Paramelle indicated water at no charge for the poor and religious communities.

In his communications with prefects, Paramelle asked local officials to inspect and certify that after excavation, the groundwater was found at the location, depth and in the quantity he indicated and to provide these reports [called *procès-verbaux*] to the local archives and to him. If landowners had used the refund guarantee to provide information on failures and local officials had reported successes, Paramelle would have been able to count his successes and his success rate. However, as he explains in *The Art of Finding Springs*, few certifications were returned to him. As a result Paramelle did not know his actual success rate or the number of discoveries he made. He therefore estimated the number by calculating the number of places he explored (about 30,000), subtracting the number of places where he did not indicate water, and then estimating the success rate of the total number of indications.

He arrived at the number of discoveries 10,275 and the information I compiled supports this estimate. According to documents I found in the archives, in 1838 the Department of Bouches-du-Rhone had compiled a list of 1200 subscribers (according to a letter written by Paramelle), in 1841 the Department of Gard had a list of 1144 (according to a newspaper account), the Department of Jura had 1600 subscribers according to an 1845 newspaper account, and the Department of Vosges had 1375, according to a 1845 newspaper account. Some of these subscribers asked Paramelle to inspect multiple locations. In other Departments the subscriber numbers were lower. In all, Paramelle worked in 40 departments.

The most reliable source of information on Paramelle's discoveries is newspaper accounts. However, these articles list discoveries in the name of the people who owned the property in the 19th century; finding those locations would entail a search of property records back more than 150 years. In some cases, the newspaper gives the location as a municipality, or a chateau, for example, but in the cases I investigated, current officials and owners have no records of water supplies discovered so long ago.

Paramelle based his rates per "indication" on the distance from his home base in Saint-Céré, Lot. Rates ranged from 10 francs in Lot to 35 francs in Côte-d'Or. Paramelle's budget had three main categories: first, charity; second, religious institutions in his diocese; and third, support for Paramelle's father in his old age and for Paramelle's book collection (*Journal de l'Ain*, 7 May 1841). His library supposedly contained 3000 volumes; we can assume that the list of references in his book, *The Art of Finding Springs*, is a short list of his library holdings. In his retirement, he wrote *The Art of Finding Springs*, which was financially successful, and he left most of his estate to charity.

### 1.5. PARAMELLE'S GROUNDWATER DISCOVERIES

I was able to locate and visit two of Paramelle's successes. Both are in Côte-d'Or, a department Paramelle visited in 1849 (Henry Darcy had left Dijon, the chef-lieu of the Department of Côte-d'Or, in 1848). In the Archives Départementales of Côte-d'Or in Dijon, I found a reference to a Paramelle visit to Moloy, a small town located 30 km north of Dijon (Figure 1.1). André Tarrisse found an on-line article written by Moloy resident Daniel Clement about Paramelle's visit, water discovery, and the water supply system the town built in 1850 to exploit Paramelle's discovery. The mayor of Moloy kindly put me in contact with Daniel Clement, who responded to my request with enthusiasm and photographs of the reservoir built to store the water (Figures 1.3 and 1.4), the fountains that still grace the streets of Moloy (Figure 1.5), a map indicating the location of the well installed per Paramelle's indication, and eventually several guided tours of the reservoir and the water distribution system. Paramelle predicted the water would be between 5 and 5.5 meters in depth and the volume would be sufficient for a 300 households. The system was built in 1850 and continued to supply water to the town until the 1970s (Clement, personal communication). The fountains are no longer connected to the well; the well is located in the middle of an agricultural field and there is no longer any surface marker of it (Figure 1.2).

Daniel Clement's article generated correspondence from another Burgundian, Mr. Gérald Naigeon of Gevrey-Chambertin, who has written about the Source de Lavaux (Naigeon, personal communication). In September 2016, Mr. Naigeon accompanied me on a short excursion to the Combe Lavaux near Gevrey to see the Source de Lavaux, a spring housed in masonry structure (Figure 1.6). In 1849 Paramelle indicated water at this site at a depth of 2.5

m. Paramelle advised the town to build a trench with a dry rock wall to intersect the numerous trickles of groundwater in this dry valley (Figure 1.7); the masonry building encloses the dry rock wall and trench. In 1866 the town measured the spring discharge as 17 liters/sec. In 1869, the town built a reservoir near the entrance to the Combe Lavaux to store the water (Figure 1.8). This well continues to provide water to some inhabitants of Gevrey-Chambertin; the water is not treated except for a few drops of chlorine added to the water as it leaves the reservoir.

### 1.6. References


Clement, D., 2014, "*Il était une fois*" (personal communication)

Darcy, H., 1856, The Public Fountains of the City of Dijon [Translated from *Les Fontaines publiques de la ville de Dijon*: Paris, Dalmont, 647 p.

*Journal de l'Ain*, 7 May 1841.

Naigeon, G., 2016, *C'était Hier N° 4, Sur les Traces du Passé* (personal communication)

Taisne, J., 1986, *L'Abbé Paramelle. Petite histoire d'une statue: Grottes et Gouffres*, Bulletin of the Spéléo-Club de Paris, No. 101, September 1986, p. 25-26.

Taisne, J., and Choppy, J., 1987, *Un des premiers hydrogéologues du karst: L'Abbé Paramelle, "Hydroscope*" in Karstologia No. 9, 1987, p. 53-58.

Figure 1.1. Location map of Moloy, Côte-d'Or, France.

Figure 1.2. Combe Aulogne, Moloy, Côte-d'Or, France.
Paramelle found groundwater here in 1849.

Figure 1.3. Reservoir entrance in Moloy, Côte-d'Or.
Reservoir constructed by the village of Moloy in 1849-1850 to store water produced by the Paramelle well.

Figure 1.4. Interior of reservoir, Moloy.
The village of Moloy built the reservoir in 1850 to store water from the Paramelle well.

Figure 1.5. Moloy street fountain built in 1850.
One of the original street fountains that provided groundwater to residents. Photo courtesy Daniel Clement.

Figure 1.6. Source de Lavaux in Gevrey-Chambertin, Côte-d'Or, France.
Paramelle discovered groundwater here in 1849. This building houses a dry-rock collector trench.

Figure 1.7. Dry rock collector trench at Source de Lavaux, Gevrey-Chambertin.
Dry rock collector trench constructed by the town of Gevrey-Chambertin on Paramelle's groundwater indication in 1850. This trench continues to supply groundwater to residents of Gevrey-Chambertin in 2016. Photo courtesy Gérald Naigeon.

Figure 1.8. Reservoir at Source de Lavaux near Gevrey-Chambertin.
The reservoir was built in 1869 to store water produced by the dry-rock collector trench.

## Chapter 2. *The Art of Finding Springs* by Mr. L'Abbé Paramelle

# L'ART

DE

# DÉCOUVRIR LES SOURCES

PAR

**M. L'ABBÉ PARAMELLE.**

SECONDE ÉDITION,

REVUE, CORRIGÉE ET AUGMENTÉE.

> On croit que des endroits sont totalement dépourvus d'eau, tandis qu'il y en a souvent beaucoup sous la terre sur laquelle on marche, et peu éloignée de sa surface.
>
> *Encyclopédie*, art. *Source*.

SE VEND CHEZ

DALMONT ET DUNOD, LIBRAIRES-ÉDITEURS,

QUAI DES AUGUSTINS, 49.

A PARIS.

1859

## 2.1. PREFACE TO THE FIRST EDITION

Finding springs has been the subject of abundant research by all humanity throughout history (1). Driven by the need to find the indispensable element of life on a daily basis and thinking that underground water must show some outward sign of its presence, philosophers and common people have searched diligently for water. Among the ancients who recorded and published the most on this subject are: Vitruvius, Pliny the Naturalist, and Cassiodorus. Modern man, who is more occupied with imagining the systems that produce springs than in observing the signs of their presence, has added almost nothing to what the ancients left us (2). These indications, it must be said, are so vague, so uncertain and applicable to such a small number of places that they cannot be used as elements of a useful technique. Thus although these methods have been included in countless books and put into the hands of everyone, we do not see that they have produced numerous or important results anywhere. I can attest that I have never seen a single spring that someone claims to have discovered using one of these processes.

For thirty years, geologists have written papers on the probability of success that different rock types offer to drillers of artesian wells but their writings contain only generalities. None of them can categorically designate the precise point to place the drill to find water nor indicate any means to determine its depth or volume. Interested only in springs located at great depths that can be reached only at great expense, none of them seems to have looked at the numerous ordinary springs often located only a few meters under the ground that are near most houses and within the reach of all incomes.

The method of discovering springs that was most in fashion, the method that has gained the most credit among ignorant people and even among some educated people, is the divining rod [Fr. *baguette divinatoire*]. Although I have used it many times and followed all the recommended precautions, and although I have crossed and re-crossed known groundwater conduits, I have never noticed the rod make on its own the slightest movement in my hands. I have read several extensive treatises on this subject and I have observed the operations of several dozen dowsers, the most renowned that I have met during my travels, to determine whether this instrument turns on top of flowing groundwater or not. From what I have read and observed, I believe that: 1) that the rod turns spontaneously in the hands of certain individuals endowed with a unique temperament to produce this effect; 2) that this movement is determined by fluids that we cannot sense, such as electricity, magnetism, etc.; 3) that it turns equally in places where no groundwater is present and where groundwater is present, and that as a result it is useless in finding springs. Thus Mr. de Tristan, an eminent dowser who in 1826 published a long treatise on this famous rod, concluded with the following words: "I am not in favor of trusting the search for groundwater to dowsing." Of the more than ten thousand springs that I have indicated, only twice have they coincided with points chosen by someone with a divining rod. I say chosen because their indications, which have been shown to me in perhaps one thousand places, were all placed precisely on the point most convenient for the property owner (which was not difficult to guess); as a result, almost all these claimed indications fail completely, and the very small number of successes involved are due only to the effect of chance.

Thus neither science nor divination has provided anything satisfactory to guide us in the search for groundwater.

However, thirty-four years ago geognosy [Fr. *géognosie*] (See Translator's Notes), the study of both visible and covered rocks, seemed to me to be the science most likely to shed light on underground watercourses. As Mr. Rozet said, this science shows a miner the probability of success in his business and shows him the path to follow in his work. It shows the architect which mountains he should excavate to find the different types of rocks he needs, and it shows the potter the clay beds he wants to use, etc. For these reasons, this science can, I believe, help us understand the formation of springs and the paths they follow underground. To resolve this problem, I spent nine years studying rocks and collecting multiple observations that will be explained in the course of this book.

Because this entire theory on the art of discovering springs is based on the external configuration and interior structure of rocks, the notions of geognosy are indispensable to whomever wants to progress in this knowledge. Those who would like to deepen this knowledge should study carefully and become familiar with the elementary geology texts of authors D'Aubuisson des Voisins, Rozet, d'Omalius d'Halloy, de la Bèche, Brongniart, Lecocq, Gasc, Lyell, Huot, Demerson, Rivière, Burat, d'Orbigny, Beudant, etc. Those who want only enough knowledge to understand this theory or to find groundwater in the simplest of cases can content themselves with the introductory information in this book, which I have drawn in large part from these fathers of geology.

Geognostic data does not consist of theorems subject to demonstration or physical laws exempt from all exceptions; they are observations of visible rocks that are known to be constant in a number of localities and that provide us a means of judging by probable induction the nature of rocks that are hidden from us. For example, if from the two sides of a mountain we see a layer of rock that has the same thickness, we conclude that the thickness is probably the same within the mountain because observation has shown that the thickness of a layer rarely varies. The forces that have contributed to the formation of various deposits that make up the outer skin of the globe are of different types and their operations have been combined in infinite ways, making it impossible for the geognost to make rigorously exact observations from which he can deduce invariable rules. Almost all have exceptions and those that have the fewest are those that approach certainty. Although this science is not based on absolute principles, it does provide us with data that is precise enough and that agrees with other data so that in the great majority of cases it tells us what exists underground.

Subsurface hydrography, entirely subject to the deposition and constitution of terrestrial deposits, has the same anomalies and the same exceptions as rock units. The knowledge of moving water, both visible and underground, offers general laws that are incontestable in almost all cases but which are for the most part contradicted by some special fact; for example, a stream that flows into a larger one converges downstream into the larger one. However, the Gier, which travels in almost a straight line from south to north, flows into the Rhone at Givors, which flows from north to south. Hydroscopy (See Translator's Notes) like geology, cannot be considered an exact science like mechanics, hydraulics, and other branches of physics. But the few exceptions found in one place or another do not mean that general laws, which are proposed on the basis of the universality of the observed facts, are not certain enough to guide the hydroscope in his research and lead him to succeed in the great majority of attempts. The exception contradicts the rule but does not destroy it. In this book exceptions will be commonly noted by the use of one of the following words often, ordinarily, generally, but I have not used these words everywhere they should have been mentioned because it would have caused them to appear in most sentences, which would have disfigured the language. Following the example of geologists, I have in many places expressed as positive what appears true to me in the great majority of cases, without compelling myself to point out each exception known to me.

The task that I undertook twenty eight years ago of providing a reasonable theory to the public on the art of finding water could naturally have been done by any learned geologist; this person would have treated this subject as a master and not left it to a poor country practitioner who did not have enough books to study rocks thoroughly, nor enough time to go far away to study them, nor have at hand men instructed in this subject to guide him with their counsel, nor enough knowledge to write a book worthy of being presented to the public.

In spite of all these reasons for discouragement and the universal ridicule that awaited me in the event of failure, I was profoundly moved by the innumerable difficulties caused every year by the lack of water in the Department of Lot. I first consulted all the books that I knew of to try to find a way to discover water but it was a fruitless search. I could not even find an author who knew how to define a spring properly, not one who seemed to have a clear idea of a spring. We will see the proof in Chapter X. From this I gained the conviction that none of these hydrographers had made the effort to look at large areas of rock units for the purpose of recognizing the presence of springs but that they limited themselves to copying the work of others or constructing unlikely systems of the origin of springs. (We will see some in Chapter XI.) Seeing that no one had written anything satisfying on this topic and that this science had yet to be created, I felt drawn to do all I could to try to lay the groundwork. I considered the project to be far beyond my ability but I recognized that the importance of a discovery is not measured by the ability of its author (3). I therefore resolved to study underground hydrography in the field, to collect the largest possible number of facts, to compare them, and to see if they corroborated each other or not. After several years of observation, I was lucky enough to be on the right track. I was reassured by looking at several thousand locations where springs form, move underground, and flow from the ground under in almost identical field environments. I was sure I had followed a good plan and I hoped that hydroscopy could finally move into the domain of rational science.

Since that time, I have endeavored to follow the light of facts and to accept only outcomes that derive naturally from them and to set aside any opinion or any system that is not based on numerous and proven facts. The reader will see in this book if I have deviated from this plan. Given the impossibility of including the thousands of facts that I observed in all the departments I have explored, I cite most mostly from the Department of Lot because it is the area I have studied most and it is the one most suitable for hydroscopic observations because it has more rock types than any other and because almost all rock types seen in France are represented there.

Prior to traveling outside this department I suspected that maybe other completely different rock types existed elsewhere and that in these places, this theory would not apply. This suspicion was unfounded. Now that I have explored in great detail almost half of France and several areas of neighboring countries, I can affirm that the laws that govern the formation and flow of springs underground are essentially the same everywhere and that variations or exceptions that the laws present are due to the composition, the arrangement, or depressions of the rocks and that they can ordinarily be anticipated.

If a theory that has not yet been proven should be received with reserve and even with doubt until experience shows that it has merit, I hope that the reader will find the proofs of this theory neither too few nor insufficient when he learns that over a period of twenty five years the theory has been tested positively or negatively in more than thirty thousand places located in forty departments, each of which has sent me between three hundred and two thousand requests. The theory has been tested positively each time it has enabled me to indicate a groundwater occurrence, and negatively each time it has revealed to me that the rock type in the area where I had been called contained no water. It has been applied, I believe, on all the rock types that exist in France, from the most compact to the most disaggregated, and from the most regularly stratified to the most upturned. It has been applied at all elevations from the cliffs of Normandy to the rounded mountains of the Vosges, from the moors of Bordelais to the highest houses in the Pyrenees, and from the mouth of the Rhône to the highest summits of the French Alps. It has also been used during very cold weather and very hot weather, during very dry periods, and during the heaviest rains. I have not noted any obstacles for hydroscopic operations except for the night and snow, which make it impossible to see the land. Indications have been made on a wide variety of rock types, in very different positions and in very different seasons; these indications have succeeded everywhere in approximately equal proportions (this topic will be discussed in Chapter XXXI). This treatise is thus no longer a simple theory to be proven; it is the summary of all the hydroscopic observations that I collected over nine years of theoretical study and twenty-five years of experience.

I add as encouragement to students of hydroscopy that after several years of travel and exploration, it was possible for me to indicate some springs and their volume from a distance, to describe the back side of some mountains and hills where I could see only one side and to point out springs on the reverse side, and also to indicate springs on Cassini maps and determine from a great distance that certain homes had cracked walls. The first audiences who heard me make these statements in areas where they had been assured I had never visited and that no one had told me about, were amazed. The best informed regarded the statements as transcendent geology and the man in the street considered them as marvels.

These first designations, which I made only occasionally and as an amusement, had barely escaped my lips when they were widely circulated. For the last twenty years in almost every place where I have appeared, people have asked me for all sorts of indications; they all want to be sure if what they have heard is true. To avoid displeasing respectable people and annoying the hordes of the curious who always surrounded me, I was obliged to repeat them thousands of times. To the extent that the occasion has presented itself in the course of this book, I have cited the designations and the observations on which they are based, and the reader will see that these were easy to make. For those who have not made these observations, it is a marvel; but for those who have observed or will do so, it is nothing.

I wanted to report these facts and many others that the reader will find in this book without mixing in anything personal but this work is based on observations I made. Not knowing how to report them while leaving the author out, I could not avoid reporting them given that these facts confirm or clarify the observations and that the precept contained in an example is much easier to remember.

The art of discovering springs is, like all physical sciences, subject to indefinite improvement; new observations will provide new means to avoid errors. Thus, I do not offer this theory as a complete treatise on this subject but rather as an essay designed to shed light on this branch of human knowledge. Capable men who go out in the field and study the water found there will correct many observations that I was not able to make and will add observations that escaped me. They will produce writings that will present a better order and style than this one. I will always applaud all efforts of those who conduct research with the goal of perfecting this theory and I will rejoice each time I see that someone has succeeded.

If among men who study the sciences, there are those who collect interesting observations on this subject but do not want to publish them, I ask them to please send them to me at Saint-Céré (Lot) and indicate the faults that they have found in this book and the corrections they would like to see added. All observations will be acknowledged and those considered well founded will be included in a second edition, if such an honor is accorded to this book before or after my death.

The publication of this method has been postponed until now for the double purpose of convincing the public more and more of its truth and of perfecting it and always adding new observations that I have collected in my many travels because my grand desire has been, if possible, to commit myself all the errors that it may lead to, to discover the causes, to point them out to student hydroscopes, and in this way to avoid them.

Now that all desirable experiments have proven this theory, have revealed almost all hidden springs, the line along which each flows, their depth and volume, whether it fails in some cases and is lacking in some areas, I see no reason to postpone publication any longer. I think that people would rather have a defective method for finding springs than none at all.

It may happen that someone sooner or later will invent a completely different method that will be infallible or at least will succeed at a higher rate than mine. If this happens, I recommend in advance to the entire world to follow those directions and pay no more attention to this essay.

Notes

1. Cassiodorus tells us (*Book III, Letter LIII*) that the art of seeking springs was cultivated among the Greeks, among the Romans, and especially among Africans, and that a certain Marcellus wrote a book on springs and groundwater. His writings have not come down to us.

2. The most remarkable modern discovery I know of is the springs of Coulanges-la-Vineuse, of Courson, and of Auxerre in Burgundy, discovered in 1705 by Couplet, engineer and academician. These three discoveries received wide acclaim and led to Fontenelle's solemn eulogy to Couplet upon his death. See *Works of Fontenelle*, *Tome VI*, Eulogy of Couplet. Unfortunately, Couplet left no written record of his method.

3. "It seems," said Racine the younger (*Relig., chant v*) that to "better humiliate those who cultivate the sciences, God has allowed the most beautiful discoveries to be made by chance, and by those who least should have been able to do them. The compass was not discovered by a sailor, nor the telescope by an astronomer, nor the microscope by a physician, nor the printing press by a man of letters, nor gunpowder by a military man."

## 2.2. Table of Contents

## 2.3. Foreword to the Second Edition

The public's reception of the first edition of this book, published in 1856 with a print run of 3,000 copies, has encouraged me to offer a second.

In the preface to the first edition, I asked all those who study science to indicate any errors they noticed in the book and to send corrections they thought should be included. After this appeal, I expected to receive numerous and broad advice that would have provided me the means to make this edition less imperfect than the first; this hope was not realized. Since the appearance of the book, I have received from very learned men in all parts of France numerous letters containing compliments on this publication. I regret that I have not received a single one that pointed out an error to be corrected.

During the year 1856, newspapers have reviewed this book very favorably and have even showered it with praise. We can cite among others: *la Patrie*, 25 January; the *Gazette de France*, 23 January and 13 February; *le Pays*, 20 March; *l'Illustration*, 22 March; *l'Assemblée nationale*, 29 March; the *Vœu national de Metz*, 9 April; the *Journal d'Agriculture pratique*, 5 May; the *Journal des Villes et des Campagnes*, 2 June; *l'Univers*, 19 December, etc. Although no doubt the book contains numerous errors, no journal pointed out a single one or proposed to introduce the least correction; they have instead granted an indulgence and pardoned the form in consideration for the content.

Thus deprived of all help and reduced to my own inspiration, I examined the book again with all possible attention and I must admit that I found nothing essential to remove or change. I added a few facts, some new observations and citations that seemed appropriate to strengthen or clarify the principles of the book. This second edition is thus a reproduction of the first with a few additions and few corrections.

## 2.4. Chapters

### 2.4.1. Chapter I. Hills

The Earth's surface is not uniform. High points and depressions are uniform within a given rock type and they occur according to similar ratios almost everywhere. The following is a list of names given to different parts of high places and the relationships between them.

A mountain is an extensive mass of rock that rises considerably above the surrounding land. The highest part is the summit [Fr. *sommet*] or the top [Fr. *cime*]. The slopes [Fr. *pentes*] are the flanks; the base is the horizontal plane on which the mountain rests; the foot [Fr. *pied*] is the perimeter of this plane; the height [Fr. *hauteur*] is the perpendicular between the summit and the base, and a cliff [Fr. *escarpement*] is the almost vertical plane formed by one of its sides. A plateau is an extended plain located on a mountain.

According to some, a hill [Fr. *colline*] is a high point located on a plain, detached from neighboring mountains and rising to at most two hundred meters; others (far more numerous) define a hill as any extensive mountain, isolated or not, that does not have a high elevation.

Small isolated mountains are called hillocks [Fr. *monticules*], and the smallest of them is a mound [Fr. *butte*] or knoll [Fr. *mamelon*] (1).

The top of a mountain may be rounded, forming what is called a dome [Fr. *dôme*] in Auvergne, a "ballon [Fr. *ballon*]" in Alsace; if the dome has steep slopes it may be called a peak [Fr. *pic*]; it may also form a very sharp thrusting point called a needle [Fr. *aiguille*].

It is rare to see isolated mountains; they sometimes occur in groups and most often are located one in front of another, forming series called mountain chains that extend in a definite direction and have branching ridges extending right and left.

The summit [Fr. *faîte*], the crest [Fr. *crête*], or ridge [Fr. *arête*] of a chain is formed by all the crests and summits of all mountains that are part of it; the flanks are called hillslopes [Fr. *versants*] because they direct water toward the plains; the axis [Fr. *axe*] is the line that passes through the center of each mountain; the foot is the lower part of each hillslope; the width [Fr. *largeur*] is calculated from one foot to the other, and the height [Fr. *hauteur*] is the vertical elevation of the summit above the two feet.

No mountain chain has regular parts; the width differs from one place to another; the crest has elevations called peaks and low points called passes [Fr. *cols*]; the axis and feet are complicated curved lines. The two hillslopes are highly undulating surfaces that are rarely inclined to the same degree; one is almost always shorter and has a steeper slope than the other (2). The steepest is simply called a slope [Fr. *pente*] and the less steep is called a gentle slope [Fr. *contrepente*].

The highest point of a mountain chain separates or divides the water; water flows down one hillslope or the other into different rivers.

Each peak is the point of departure of two ridges [Fr. *rameaux*] that extend in opposite directions and each pass is the point of departure of two opposite valleys. The ridges that depart from the principal chain have additional ridges called foothills [Fr. *contreforts*] or spurs [Fr. *éperons*]. A very short foothill or a spur is called a bulge [Fr. *renflement*].

Each ridge, even each foothill of a certain length, can be considered a simple chain since it has all the parts of a principal chain.

The end of a mountain or hill that terminates at a plain is a "*croupe* [French]" or rounded hilltop. The two sides that form the valley walls are ordinarily made up of a series of rounded hilltops that terminate at almost the same line; to the eyes of the observer on the plain, the sides form a trapeze, a triangle, a soft slope, or the shape of an overturned boat.

The chain that forms the divide between two rivers has a certain parallelism to the rivers and the ridges that come off the chain always decrease in height and converge downstream into the rivers where they terminate (3). Foothills have the same arrangement with respect to the streams that flow at their feet.

Notes

1. Neither geographers nor geologists have described how these four types of heights differ from each other; names that should be used exclusively for each are still so arbitrary that the same hill is called a mountain by one, a hill by another, and a hillock by others. Because the words in this book should have as precise a meaning as possible and while waiting for others to propose precise definitions, I define a mountain as any elevation higher than 200

vertical meters above the surrounding land surface; a hill, any extensive mountain that is 100 to 200 meters high; a hillock, any small isolated mountain 50 to 100 meters tall; and a knoll or mound any isolated hillock less than 50 meters high.

2. The Vosges and the French Alps have steeper slopes on the east than on the west; the Pyrenees are steeper on the Spanish side than on the French side. The southern hillslope of the chain that traverses the Department of Lot drains water to the Lot River; it is steeper than the northern hillslope that drains water to the Dordogne River.

3. Ridge tops are sometimes higher than the crest of the principal chain. Mont-Perdu in the Pyrenees and Mont Saint-Bressou in the Department of Lot lie outside and higher than principal chains but are very close to them. These anomalies are extremely rare.

### 2.4.2. Chapter II. Depressions on the Earth's Surface

Intervals or depressions are present between the ridges that extend from the principal chain (foothills) and spurs that extend from ridges. These intervals or depressions, which may be of various magnitudes, are called valleys [Fr. *vallées*], vales [Fr. *vallons*], defiles [Fr. *défilés*], gorges, ravines [Fr. *ravins*], and depressions [Fr. *plis de terrain*] (1). Valleys are large depressions that descend from the principal chain to a river; vales separate ridges or form only small valleys; defiles or gorges separate foothills or are very narrow and bordered by steep cliffs; ravines are elongate, narrow excavations with steep slopes that have been excavated by streams; and finally, depressions are shallow hollows.

The flanks or hillslopes of the hills, ridges, and foothills that form the sides of these depressions are called flanks or hillslopes of the valley, vale, gorge, ravine, or depression. The sinuous line of intersection formed at the bottom of the two flanks or hillslopes is called the thalweg (2) [See Translator's Notes]. Rainwater follows this line in a valley or vale.

Each valley receives a number of vales, defiles, gorges, ravines, and depressions from right and left; each vale receives multiple depressions of a lesser order.

In these valleys and vales, etc., the observer should notice that every time the end of a mountain advances into the valley on one side [Fr. *côté*] and creates a feature called a salient [Fr. *angle saillant*], a recess called a reentrant [Fr. *angle rentrant*] is present on the opposite side. Along one side of a valley, salients alternate with reentrants; thus each salient is formed by two reentrants and each reentrant by two salients. The arrangement is the same on the opposite side of the valley but the salient on one side never occurs opposite a salient on the other side; likewise, reentrants do not occur opposite reentrants. Instead the salients on one side of the valley correspond exactly to reentrants on the other, and vice versa. If the two hillslopes of the valley were to come together, the salients would interlock with reentrants on the other. These rules have exceptions only in very wide valleys and in some places in primitive rocks [See Translator's Notes].

When the two hillslopes of a valley or a vale have a gentle slope, the valley is generally flared and its stream is regular; the thalweg is located at a distance almost equal from the two hillslopes, but where the slope is steeper on one side, the thalweg inflects toward this point.

Valleys formed by two steep hillslopes [Fr. *versants escarpés*] are generally very narrow and irregular: an observer can see numerous narrow and wide places; the thalweg follows infinite inflections but is always closer to the steeper side.

It is important to note the relationship between valleys. A principal valley is similar to a stem [Fr. *tige*] to which other branches or lateral valleys are attached. Each lateral valley of considerable length branches and receives a number of lower-order depressions that in turn bifurcate upstream. Where two lateral valleys on opposite sides of a principal valley flow into the principal valley, they never do so across from each other. Outlets on one side alternate with those on the opposite side and they are located at widely varying intervals. This alternation has some exceptions; in some places the principal valley may receive two or three valleys in succession on the same side without any valley arriving on the opposite side.

Plains are large spaces that appear to be horizontal although they are never completely so. The observer can see crests or drainage divides [Fr. *crêtes de partage*] and ridges and slight depressions that form valleys where streams often flow. Although at first glance the observer may not be able to determine the inclination of the plain, after some exploration and attentive observation, an observer can usually determine not only the general slope but can also see several basins that divide it and even small ridges in these basins. The plains are sometimes very extensive.

Notes

1. These six types of depressions differ only by size; they cannot be distinguished from another by any particular characteristics because all the surface features seen in one are found in all the others. To avoid constant repetition of this nomenclature, I will commonly use the word vale, which by extension will imply all the others.

2. This German word means valley path. In all valleys and vales with a river or stream not yet disturbed by man, the stream always follows the thalweg, which is always the lowest line on the plain. In valleys and vales with no visible stream, the real thalweg can be found by imagining a stream running the entire length of the valley; the line this imaginary stream would

follow is the real thalweg of the valley or vale. The student hydroscope should carefully study this line in the field because it is important for finding groundwater.

### 2.4.3. Chapter III. Internal Structure of the Earth

The various rock types that make up the globe's crust are not arranged in a confused or haphazard manner. They follow a certain order of superposition and transition from one rock type to another according to certain laws. For this reason, upon simple inspection of the visible rock type, an experienced geognost can almost always determine with good probability what is underneath and what cannot be seen. Thus, gneiss is ordinarily superimposed on granite; limestone rests on clay; coal-bearing sand contains coal deposits; detrital, water-deposited, and alluvial rocks rests on the same rock type that surrounds them, etc. Quarry-workers are very skilled at predicting the types of rock they are looking for.

There are numerous rock types and their combinations vary almost to infinity and so to be able to discuss them, geognosts have been required to name, divide, and subdivide them and to describe them separately. To treat this subject in depth would require a complete description of each rock type, which would fill several volumes and would cause us to deviate too much from our subject. It would also be a superfluous task since this nomenclature, division, and description are found in elementary treatises on geology. I will thus restrict myself to explaining a number of terms most commonly used in this treatise and in all geology books. In following chapters I will describe the most common and most useful rock types to know (1).

By soil or ground surface [Fr. *sol*], we mean the surface of the crust of the globe, the surface we walk on, on which water circulates, and the layer the farmer exploits.

A rock [Fr. *roche*] is a mineral mass, simple or mixed, usually hard, with large enough dimensions that it can be considered a constituent of the Earth's crust. When rocks are massive in form and when they have a considerable thickness not separated by bedding planes or fissures they are called unstratified masses. But rocks are not usually present in shapeless masses; a particular structure can almost always be noted: some are divided into layers, some into prisms, others into sheets, etc.

A layer [Fr. *couche*], also called a stratum [Fr. *strate*], bench [Fr. *banc*], bed [Fr. *lit* or *assise*] is a part of a rock that is wider and longer than its thickness. It is bounded by two fissures parallel to each other and parallel to all other fissures that separate the layers of the same rock. The fissures that separate the layers are called fissures or bedding joints [Fr. *joints* *de stratification*], and the two surfaces of each layer are called bedding planes [Fr. *plans de joint*]. In addition to bedding joints, one can often see in each layer a number of other fissures that are vertical or oblique to stratification fissures; these are called joints [Fr. *fissures accidentelles*]. It is easy to distinguish one from another, given that bedding joints always separate beds or strata, extend for long distances, remain parallel through all inflections, and are parallel to the surface of superposition; these are not joints.

Schistose rocks or schists are separated into strata or layers and each layer is subdivided into countless thin layers attached to each other, more or less coherent, parallel among themselves, and also parallel to the stratification of the rock. These layers often have uneven thickness, are wavy, and are sometimes folded over on themselves. Gneiss, slates, etc. are schistose rocks.

The arrangement of the layers in a rock is called its stratification. Stratification of different rocks can be arranged in very different ways; sometimes the strata are almost horizontal, sometimes inclined and even vertical, and sometimes contorted or folded over. By convention, we use the term horizontal stratification for layers that are generally slightly inclined, which is the most common case, and inclined stratification for layers that are highly inclined or almost vertical. The term undulating stratification [Fr. *stratification arquée*] is used for undulating layers and for layers on a mountain or hill that follow the direction of the slope on one side, curve at the summit, and re-descend on the opposite slope, or that descend along the slope of a hillside, curve at the bottom of the valley, and follow the upward slope of the opposite hillside. Contorted layers [Fr. *couches contournées*] are those that have multiple curvatures in different directions.

A layer is said to be subordinate to other layer or to a group of rocks when it is interbedded within them.

Stratification is called regular when all beds are parallel to each other and have the same general direction. It is irregular when the layers do not show this parallelism.

Because the layers of a rock are almost never perfectly horizontal, one can usually determine a dip [Fr. *inclinaison*] and strike [Fr. *direction*].

The dip of a layer is the angle between the bedding planes and the horizon; and its strike is that of a horizontal line drawn on the bedding plane; thus, a geologist says that a layer is inclined so many degrees or that it plunges at such an angle and that its direction is toward a cardinal point. The direction of the layers in a mountain chain is generally that of the chain itself.

The upper surface of a layer is the top [Fr. *tête*]; when this part is exposed at the surface it is called an outcrop [Fr. *affleurement*] and the other sides of it are the tips [Fr. *extrémités*]. When the thickness of a layer is exposed on its side at the surface geologists say the stratum is tilted [Fr. *sur sa tranche*]. The thickness of a layer, a rock or a mineral mass is called its thickness [Fr. *puissance*].

When two or more rocks that are superimposed on each other or located next to each other have parallel layers, they are said to have concordant stratigraphy; on the contrary, when their inclination is different, their stratifications are discordant or transgressive.

Layers are said to form a cliff when they terminate in an abrupt manner.

The word fault [Fr. *faille*] is used for a dislocation or fracture of rock layers where one of the two sides has remained in place and the other has dropped down or been raised and the layers on one side no longer correspond to layers on the other. A fault can be empty or filled.

A dyke is a rocky or disaggregated mass that has come to occupy the space between two sides of a dislocated rock. The nature and arrangement of the dyke differs from that of the two rocks that have separated. A dyke may be very thin and of limited extent and other times it may be several kilometers long; it can be several hundred meters thick and very deep.

The word block [Fr. *bloc*] is used for portions of coherent rocks found on the ground or buried in masses of a different rock type; blocks have a large volume, larger than a human head, for example. They are sometimes rounded and may also be angular or mammillary.

A deposit [Fr. *dépôt*] is the result of a mechanical or chemical precipitation in a liquid environment. This word is also used to designate a mineral mass found emplaced in any part of the terrestrial crust, without regard to the manner in which it was emplaced.

Note

1. "Twenty-five to thirty species at the most," says Mr. D'Orbigny (*Géol*., Chap. VII) "because of their abundance, play a major role as essential materials of the mineral composition of the globe."

"Observation has shown," says Mr. Carlet (*Traité élémentaire des Roches*, introduction) that of four hundred different minerals species that have been recognized on the solid crust of the earth, only thirty are essential elements or constituents in the composition of rocks; the other species show up only as accessory or accidental parts, so to speak. Of these thirty mineral species, Mr. Cordier noted that only about a dozen at the most are present in abundance in nature."

### 2.4.5. Chapter IV. Unstratified Rocks

Different rock types affect the formation and flow of springs in various ways; following the example of Mr. Labèche, Mr. Boué, and Mr. Brongniart, I divide rocks into two categories: unstratified and stratified. This division, which is very real in nature, is easy to grasp and sufficient for the information that will follow.

By unstratified rock we mean earth materials that lack layers or parallel bedding and whose stratification is completely irregular or not apparent.

Unstratified rock occurs in each of the five large commonly accepted divisions: primitive, secondary, tertiary, diluvium [Fr. *diluvien*], and modern terrain [See Translator's Notes].

Primitive rocks consist of granites, porphyries, micaschists, syenites, quartz, trachites, primitive limestones, etc.

Unstratified secondary rocks include compact limestones, clays, thick layers of lava, ophiolites, etc.

Unstratified tertiary rocks include marl, molasse, gypsum, crystal salts, etc.

Unstratified alluvial or transported material includes sands, dunes, peats, and among modern rock types we find detrital deposits [Fr. *terrain détritique*], scree [Fr. *éboulis*], tuffs [Fr. *tufs*], deposits from active volcanoes [Fr. *déjections des volcans en activité*], silts [Fr. *limons*], etc.

Granite is a word formed from Latin *granum*, grain; it is a rock composed of feldspar, quartz, and mica. These three crystalline and mutually penetrating materials have been melted together. Feldspar is more abundant than the two others and quartz is more abundant than mica. Granitic masses have no trace of real stratification. Granite has neither caverns, nor voids, nor debris of organisms. Metals are rare in granites. The cracks that split granite up into blocks of all shapes and sizes go in all directions and do not parallel each other. Of all ancient rock types, granite is the most widely distributed at the surface. It occupies most of the Limousin and large areas of Brittany, the Vosges, Auvergne, the Pyrenees, Vivarais, etc. It covers areas of extensive plateaus, mountains of medium heights, and rounded hills. However, toward the middle of mountain chains it sometimes forms very high mountains with sharp summits from which enormous blocks break off and roll down the hillslopes to the valley bottom; some blocks remain angular and others are rounded as a result of weathering. In this rock type, valleys ordinarily begin at a cirque with vertical walls. The most common color of this rock is milky white; it may also be yellowish, reddish, violet, or blackish.

Porphyry is a rock composed of siliceous paste containing black or gray feldspar crystals, and sometimes quartz grains and pyroxene. The most common color is gray or blackish; more rarely it is reddish or greenish with white spots. Porphyry has a strong resemblance to granite; the primary difference is the tendency of porphyry to form dykes, which are most often found in the interior of granitic masses or near them. Porphyry is also interbedded in sedimentary rocks. The small cavities found in this rock are filled with quartz or calcium carbonate. This rock type is very common but it rarely occupies extensive areas. The areas of France where it is most abundant are the Morvan, Beaujolais, and the Forez. Almost all mountains composed of porphyritic rock are conical and have rounded hills. There are three types of porphyries: red or quartz bearing, green or serpentinous, and black or pyroxenite.

Gneiss, like granite, is composed of feldspar, mica, and quartz, but differs from it in several ways. Quartz is present in a lesser proportion in gneiss and gneiss is stratified and has a schistose texture. Its foliation and strata, which are highly variable in thickness, are folded and contorted in all directions. This distinguishes it from sedimentary rocks. Gneiss is not productive in terms of agriculture but is rich in precious minerals; it contains gold, silver, tin, copper, iron, garnets, rubies, topaz, and other materials, but no organic debris. Its color is ordinarily gray; however, because its color depends on that of mica, it ranges from white to black. Gneiss forms extensive very thick masses and occupies the upper parts of [or "occurs on top of" –tr. note] primitive rock units where it rarely constitutes high mountains. Valleys in gneissic rocks are ordinarily narrow and they begin at cirques with highly inclined walls. This rock is widespread in Limousin, Auvergne, Brittany, Vendée, etc.

Micaschist is composed of mica and quartz, and has schistose structure. In some micaschists, quartz is hardly apparent; in others, veins of pure quartz cut through the mass. Mica, the predominant mineral in this rock, is distributed in continuous layers and gives the rock its color. The color of micaschist ordinarily ranges from black to white; some samples have reddish or violet tinges. Micashist is stratified but its layers, which are very fine, are almost always disturbed, are of minor extent, and are folded, undulatory, and even contorted. Masses of micaschist descend to very great depths and cover large areas; they usually form low elevation mountains with rounded hills that are arranged in groups, terminated by vast plateaus, and separated from each other by numerous ravines. It sometimes contains garnets, feldspars, oligist [See Translator's Notes], iron hydroxides, etc., but no organic debris. This rock is used for construction; it is easy to extract, easy to prepare, and highly durable.

Trapp is a rock composed of an intimate mixture of feldspar and amphibole; it sometimes contains pyroxenite, leptynite [See Translator's Notes], and eurite [See Translator's Notes]. Its name comes from a Swedish word *trappa*, which means stairway because on mountain slopes it ordinarily outcrops as terraces; it may also be present in dykes, where the central parts are more crystalline than the extremities. This rock has a homogeneous appearance, is hard, compact, has high tensile strength, is sonorous, and lacks organic debris. It is gray, black or greenish in color, rather like basalt, but rather than separating into prisms like basalt, it breaks up into fragments of various sizes and shapes. When these fragments remain on the ground a long time, they take on a rounded shape and are covered with rust. This rock occurs all over the world. In some places it forms shapeless masses or irregular cones; in other areas, it forms entire hills.

Breccias, puddingstones, and conglomerates are called aggregated rocks [Fr. *roches d'agrégation*], composed of old rock fragments agglutinated by recent cement. Most fragments in these rocks, such as quartz, feldspar, granites, porphyries, etc. come from primitive rocks. Some fragments have come from basaltic and calcareous masses. Rocks composed of angular fragments are called breccias; others composed of rounded pebbles are called puddingstones. The size of these fragments ranges from one centimeter to a decimeter in diameter. When the diameter of the fragments is between a decimeter and several meters, the rock is called conglomerate. The cement that binds these fragments is silica and iron-rich calcite. The strength of the rock varies significantly and the rock decomposes more easily than pebbles. Thus, because each fragment protrudes, the surface of the rock is usually highly unequal. These rocks are called *homogeneous* when the fragments are of the same type and are cemented together by the same type of cement; they are *heterogeneous* when the fragments are of different types. In some places, they form horizontal or almost horizontal layers. These rocks are widespread in Provence. In some places, they fill very large valleys; in others, they form extensive plateaus and hills of medium height where present-day streams cannot reach them. The cantons of Mécs, Valensolle, and Riez (Basses-Alpes) are almost exclusively this rock type. Thickness of this rock type ranges from several decimeters to hundreds of meters.

The descriptions of several other types of unstratified rocks are found in parts of this book where they are required. To avoid repetition, I indicate here the chapters where they are found: *scree*, Chapter VII; *tuff*, Chapter XIX; *volcanic rock*, Chapter XXI; *chalk and marls*, Chapter XXII.

### 2.4.5. Chapter V. Stratified Rock

Stratified rock formed during the time when water covered the earth. The molecules of which these rocks are made were held in solution and suspended in water for long periods. Due to their specific gravity they were deposited and consolidated slowly; they formed extensive layers emplaced one on top of the other. Each layer differs from overlying and underlying layers in terms of thickness, constitution, or color. These layers are generally horizontal and parallel to each other, have quite diverse thicknesses, and they contain debris of shells or petrified plants.

However, the primitive surface on which these layers were deposited and shaped had high and low places, and we observe that the layers follow the unevenness of this land surface and rise and fall as the surface rises or dips. Later movements produced by uplift or down-dropping of the ground surface have also disturbed the horizontality and parallelism of the layers in many locations, have left many layers tilted, some even entirely overturned, and others broken and split up into blocks or fragments of all sizes. Stratified rocks, also called *sedimentary*, occupy large areas and cover most of the continental area. Mr. Burat (*Géol. appliquée*. ch. II) *claims that they cover four-fifths of the emergent land surface*.

The various materials that seawater held in suspension are not the only materials deposited and consolidated in parallel beds. The materials deposited on primitive rocks also seem to have obeyed the law called the *affinity of composition by precipitation*, and to have grouped themselves by species. Thus sandstones have been deposited in one area, limestones in another, farther away are clays, marls are in another place, etc. Each rock type has well-established limits and is distinguished from surrounding rocks by its nature, form, and color. If rock types are mixed in some places, it is because ocean currents have picked up certain elements from many already-formed rocks and mixed them up and transported them onto the top of others. This is how present-day water currents erode and carry away all sorts of debris from higher regions and deposit the debris in a jumble on lower plains.

Almost all rocks that make up secondary rock types, such as sandstones, limestones, some chalks, etc., are distinctly stratified.

## Sandstones [Fr. *grès*]

*Sandstone* is ordinarily a stratified rock composed of grains whose size ranges from a millimeter to a centimeter in diameter; it is usually consolidated by cement. The grains are fragments of granite, porphyry, quartz, etc. that have been eroded from their respective rocks and violently transported by ocean currents. Fragments that were eroded nearby have angles that are almost intact; others are rounded in relation to how far they have been transported. The fragments are bound and agglutinated together by a quartz or ferruginous calcite or ferruginous clay cement; they form layers that are ordinarily horizontal, that are sometimes hard and sometimes friable, and that vary significantly in extent and thickness. The lower part of each layer includes larger fragments than the upper layers. Sandstones have all shades of color that can result from mixing colors.

There are three species of sandstone: *red sandstone [Fr. grès rouge], spotted sandstone [Fr. grès bigarré], and tritonian sandstone [Fr. grès tritonien*].

*Red sandstone* or *Old Red Sandstone* [Fr. *vieux grès rouge*] is composed of small fragments of quartz, feldspar, and mica, most often cemented by clay-iron pasty cement; it is reddish purple or amaranth in color. The stratification of this rock mass is perfectly concordant; its thickness ranges from 60 to 200 meters.

*Spotted sandstone*, composed primarily of fine quartz grains and some mica flakes, is multicolored in red, violet, blue, green, and white; however, red always predominates. As in red sandstone, the grains are cemented by an iron-clay paste. Layers of multicolored sandstone are ordinarily solid, only slightly inclined, and have few faults. The lower layers are thickest and are used for building stone [Fr. *pierre de taille*]. Moving upward in this formation, finer layers are used for whetstones and grindstones [Fr. *pierres et meules à aiguiser*], of which experience has shown the value, and higher still the formation provides thin layers that can be used as paving stones [Fr. *dalles*] and are fissile enough to use as slate roofing [Fr. *ardoise*]. This sandstone is very poor in metals and contains very little organic debris. The location of the thickest and most extensive multicolored sandstone known is the Vosges, which has given its name to *Vosgian sandstone* [Fr. *grès vosgien*]. It extends over five departments and occurs in very deep valleys where no other rock type is seen. It is also found near the towns of

Périgueux, Brives, Rodez, Saint-Affrique, Saint-Girons, and Brignoles. This sandstone forms mountains up to 300 to 400 meters in height that are terminated by rounded crests or sharp summits. The valleys that separate them are ordinarily very flared.

*Tritonian sandstone*, also called *Fontainebleau*, is commonly a very thick rock that extends over a large area [See Translator's Notes]; it is composed of grains of very fine, pure, white sand cemented by ferruginous quartz, calcite, or clay. When quartz dominates in the cement, this rock is very hard; when calcite [Fr. *calcaire*] dominates, it is less so, and when clay [Fr. *argile*] dominates, the rock is friable. Instead of regular layers, this rock is composed of benches of very unequal thicknesses, variable at each step, and the bedding planes are rarely parallel. Their surfaces have many salient points and rounded cavities. There is no trace of organic matter. Although the most common color of this sandstone is white, in some localities it takes on slight tinges of green, yellow, and red. In this formation, rounded blocks are progressively detached from high points on all hillslopes and pile up on their slopes, principally toward the base. Some of these sandstones are fine enough and porous enough to be used for water filtration; the very hard types are used for building and to pave streets. Paris has no other kind of pavement. This sandstone is very widespread in the area of Fontainebleau, which is why the rock bears the name of the town. In other places, such as near Lalinde (Dordogne) only small areas of this rock are present; these rocks have been used to pave the streets of Bordeaux.

### Limestones [Fr. *calcaires*]

*Limestones* are compact rocks composed of calcium carbonate; they are easily scratched by steel, effervesce with acids, and are converted into lime after prolonged calcination. Their composition varies only slightly: carbonate, clay, and silica are essentially the only elements. All limestones hard enough to take a good polish are called marble. Foreign material found within limestone layers is arranged parallel to their longest axis; thus, flattened shells lie on one of their two faces; ovoid shaped pebbles are deposited flat-lying. The most common color of limestone is yellowish; others are bluish, reddish, or greenish and still others range to white, gray, or black. The latter two owe their color to sulfurous, carbonaceous, or bituminous material that has impregnated them. When broken these rocks exhale an odor for which they have been named *fetid limestone* [Fr. *calcaire fétide*]. A prodigious amount of shells, preserved to varying extents, are found in limestones; these shells can be used to tell the rocks apart. Some animals that lived in these shells have analogues that live in our oceans today; others have disappeared entirely. Calcareous rocks have the widest distribution, have been studied the most, and because of their regularity provide the best evidence for recognizing the presence of moving groundwater. Limestones have been divided and subdivided to such an extent that I will discuss only the major ones: oolitic, compact, saccharoidal, siliceous, shell-bearing, marly, and coarse.

*Oolitic limestone* or *oolite* is composed of an infinite number of small grains that resemble fish eggs; the grains are glued together with calcite cement. Each grain commonly contains a small nucleus of sand around which concentric layers of calcareous material have been deposited. These grains are generally ovoid and vary in size; they range from the size of a millet grain to that of a pea. This limestone is ordinarily yellowish and of variable strength.

*Compact limestone* has an excessively fine and very tight grain, a homogeneous appearance, and occurs as many varieties. It breaks unevenly and is rough to the touch. It is sometimes fragmentary and easy to break but sometimes has a remarkable hardness. It is yellowish, bluish, gray, or black. This species is widespread; it contains numerous fossils and can sometimes take a good polish.

Oolitic limestone and compact limestone form a *limestone* called *jurassic* because it makes up almost all the mountains of the Jura. This rock type has the greatest thickness and the highest elevation. It is 700 meters thick in some places; it extends from the Corbières Mountains south of Narbonne to La Rochelle. It occupies a surface area of approximately 10,500,000 hectares (105,000 km$^2$).

*Saccharoidal limestone* [Fr. *calcaire saccaroïde*], so called because its texture resembles sugar, is a marble with a crystalline or semi-crystalline texture. It has an uneven fracture, is harder than other limestones, is sometimes stratified and sometimes occurs in shapeless masses, takes a good polish, and may be mixed with a number of minerals that imprint their colors and nuances, creating all sorts of designs.

*Siliceous limestone* [Fr. *calcaire siliceux*] is composed of calcium carbonate and silica so intimately mixed that the two cannot be distinguished. Siliceous limestone is harder and more compact when siliceous material predominates. When siliceous material is present at a high concentration, the rock sparks when struck and ceases to be effervescent with acid. This limestone is sometimes cellular, even cavernous, and the cavity walls are often covered with quartz crystals. Siliceous limestone is white, gray, or yellowish.

*Shelly limestone* [Fr. *calcaire coquillier, conchylien*] or muschelkalk is a compact limestone, regularly stratified, sometimes laminar, that seems to be entirely composed of a paste of shells reduced to dust; during solidification, it may be thickened by a large number of shells, some broken and others perfectly preserved. Ordinarily smoky gray in color, it can also be yellowish, greenish, or reddish. When shell debris is not abundant, its fracture is conchoidal or flat; when debris is abundant, the fracture is uneven. Some marly, sandy, and thin layers are interspersed between its layers. This limestone occurs as limited patches in many areas. It does not form high elevation mountains; its hills have rounded contours and gentle slopes and they terminate in plateaus. Its layers are horizontal or gently inclined. In the Vosges, it is bounded on one side by multicolored sandstone, on which it rests in concordant stratification; on the other side it is bounded by iridescent marls. It is found near Epinal, Luxeuil, Bourbonne-les-Bains, Lunéville, Aubenas-en-Vivarais, between Cahors and Labastide-Murat, at Cap de Seine, at the foot of Mount Faron near Toulon, in Poitou, Dauphiné, Jura, Burgundy, etc. The shape of muschelkalk mountains resembles that of rocks in the Jura. The shells most commonly found are: terebratulids, encrinites [crinoidal limestone - tr. note], plagiostomes [fish with ventral mouth - tr. note], avicules [generic name for mollusks that provide nacre and pearls - tr. note] belemnites, turbinites [petrified shell resembling a member of the genus Turbo - tr. note], crinoidal fragments, etc. Mr. de la Bèche has counted ninety-one species of shells. Dinosaur bones and imprints of ferns and fucoids [trace fossils – tr. note] are also found. A variety named *lumachelle* can take a good polish and appears to be entirely composed of broken shells; some of them have preserved their brilliant nacre.

*Marly limestone* or *lias* is a mixture of fine-grained limestone and clay. The higher the clay content of the rock, the softer, more friable, and more easily it is weathered by atmospheric agents. Its layers are almost everywhere horizontal or slightly inclined. This limestone does not resonate when hit with a hammer, does not take a polish, is easily penetrated by water, and breaks as it dries. It is characterized by the presence of a shell called the *gryphea archée* [*gryphaea arcuata*]; crinoid fragments, terebratulids, trilobites, and madrepores are also found. This limestone contains the greatest number of shell species and minerals. One of its varieties is used to make hydraulic lime and Pouilly cements. Silica is rare in this rock.

*Coarse limestone* [Fr. *calcaire grossier*] or *rubble stone limestone* [Fr. *calcaire moëllon*] is a rock with a coarse, sandy, loose, and impure texture. It is mixed with ochre marl, etc., forms large masses with numerous thick horizontal layers, and its texture ranges from very fine and compact to very coarse. It is yellowish or whitish in color. Its fracture in uneven and rough to the touch; it contains a large quantity of organic, plant, and animal debris. Almost all the animals are marine in origin. This limestone is used to build almost all the houses in Paris; the filter stone from the Paris area is one variety.

Rock hardness

Everyone knows that rocks constitute the major obstacle to drilling a well to provide groundwater. Some are soft and easy to break, such as molasse, marls, chalk, gypsum and marly, lacustrine, and madrepore limestone, etc. Others have average hardness, such as sandstones, schists, oolitic limestones, etc. Still others are very hard, such as quartz, marble, gneiss, granites, porphyries, traprock, puddingstone, siliceous limestones, etc. It would take more than a few lines or several chapters to discuss the relative hardness of different rocks and the probable deposits of them beneath the surface. This knowledge can be gained only by studying the complete treatises of geognosy and by long and repeated observation in the field.

Rock types of various areas

Most of our departments host only a small number of different rock types. The student hydroscope will ordinarily be able to learn their configurations without leaving his department since the rocks are subject to the same laws and the shapes of high places and depressions show little significant variety. But to study the nature and arrangement of the different rock types discussed in this book on-site and over large areas, he will have to visit areas that are for the most part located far from one another. Thus, to study the vast expanses of chalks, the student should explore Champagne; multicolored sandstone in the Vosges; limestones in Franche-Comté and the Alpes; marls in Lorraine; volcanic rocks in Auvergne and Vivarais; water-deposited rock units in Provence and Alsace; subsidence in Charente, Lot, and Vaucluse; landslides and upheavals in the Alps and the Pyrenees.

Rock types of the Department of Lot

The student who would like to spare himself long travel and wants to study rock types in the most compact area possible can explore the Department of Lot, where he will find almost all the rock types that exist in France, some of them extensive areas and others limited areas. Although the list that follows contains only the names of principal rock types, and does not present their numerous subdivisions nor the names of all communes where they are found, the list will suffice to show that this department has more rock types than any other, and that consequently it is suitable for geologic and hydroscopic study. The student hydroscope will find:

*Granites* at Comiac, Sousceyrac, Sénaillac, Lâbastide-du-Haut-Mont, Bessonies, Lawresse, Saint-Cirgues, Saint-Bressou, Felzins;

*Gneiss* at Gagnac, Teyssieu, Frayssinhes, Latronquière, Terrou, Molières, Aynac, Lacapelle-Marival, Banhac;

*Porphyries* at Latronquière, Lacapelle-Marival, Saint-Bressou, Cardaillac, Planioles, Figeac;

*Micaschists* at Frayssinhes, Labastide-du-Haut-Mont, Latronquière, Gorses, Terrou, Molières, Leyme, Aynac;

*Trapps* at Saint-Céré, Lacapelle-Marival, Saint-Bressou, Latronquière;

*Quartzites* at Saint-Cirgues, Sabadel, Cardaillac, Felzins, Montredon;

*Serpentine* at Cahus, Saint-Céré, Terrou (not exploited);

*Saccharoidal limestone* at Bastit, Reilhac, Espédaillac;

*Marble* at Marmignac, Floirac, Loubressac, Saint-Médard-de-Presques, Saint-Simon, Capdenac (not exploited);

*Arkoses* at Saint-Céré, Saint-Vincent, Terrou, Labathude, Saint-Médard-Nicourby, Cardaillac, Planioles, Figeac, Cuzac;

*Sandstone* at Aynac, Leyme, Anglars, Cardaillac, Planioles, Saint-Perdoux; they are also very common in the cantons of Catus, Cazals, and Gourdon;

*Puddingstones* and *conglomerates* at Lacapelle-Marival, Saint-Bressou, between Faycelles and Montbrun, in the band of intermediate rock types that extends from Dordogne to Lot;

*Breccias* at Luzech, Cabrerets, at the foot of most limestone slopes, under scree;

*Dolomite* at Lacapelle-Mauroux, Baladou, Figeac;

*Coal-bearing rock*, veins of coal that rarely reach one decimeter in thickness, at Teyssieu, Saint-Vincent, Lacapelle-Marival, Le Bouissou, Fourmagnac, Cardaillac, Saint-Perdoux, Cadrieu (not exploited);

*Compact limestone* at Souillac, Cahors, Vers, Bouziès, Saint-Cyr-la-Popie, Faycelles;

*Limestone* with *gryphaea* at Cahors, Mercuès, Montvalent, Miers, Livernon, Assier, Lissac;

*Limestone* with ammonites at Lavergne, Alvignac, Belmont, Saint-Laurent-les-Tours, Boussac;

*Limestone* with belemnites at Alvignac, Assier, Béduer, Figeac;

*Oolitic limestone* at Souillac, Saint-Denys, Carennac;

*Limestone* with sinkholes and cavernous limestone in the entire central part of the department, including ten cantons;

*Cellular limestone* at Esclauzels, Caniac, Quissac, Espédaillac, Grialou, Issendolus, Saint-Médard-de-Presques, Saint-Jean-Lespinasse;

*Shelly limestone* at Gramat, in most of the area between Cahors and Labastide-Murat;

*Marls* and *chalks* in most of the communes of the cantons of Lalbenque and Castelnau-Montratier;

*Clay* is widespread in the communes of Alvinac, Padirac, Thégra, Lavergne, Mayrinhac-Lentour, Bios, Saignes, Aynac, and Bueyres;

*Iron ore*, abundantly distributed in the cantons of Catus, Gazais, Salviae, Gourdon, Souillac;

*Coarse limestone* at Catus;

*Siliceous limestone* in almost the entire western part of the department;

*Gypsum*, some deposits in the cantons of Castelnau-Montratier;

*Alluvial deposits* [Fr. *terrain clysmien*] in the vicinity of Bretenoux, Vayrac, and Gourdon, on plateaus of the cantons of Catus, Saint-Géry, Lauzès, Labastide-Murat, Limogne, Livernon;

*Lacustrine limestone* near Castelnau-Montratier;

*Volcanic rocks*, a mound two kilometers south of Lacapelle-Marival;

*Tufa* at Autoire, Saint-Michel-Loubéjou, Lacapellè-Marival, Fons, Cajarc, Saint-Sulpice, Corn;

*Recently transported sediments* on all plains that form valleys and small valleys, often covering alluvial formations;

*Peat* at Souillac, Latronquière;

*Subsidence* and *landslides* at Flaujac, Rilhac;

*Collapses* and *landslides* at Carennac, Mézels, Gintrac, Lavergne, Saint-Michel-Loubéjou, Saint-Médard-de-Presques.

After the Department of Lot, the areas that contain the most rock types are Aveyron, then Gard.

### 2.4.6. Chapter VI. Examination of High Places

To memorize all the names that have just been explained and to apply them precisely when the occasion presents itself, it is not enough to read attentively or to memorize known rock types. Instead, the reader must travel to and examine in detail the mountains, hills, and valleys in the area where he lives. If his department has several rock types; for example, one location is granite, another limestone, another clay, etc., in other words, if the configuration of one is not similar to the others, he should study at least two or three examples of each type.

If a student wants to collect useful observations and not let important observations escape him in his geologic travels, he must study and remember the advice provided in books written by the most experienced geologic travelers; including: *L'Agenda* [*The Agenda*] by Saussure, which follows his *Voyages dans les Alpes* [*Voyages in the Alps*]; *Guide du géologue-voyageur* [*Guide for the Traveling Geologist*], by M. Boué, 2 vol. in 12; and *l'Art d'observer en géologie* [*The Art of Observing Geology*] by Mr. de la Bèche, 1 vol in-8, translated from English by Mr. de Collegno.

In France, the principal chain is a watershed divide between the Atlantic Ocean and the Mediterranean. After crossing Asia and Europe, this chain enters France through the commune of Rousses (Jura) and follows the border to Verrières-de-Joux (Doubs) where it returns into Switzerland. It returns to France near Ferrette and crosses our departments in the following order: Haut-Rhin, Vosges, Haute-Marne, Côte-d'Or, Saône-et-Loire, Rhône, Loire, Ardèche, Lozère, Gard, Aveyron, Hérault, Haute-Garonne, Aude, Ariége, and the Pyrénées-Orientales; from there it follows the crest of the Pyrenees and serves as the border to above Saint-Béat (Haute-Garonne) where it enters Spain. The study of this large chain is important only to those who want to discover springs near the crest of this chain.

In each department, a student can consider the chain that completely crosses the department to be the principal chain: thus in the Department of Lot, two mountain chains or high peaks cross from east to west and divide the waters into separate rivers. The principal of these chains, which is the watershed divide between the Lot and the Dordogne, comes from Cantal and passes through the department at Labastide-du-Haut-Mont, passes through Latronquière, Saint-Medard-Nicourby, Bouxal, Puy-les-Martres, Sonac, Flaujac, Reilhac, Lunegarde, Fontanes, Labastide-Murat, Montamel, Montgesty, Gindau, Cazals, and finally Boissiérette, where it enters the Department of Dordogne. The chain that comes from Aveyron and separates the watershed of the Lot and the Tarn enters the department of Lot at Puy-la-Garde, crosses the communes of Beauregard, Varayre, Bach, Vaylats, Lalbenque, Hospitalet, Labastide-Marniac, Villesèque, Fargues and Saux where it enters the Department of Lot-et-Garonne.

Near these crests innumerable ridges undergo multiple bifurcations as they descend, and vales flow into others that terminate in their respective rivers.

Beginning with an examination of high places, the student must first walk several leagues [See Translator's Notes] along the principal chain and then walk the entire length of some of the large ridges, keeping to the crest, advancing slowly, carefully examining the two hillslopes and the appearance of the foothills and spurs that detach from them while giving each elevation its proper name.

Standing first at the top of the principal chain, at the point of departure of the ridge of interest, he sees another ridge extending from the same point toward the other side. To the right and left, he sees other peaks at different distances on the crest of the principal chain. Other ridges depart from these other peaks; they run more or less parallel to the ridge of interest. Some terminate at the confluence of various streams and others terminate at the edge of the same river. Although their crests are composed of peaks and passes of different shapes, the overall crest always decreases in elevation until it dies out near the river.

Moving away from the principal chain, the explorer will ordinarily descend along a steep slope to the first pass of the ridge, and will ascend onto the first peak, where he will see one or two foothills branch off; reaching each new peak, he will see others branch off. These new peaks are always at lower elevation than the principal ridge and their elevations decrease toward their extremities. Some foothills are perpendicular to the ridge crest but most are not; they converge downstream in the valley. The peaks are sometimes needle-like or have sharp crests; they are sometimes composed of plateaus of varying widths and lengths, on which the highest point is easy to distinguish. Some passes are very short, some extended, and almost all have sharp crests. The observer should occasionally leave the ridge crest he is examining to examine the crests of the principal foothills, especially when they are long; in this way, he will become familiar with their configuration, the forms of their spurs, their little ridges, and their relationships with neighboring foothills. Returning to the ridge crest, which is the principal object of his exploration, as he approaches the river he will note that foothills become less common and less extensive and at the river the ridge terminates as a low hill, often scarped and steep.

While examining high places, the observer should be sure to determine: a) if the layers extend straight through the mountain from one side to the other without any offset; b) if along the length of the crest line, they are curved and discontinuous; c) if, with distance from this line, called the anticlinal axis, they plunge regularly toward each side of the valley; or d) if they are offset, the observer should note the direction, length, and depth of the fault.

### 2.4.7. Chapter VII. Examination of Hillslopes

After examining the summit of a principal chain and the crests of several ridges, the observer will need to examine the hillslopes between this crest and the adjacent river and also examine the hillslopes of several ridges.

A *hillslope* [Fr. *versant*] is the flank of a mountain or hill that conveys its water onto the neighboring plain. The hillside is usually subdivided into three areas that should be considered separately: the plateau, the *escarpment* [Fr. *coteau*], and the plain.

A *plateau* is a plain located on a mountain or hill. A watershed divide usually separates it into two parts along its length; its waters flow into two different valleys. The part of the plateau that directs its water into a secondary valley is thus part of its hillslope. The width of one side of the plateau is the area between the watershed divide and the top of the escarpment. The two parts of the plateau are rarely equal in width because the watershed divide is usually closer to one side than the other. Sometimes the divide coincides with the top of one of the two escarpments and then all of the water from the plateau flows into the valley toward which the plateau is inclined.

The *escarpment* (1) is the steepest part of a hillslope. It is bounded at the top by the lower margin of the plateau and on its two sides by the opening of vales; an escarpment is bounded at the bottom by a plain. The line separating the gentle slope of the plateau from the steeper slope of the escarpment is nearly horizontal. Where the line is rocky, there are cliffs. Where several consecutive escarpments are present on the same side of a valley, they have more or less the same height, the same steepness, and often the same layers. Because the line separating the plateau from the escarpment does not have a name [in French], I propose to call it the *top-of-slope line* [Fr. *corniche du coteau*].

The line that separates the escarpment from the plain follows the visible base; it is called the *foot of the slope* [Fr. *pied du coteau*].

The feet [or bases] of all the escarpments in a river basin form a single line that embraces not only the plain of the principal valley but also all the plains of the tributaries. It starts from the mouth of the river and returns to the river at the foot of the opposite escarpment. Because the word foot has no similarity to such a tortuous line and its length is often one hundred (100) times the length of the principal valley, I proposed to call it the *foot-of-slope line* [Fr. *côtière*].

The *plain* of a hillslope extends from the foot-of-slope line to the thalweg. This part of the hillslope is ordinarily the least inclined.

Some hillslopes are made up of only a plateau and an escarpment; others are composed of an escarpment and a plain; others have neither plateau nor plain, and their slope is uniform from the watershed divide to the thalweg.

The watershed divide, the top-of-slope line, the foot-of-slope line, and the thalweg of a hillslope share a certain parallelism and follow almost the same curves.

As the observer enters the valley, he will ordinarily see two steeply dipping escarpments. He will note that in valleys and vales the two escarpments are nearly parallel over long distances and that there is a regular plain between them that gradually retreats from the outlet toward the head of the valley. In other valleys and vales, the two escarpments are far apart and they approach each other in an alternating fashion. In some places, their bases are contiguous or very close; in others, the two escarpments are far apart with a broad and long plain between them; as a result, the valley is made up of a series of gorges and basins formed by narrowing and widening.

The slope of an escarpment [Fr. *pente d'un coteau*] is far from uniform. It may be gentle or abrupt or very steep. In one place it may be a regularly inclined plane, in others it may have undulations from the base to the top, and nearby it may have horizontal terrace-shaped steps on top of each other.

The observer should also study the dip of the rocks that make up the two escarpments to see if the layers dip in the same direction as the exterior surface of the escarpments, if they plunge from the interior to the exterior from one side to the other toward the bottom of the valley, or if, on the contrary, they plunge toward the interior of the escarpments, determine if the slope of the beds is the same from the base to the top of the escarpment or if it varies at different heights, if it is the same on the opposite faces of the same mountain, or if it is different, observe between bedding planes for the presence of material, and if present, note its nature and thickness. If an escarpment is composed of layers of different composition or different thickness, see if there is a periodicity in their repetition; that is, if after a number or determined interval, the same order begins again, observe again if the directions of the beds are parallel to the direction of the mountain chain or not. If the two escarpments have gentle slopes, the rock layers are horizontal or slightly inclined toward the valley bottom. In this case, the observer will determine whether the layers found on one escarpment are also found on the other and in the same order of superposition. If one escarpment has a gentle slope and the other has a steep slope, the layers of the escarpment with the gentle slope are slightly inclined toward the bottom of the valley and show their upper bedding surfaces [Fr. *têtes*], whereas those on the steep slope show their sections [Fr. *tranches*] and plunge toward the bottom of the neighboring valley.

Rainwater, freezing, and agriculture constantly erode blocks of rock, scree, and topsoil from all steep escarpments; these materials fall to the base of escarpments where they are deposited as talus. The inclination of this talus, also called *scree*, is less steep than that of the escarpment. Its thickness depends on the height of the escarpment and how easily it weathers. The largest rocks are found at the base and the smallest at the top. This talus is missing where a stream touches the base of the escarpment because the debris that falls into the streambed is picked up and distributed on the lower plain.

As the observer continues walking up the valley, he will see on both sides of him vales, gorges, ravines, and depressions that he will not hesitate to examine in turn, walking up one side to the place where it starts and following the other side as he goes back down to the principal valley.

When he is near the head of the valley, which will be no larger than a small vale, he may sometimes be hard pressed to distinguish other vales, gorges, etc., that start at the principal chain and have nearly the same shapes and dimensions. But at a greater distance, he will be able to recognize easily that the thalweg is always lower and less steep than the thalwegs of tributaries that have just discharged into it. After the juncture of several valleys and gorges, the principal valley can be easily distinguished by its width and general direction.

Note

1. There is no difference between a *côte* [translates as cuesta but does not fit the context here - tr. note], a *coteau* [translated as “escarpment” in this text, can also be hillside or slope – tr. note], and *rideau* [no longer used in geologic context – tr. note], which differ only in their height, and everything that has been said about one can be applied to the other two. For this reason, I propose to call the steepest part of the hillslope a *côte* where it has a vertical height greater than one hundred (100) meters; a *coteau* when it is between fifty and one hundred (50 - 100) meters thick, and a *rideau* when it is less than 50 meters. [Paramelle doesn’t mention this classification again. – Tr. note.]

### 2.4.8. Chapter VIII. Examination of Lowlands

The surfaces of the plains over which rivers and streams now flow were once at much lower levels. The two escarpments connect under this plain at a depth of several hundred feet and are covered by a considerable thickness of transported material. The original valley was filled gradually with a mass of stones, sand, and soil deposited there by water. When seawater was present on the continents, it filled the lowest part of valleys; present-day rivers continue to fill valleys by transporting debris from higher regions. This transported material is composed of a highly variable volume of fragments of various shapes. It has the same composition as the rock type that makes up the portion of the basin upstream of the deposit but it differs from the ground that supports it and surrounds it and to which it does not adhere. Five types can be distinguished: coarse debris, pebbles or rolled boulders, gravel, sand, and sand and silt; but these types are interrelated and mixed so intimately that it is difficult to establish their limits and to separate one from another (1). The thickness of this alluvium generally increases from the head of the valley to its outlet.

Geognosts call the rock types deposited by the sea *antediluvian, diluvial,* or *alluvial* [*Fr. terrain antédiluvien, diluvien ou clysmien*] [See Translator's Notes]; these will be discussed in Chapter XXII. Material deposited by present-day rivers, called flood deposits, alluvial deposits, or terrace deposits [Fr. *terrain d'inondation, d'alluvion, d'atterrissement*] etc., ordinarily contains bones of cattle, stags, and other animals that inhabit the area today, shells of river and terrestrial animals, remains of buildings and numerous fragments of bricks, tile, pottery, glass, iron, overturned trees, etc.

Everyone who lives on plains along the banks of rivers and streams knows that the land surface continuously rises; the doors of houses built at the ground surface two or three hundred years ago are now partially or completely below ground. Over time, the people have to abandon lower living quarters and house themselves at higher levels and to continually raise their houses.

The ground rises in the following way. Everyone knows that agriculture, rain, and freezing disaggregate and break up solid and surficial parts of high plateaus and escarpments, that these fragments are carried by rain water into depressions, and that streams and rivers that exceed their banks carry and deposit these materials onto lower plains in places where the configuration of the ground moderates the impetuosity of the currents. The largest blocks are the first to stop, the medium-size ones travel a bit farther, and the gravel even farther; the smallest debris is finally deposited even farther on as mud or silt. When the fragments were eroded from the rock mass they were angular and had all sorts of shapes but as they traveled downstream they rolled, bounced, and banged against each other, their angles were worn away little by little, and they acquired the spherical shape that we see today. When walking up a stream and its tributaries it is almost always possible to find the rock from which the fragment was eroded.

After each overbank event, a layer of rock, sand, and mud overlies every portion of the plain that was covered by water; the thickness depends on the strength and duration of the flood. This layer is thickest near the riverbank and it decreases toward the foot-of-slope lines [Fr. *lignes côtières*]. After several centuries, the difference in this thickness becomes so noticeable that the river now occupies the highest part of the plain; breaking levees that have been constructed to maintain it, the river leaves the high area, which is no longer its true thalweg, flows to the lowest part of the plain and digs a new channel, which it will abandon in turn later when it has raised its banks above the plain.

The process of raising the plain varies considerably from one valley to another and even from one point of a valley to another. In some places, the plains rise only several inches per century, and in others, they rise several feet. Mr. Reboul (*Géolog*., chapter xv) estimates that at the old bridge of Narbonne and on the plain south of Lake Capestang, the Aude raises the soil by about one foot per century. At Figeac (Lot), which was founded in 755 A.D., three aqueducts located adjacent to each other attest that since that time the Cellé River has deposited about 18 feet of terrace material, equivalent to about a foot and a half per century. In the city of Saint-Céré, founded in 1040, buildings are found from time to time that have old entrance doors with a threshold eight feet below the ground surface; this proves that the Bave has raised the alluvial deposits [Fr. *terrain d'alluvion*] by about one foot per century.

Low plains generally have three slopes: one that extends from its origin [the head of the plain] to its mouth, which I propose to call the *longitudinal slope* [Fr. *pente longitudinale*].

Two others depart from two adjacent foot-of-slope lines and decrease in elevation as they join the thalweg; they can be called *lateral slopes of the plain* [Fr. *pentes latérales de la plaine*].

Longitudinal slopes of low plains are highly variable. Some begin in a very slightly inclined elevated section made up of a rounded hollow that lacks an obvious thalweg but all portions of it converge toward a point at a lower extremity; other slopes begin on a similarly elevated section, are slightly inclined and slightly depressed, but they have one or more depressions with a thalweg. Each depression is made up of two small slopes or hillslopes that direct water into the thalweg; other slopes leave from the bottom of a cirque-shaped hollow, which may be deep. This cirque may be located at the upper end of the valley and may not be preceded by a plateau. In other locations, it [the cirque] is preceded by an elevated crescent-shaped section [Fr. *plage élevée*] inclined toward the cirque into which it directs all its water. This elevated section ordinarily has a gentle and uniform slope toward the edge of the cirque. But starting at this margin, the upper section suddenly steepens toward the bottom of the cirque. At the least, it is steeper than in the rest of the vale.

The steepest slope in the base of a vale ordinarily occurs near its origin. Although over the remainder of its path the slope is far from uniform, we can reduce the principal varieties to two: steep slopes and gentle slopes. Steep slopes and cascades are found wherever there are constrictions, a bank of rock, or a compact formation at the ground surface. Gentle slopes are found in broad areas where the two escarpments are far apart, separated by an extensive plain, and inclined in the same direction as the general slope of the vale, and where the bottom of the vale is full of alluvium. The floors of other vales have an almost uniform slope; however, all are steep at the beginning, less steep a bit lower, and less steep still as they continue descending, so that the slope always decreases from their head to their outlet, where it becomes almost imperceptible. In high mountains, the bottoms of most vales have no plains, the bases of the escarpments touch, the slope of the thalweg is very steep everywhere, and cascades often interrupt the slopes. Some vales become steep again toward their outlet but these are rare and they occur only where the bottom is rocky.

In addition to natural drop-offs [Fr. *descentes*], there are man-made ones. Any wall built across a vale to enclose a property or to hold back soil causes an accumulation to form gradually at the base of the property. A simple barrier between two properties, one higher and the other lower, creates the same effect. Although the owner of the higher property never wants to let his soil move toward the lower property, by cultivating his land, he erodes the high part and imperceptibly accumulates soil on the lower part of the property to such a point that in many places that have been cultivated over the centuries, piles of topsoil four or five meters high are present at the base of fields and vineyards. Rainwater also contributes to denuding the elevated part of each property and causes loose soil to move downward.

Note

1. To differentiate these five types of deposits as much as possible, I propose the following terminology: *blocks* [Fr. *blocs*], rock debris that has a volume greater than a human head; *pebbles* [Fr. *galets*] or *boulders* [Fr. *cailloux roulés*], rounded rocks or rocks with blunt corners, smaller than a human head and coarser than a walnut; *gravel* [Fr. *graviers*], deposits of small stones whose fragments are smaller than a walnut and larger than a pea; *sand* [Fr. *sables*], deposits of small rock fragments finer than a pea; and *silt*, deposits that are purely earthy with or without plant debris.

### 2.4.9. Chapter IX. Examination of Flowing Water Bodies

Major rivers [Fr. *fleuves*, no English equivalent - tr. note. A *fleuve* is a sea-going river as compared to a tributary], rivers, and streams (1) provide many observations common to those I make on underground watercourses. It is thus necessary to study and to establish the laws that govern the formation and flow of these surface water bodies to be able to apply these laws to invisible flowing water bodies.

All major or minor rivers and even streams have a basin, a source, a bed, a steep bank, a gently sloping bank, a right, a left, an upstream, a downstream, and a confluence that is called its mouth.

The *basin* [Fr. *bassin*] of a major or minor river or stream is composed of all the valleys, vales, gorges, and depressions that direct water into its channel. Its *source* is the taproot of water farthest from its mouth. The *bed* [Fr. *lit*] is the channel into which water flows and from which water flows only during flooding. The *banks* [Fr. *berges*] are the vertically cut parts at the river's edge; the *gently sloping banks* [Fr. *talus*] are the parts of the bank that have a gentle slope. The *right* [Fr. *droite*] is the area located to the right of a man progressing downstream in the middle of its channel; its *left* [Fr. *gauche*] is the part located to the left. *Upstream* [Fr. *amont*] denotes the part of its channel above a designated point; *downstream* [Fr. *aval*] is the area below this point. The *confluence* [Fr. *confluent*] or *mouth* [Fr. *embouchure*] is the place where it flows into another water body. The word mouth is used only to designate the point where the stream or river flows into the sea or into a lake.

Flowing water bodies are categorized as *principal* and *accessory*; the latter are also called *secondary* or *tributaries* [Fr. *affluents*].

The *principal* flowing water body receives all the water of the basin and occupies the lowest region of the basin. It is longer, has more volume, and moves more slowly than *tributaries*. It keeps the same name over its entire length whereas the accessory or tributaries lose their name when they flow into a principal watercourse.

Tributaries that approach the principal stream from right and left do not flow into the principal stream in pairs. They are like tree branches that grow alternately on a tree trunk. Each accessory stream flows into a principal stream, not opposite the mouth of another stream coming from the other side, nor opposite a reentrant, but always opposite a salient.

When a stream basin is composed of several tributaries, the basin is very wide where it begins; it can be wide as its length. This width decreases toward the mouth, where the width is always greatly reduced. For example, the greatest width of the Garonne basin extends from its source in Dordogne at Mont-d'Or to the highest point in the Pyrénées-Orientales. This width is almost equal to the total length of the river from its source in Spain to its mouth at the Cordouan lighthouse.

The flow of watercourses is not uniform; it ranges from *rapids* to *slack areas*. An oblique drop [Fr. *chute*] in a watercourse is called a rapid; but if it is perpendicular it is called a *waterfall* [Fr. *saut*] or *cataract* in rivers and a *cascade* in streams and torrents. Slow water extends from one rapid to another.

Except in limestone, marl, and chalky regions, any valley of considerable length contains a river or stream and the tributaries it receives are more numerous and larger the longer it is. At the beginning, the channel of a watercourse is ordinarily a rivulet [Fr. *rigole*] several decimeters wide and deep. In some rock types, the source or point of departure is an elevated plain, often swampy, with an almost imperceptible inclination; in others, the watercourse begins in a small vale that may be deep and cirque-shaped. At intervals, the channel receives a new stream flowing from the bottom of a reentrant; the channel inflects toward it to receive it.

If two watercourses that are joining are almost equal, their new direction does not follow either one; if they are not equal, the smaller changes direction to follow that of the larger. The greater the size of the larger, the less it changes its direction.

Some watercourses follow a line that is almost straight and they flow parallel to two adjacent escarpments over long reaches; but more commonly their course is highly sinuous, with the lowest slopes being the most sinuous. The two escarpments that accompany a watercourse indicate the *general direction of a watercourse*, disregarding all the small turns.

The channel of a watercourse becomes larger with each new tributary it receives but the watercourse does not increase its capacity because of the added water; thus, a watercourse that receives another stream no doubt increases its width and depth but its capacity does not double. Because the combined watercourses have only one bottom and two margins, friction decreases and the combined watercourse encounters fewer obstacles than the two separate watercourses with their two bottoms and four shores. A watercourse increases in volume from the source to the mouth; it maintains channel dimensions that are everywhere related to the ordinary water volume; its slope and velocity thus continually decrease.

If the two escarpments that form a small vale have equal slopes, the watercourse flows at equal distance from both; if one of the two is steeper than the other, the watercourse flows closer to the steeper slope, and if one of the two escarpments is a cliff, the watercourse flows at its base. Although this steep slope or this cliff may extend a great distance, the watercourse does not stop following the base until a salient intervenes and forces it to the foot of the opposite escarpment. If the reader makes the effort to examine carefully or recall watercourses whose direction has not been changed by the hand of man, he will recognize that these observations are constant.

Islands and islets often form in rivers and streams, separating them into several branches. These islands and islets are always elongate in the direction of the watercourse.

In the channel of a stream or river that is not incised and whose watercourse is sinuous, the gently-sloped banks and steeper banks behave the same way as escarpments do on a larger scale; they are opposite one another and they alternate. Each gentle embankment forms a salient and each steeper bank forms a reentrant at the bottom of which the gentle embankment dies out; as a result, a person walking along one side of a watercourse alternately encounters the gentle embankment and the steeper bank on the side where he is walking. He can also see that the watercourse erodes continuously at the foot of the steep bank; this process makes this part of the channel increasingly deeper and deposits the eroded material on the next gentle embankment, which is located on the opposite shore.

Note

1. *Fleuves*, rivers and streams form, flow, and behave in the same way. The analogy between these three types of flowing water bodies differs only in their size. Until now, this fact has made it impossible to assign to each their own characteristics, which can in all cases

distinguish one from the two others. No author that I know has satisfactorily established how a *fleuve* [French word for “sea-going river”] differs from a river and a river from a stream. In some places a *fleuve* is defined in a way that is vastly different from the definition of a river in another area; in some places people give the name of river to what would be called only a stream anywhere else. Some authors, however, characterize them as follows:

"If a river is not strong enough to float small boats, it is called a *stream*; if it is strong enough to float a boat, it is called a *river*; finally, if it can carry large boats it is called a *fleuve*. (*Encyclopédie*, article on *Fleuve*.)

De la Métherie, in his *Théorie de la terre*, § 1275, characterizes watercourses as follows: "A mass of flowing water of considerable size that flows into the sea or into a large lake is called a *fleuve*. Other flowing water bodies are called *rivers* or *streams* depending on their volume.”

In Mr. Huot’s article on *hillslopes* [Fr. *versants*] in the *Encyclopédie moderne*, he describes the three types of flowing water bodies as follows: "A *stream* is the smallest of flowing water bodies; a *river* is supplied by one or more streams, or by one or more rivers; a river may or may not be navigable; it can flow into a fleuve or into the sea. A *fleuve* is supplied by one or several navigable rivers; it always flows into an ocean.”

It is obvious that these definitions are much too elastic.

I prefer to call a *fleuve* any flowing body of water that flows into the ocean and discharges more than 50 cubic meters of water per second in its ordinary state; a *river* any flowing water body that in its ordinary state discharges 3 to 50 cubic meters of water per second into another river, into a *fleuve*, into a lake, or into the ocean; and a *stream* any flowing water body that in its ordinary state discharges less than three cubic meters of water per second into another stream, a river, a *fleuve*, a lake, or the sea.

The three definitions that I propose are not exactly rigorous, it is true, because the volume of a flowing water body, called its *ordinary state* or its *average height*, varies continually and can never be measured with precision. However, these terms seem to characterize water bodies much better than the criteria previously discussed.

### 2.4.10. Chapter X. Meaning of the Word "Spring"

The meaning of the word *spring* [Fr. *source*], which the Romans called *fons*, or *scaturigo*, is still not well established in our language. Some people apply this word to *water that issues from the ground* (1); others insist that, in addition, once outside the earth the water continues to flow uncovered and they define a spring as the *water that comes out of the ground to begin its travel* (2); still others define a spring as *the orifice of an underground channel that pours out water directed there by the slope of an organized tributary* (3); the latter understand this word to mean *the channel that leads water out of the earth* (4); the former are thinking of the masses or water reservoirs that they assume to exist underground and that pour forth gradually to the outside (5). *Springs*, according to Mentelle and Malte-Brun, *are small water reservoirs that receive water from neighboring land through small lateral channels and that spread their overflow either by flow or another manner* (6); there are those who apply the name of spring to cavities or basins that receive water as it flows out of the earth (7): others apply the word to the water contained in the cavity or basin; which allows them to say *make a spring cloudy, or poison a spring* (8).

We have to admit that these definitions and several others that have been listed are far from being exact, given that they apply only to the uncovered portion of the spring and say nothing about its formation or its movement underground. The visible part that these definitions refer to is always minimal compared to the entire body of a spring, which appears only after having traveled a considerable distance and, for large springs, after traveling several leagues [See Translator's Notes]. The appearance of a spring is not even an essential condition for its existence because an untold number of springs travel underground from their origin to outlets in rivers; they are not seen at any point during their travel. Authors who want to inform us about springs but limit themselves to talking about outlets are like people who explain a river or a stream by defining or describing only its mouth.

Many authors confuse the word *fountain* [Fr. *fontaine*] with *spring* [Fr. *source*].

By the word *fountain* I mean the shallow basin, constructed or not, that holds in reserve an amount of water produced by one or more springs.

By the word *spring*, I mean an *underground watercourse* [Fr. *cours d'eau souterrain*] [See Translator's Notes]. The word *watercourse* [Fr. *cours d'eau*] makes it clear that to form a true spring, the water must first be collected into a current large enough to be perceived; this does not include the humidity or humors that circulate in the earth; second, the water must be moving; a spring is not a mass of water or a long underground conduit full of non-moving water; third, the movement of the current must have a certain duration, meaning that water currents that form underground during rainy times and that cease at once or soon after, reappearing only after the next rain, are not springs. However, it is not necessary that the continuity be absolute because it would follow that one could call *springs* only those that do not fail. We say every day during a drought that *such spring dried up or ceased to flow*; this makes it obvious that the word spring is used for watercourses whose flow ceases during a portion of the year. It is obvious that it would be impossible for me to establish with precision what duration an underground water current should have each year to merit the name of spring; I will limit myself to saying that it should last at least several weeks after the rain has stopped and produce water during most of the year.

The watercourse must finally be *underground*, from which it follows that a spring is not a water current flowing on land, even if it comes from one or more springs; these currents should be called *rivulets, streams*, or *rivers*.

The volume of an underground watercourse does not change its name: whether it is as thin as a thread, fat as a finger, arm, or a man's body; whether it is as large as a large stream or even a river, it is still a true *spring* even if it is called a stream, torrent, current, underground flow, jet, branch, trickle, vein, or veinlet of water.

Its shape underground does not change its nature; thus some springs move in narrow jets, others form layers or water layers that are thin but very wide.

Some springs have continuous nearly uniform flow; they are called *perennial*. The flow of others, while not entirely ceasing, increases and decreases depending on rain and drought; they are called *variable*. Others that cease to flow during a part of the year are called *temporary*. Some people claim that there are *uniform* springs, that is, springs that constantly produce the same amount of water. I do not believe that they exist in nature.

Notes

1. *Dict. de l'Acad*., *Dict. de Trévoux*, at the word source.

2. *Dict. of M. Landais*, at the same word; d'Omalius d'Halloy, *Géol*., chap. II

3. *Géographie physique*, by Desmaret, art. *Sénèque*.

4. *Encyclop*. and Valmont de Bomare, art. Fontaine.

5. D'Aubuisson, t. I, note VII.

6. *Géogr*., book VI

7. *Encycl*., art. Fontaine.

8. *Dict. de l'Acad*., at the word *Empoisonner*; Huot, *Géol*., chap. VIII.

### 2.4.11. Chapter XI. Erroneous Opinions on the Origin of Springs

Prior to discussing how springs form and move underground, it will perhaps be useful to discuss some erroneous opinions on this subject. The ancients and most modern writers prior to the eighteenth century have left us only hypotheses or systems that are so devoid of satisfactory proof that it is profoundly astonishing that the truth took so long to come to light. I will give a short analysis of the main writings containing these aberrations, without stopping to refute each in particular, hoping that they will be sufficiently refuted by what will be said in the next chapter and the rest of this book.

Plato, in his dialog entitled *Phaedo,* says that all rivers flow into a vast opening that goes through the entire earth. The vast opening is called Tartarus and from it exits all the water that forms seas, lakes, rivers, and springs in different places; the four principal outlets from this chasm are the Ocean, the Acheron, the Pyriphlilegethon, and the Cocytus, and that later all these waters return by various paths to Tartarus from where they came.

Aristotle thought that cold, which is always present in caverns in the earth, condenses air and turns it into water, and that this water gives rise to rivers and springs, that they are converted into humidity like the vapors that the sun attracts to high places, and that some parts combine with each other to form drops that fall as rain, just as vapors in the earth turn into wetness because of the cold, form water drops that combine, then flow and produce springs, streams, and rivers. He also believed that large underground lakes provide water to rivers and springs.

Epicurus, in his letter to Pytoclus, says that springs can come from a quantity of water amassed at their *source* that is *sufficient* to provide for their continual flow or can be formed by waters coming from farther away and flowing as small trickles that come together continuously at the place where their sources are.

Seneca, who of all the ancients talked at most length about the origin of springs, believed that large concavities full of air are present in the earth and that this air, having no movement, is converted into water by the deep darkness and the severe cold that reigns in these places, which causes the continuous flow of springs and rivers, that this change occurs in the same way on the earth where air that is in uninhabited wet places is converted into water. In addition, he believed that some parts of the Earth turn into water.

Pliny the Naturalist, without bothering to explain how water is found in mountains, tries to explain why water rises to the summits of mountains; wind pushes water high and the weight of the earth acts on water and makes it rise. Thales, according to Seneca, was of the same opinion.

Joseph-Jules Scaliger says that in the beginning the Earth was exactly round and surrounded by a mass of water of the same depth everywhere; that God dug some parts of the Earth to make them into seas and that he used the rubble from their basins to form the mountains in which caverns and concavities are still present; that water, being displaced by these new masses, was forced to rise above its natural level and thus it weighed on lower waters that found openings and channels into the earth and rose as far as the mouths of springs where the water flowed, and that this is how all the springs and fountains of the Earth were produced.

Jerome Cardan is of the opinion that the principal cause of water underground is air, which transforms easily into water; that the ferocity of the marine tides pushes some waters into the earth, forcing them to pass through several rock types, and thus produces fresh-water springs, and that rain, snow, summer morning dew, and wintry weather also contribute greatly to spring formation.

Dobrzenski of Nigro-Ponte, in his *Traité de la nouvelle philosophie* [*Treatise on the new philosophy*], printed in Ferrara in 1657, accepts that air changes into water and that the sea flux is the principal cause of springs but he adds that the prodigious quantity of water that at any time is swallowed up in spacious caverns such as those of Charybdis and Scylla do not enter into the Earth uselessly and without moving into other places such as springs. He claims that the waters of all springs have a slight taste of salt, which increases with decreasing distance to the sea.

Jean-Baptiste Van-Helmont, in the treatise he entitled *Principes inouïs de physique* [*Extraordinary principles of physics*] represents the core of the Earth as composed entirely of pure sand, mixed everywhere with an inexhaustible quantity of water and covered with a simple crust of soil, stones, and some veins of this sand, which in some places extends to the surface of the earth. According to him this sand is the screen or filter by which nature clarifies the inexhaustible treasures of these springs for use by the universe; the sand has a life-giving virtue which means that as long as the water stays there the water is in general movement but not subject to the laws of high or low position, such that they move indifferently toward whatever part of the sand they want.

All parts of this sand, even those that rise to the surface of the Earth and up to the summits of mountains, have this life-giving property and everywhere provide moving water [Fr. *eaux vives*] that the heat of the summer cannot diminish. But once the water leaves this sand, it loses this property and becomes subject to the laws of gravity and is forced to flow on the land to the lowest places until it reaches the sea. Water is just like blood in the human body when it is in the head or the feet, where it flows indifferently toward the top or the bottom, but as soon as the blood comes out of the body, it becomes subject to the laws of gravity. Seawater penetrates continuously at the bottom to descend into this pure sand and to replace the water that is continuously coming out.

Lydiat, an English academician who wrote a treatise published in London in 1605, attributes the origin of rivers to the sea; rivers draw their water through multiple channels and numerous underground veins. He maintains that as the sun's heat turns seawater into vapors and raises it to the middle region of the air, in the same way the heat that is in the Earth turns water found there into vapors and raises the vapors to the summit of mountains where they form springs and rivers.

Pierre Davity, in his book entitled: *Empire du monde* [*Empire of the World*], printed in 1637, states that springs come from the sea because he cannot believe that the sea can receive so much water without overflowing or that the sun and the wind can evaporate as much water as reaches the sea. Because the world is round and full of openings and channels, the sea by its greater gravity pushes its water into these channels and forces it to rise to mountaintops. The vapors in the earth thicken in the concavities where they are found and can be converted into water and combine with water of the sea to make springs more abundant.

Descartes, in his book *Principes de la philosophie* [*Principles of philosophy*], proposes his system of the origin of springs as follows: Under mountains, large water-filled cavities are heated continuously, causing water to rise as vapor. These vapors permeate all the pores of the Earth and reach the highest surfaces of the plains and mountains where they produce springs, and the water flows down the slopes of valleys, comes together, forms rivers, and flows to the sea. In the Earth, there are several large passages through which as much seawater travels to the mountains as the amount of water that leaves the mountains and returns to the sea. The path that water follows within the Earth imitates that of blood in the body of animals, where it passes continuously and rapidly from veins to arteries and from arteries to veins. The reason that seawater is salty and springs are not is because the portions of seawater that are soft and pliant change easily into vapors and pass through tortuous pathways between small grains of sand whereas waters that contain salt are rough and rigid and are more difficult to raise with heat so they cannot pass through the Earth's pores.

Nicolas Papin, a medical doctor in Blois, wrote a short treatise on the *origine des sources* [*Origin of springs*], printed at Blois around 1647, in which he says that the sea is the true origin of springs and fountains, that at the beginning of the world a *shape-forming spirit* [Fr. *esprit concrétif*] was created that united and tightened the bodies to which the world was connected, primarily liquids, and caused them to take on a spheroidal shape, that the waters of the sea were compressed and drawn together by this force and took on a roundness such that in places where the ocean is wider, its convexity represents almost a half globe placed on that of the Earth; that toward the middle the water is much more elevated than the highest mountains of the world, and that it is easy for this water, raised in this way in the middle of the ocean to raise other water through underground channels to the height of mountains.

Jean-Baptiste Duhamel in his *livre des météores* [*Book on meteors*] printed in Paris in 1660, describes two types of springs [Fr. *fontaines*]: those that stop flowing in summer and depend on water from rain and snow and others that flow perennially and provide seawater that spreads everywhere under the land surface through underground conduits. This water deposits its salts as it moves through different rocks and is taken as vapors up to the height of mountains by the heat that is always present in the central region of the Earth. Within the Earth these vapors rise easily in conduits that are narrow and that prevent them from descending, since vapors rise in air that is fluid and always in movement.

To avoid falling into fastidious repetition, I will pursue no farther the analysis of authors who have adopted and upheld opinions analogous to those just discussed, given that they are all more or less the same and are based on the same reasoning. Those who would like to know more about these systems can read the works just cited and the following:

*Mundus subterraneus*, 2 vol. in-fol°. by Kircher, 1678.

*De origine fontium*, by Robertum Plot, 1 vol. in-8°, Oxonii 1696.

*Théologie de l'eau*, by Fabricius, 1 vol. in-8°, Paris 1743.

*Traité de physique*, by Rohault, 2 vol. in-12, Paris 1676.

*Indications sur l'origine des fontaines et l'eau des puits*, by Kulm, 1 vol. in-4°, Bordeaux 1741.

*Architecture hydraulique*, by Bélidor, 4 vol. in-4°, Paris 1737.

### 2.4.12. Chapter XII. Responses to Erroneous Opinions on the Origin of Springs

Some of the opinions expressed in the previous chapter have such a degree of unlikelihood that any reader with a minimum amount of instruction has already seen the falseness of them and it would be a waste of time to discuss them. These are the opinions of those who claim that water underground is exempt from the laws of gravity, that it flows up and down like blood in the human body, and that air and land change into water to maintain springs, an even more unlikely idea. To state these opinions is to refute them but as we have seen, one opinion has been upheld by a number of renowned physicists, who have supported it by rather specious reasoning. As a result, this opinion merits serious discussion; these physicists attribute the origin of springs to the sea.

The innumerable springs that issue from the land in all regions, that combine, form streams and rivers, which for so many centuries have poured water into the sea without causing it to overflow, without even raising its level, have led all learned men to conclude that the sea must send back a portion of its water into land to make springs there. Agreeing on this point, they were not sure of the means that nature uses to transport this water and spread it over all the continents.

Some have said that the Earth is porous enough to transmit water from the sea to the center of the Earth through an infinite number of small channels that begin at the seafloor and furnish water to springs. Others have claimed that all the continents are furrowed within by innumerable and vast channels that start at the sea and that divide and subdivide into an infinite number of streams, each of which supplies a spring on land. Others maintain that rainwater and other atmospheric water that falls on the continents is alone responsible for spring flow. This last opinion, which I share, will be discussed in the next chapter.

To destroy the opinions of those who believe that seawater supplies springs via underground pathways, I will pose and briefly resolve the following three questions:

First: Are there underground channels within the Earth that lead away from the sea? Second: Can seawater rise to springs, given that the springs issue from the Earth at heights ranging from one to several thousand meters? Third: Given that seawater is salty, how does it get rid of its salts underground and produce fresh water springs?

First Question. Are there underground channels within the earth that lead away from the sea?

Authors who have maintained the existence of small underground channels have attributed to the Earth a universal porosity that it does not have, because it is generally recognized that impermeable rocks form most of the mass of the Earth and that in general the Earth is compact enough to preserve each water mass within its basin. If we suppose for a moment this abundant porosity, we are forced to admit that the entire Earth is pierced by as many channels as there are springs at the surface, that these small channels begin at the sea, move parallel to but never flow into each other, that they diminish in number as they advance, and that each of them stops at the mouth of the spring it supplies. It also follows that near the sea these small channels are incomparably more numerous and less deep than in the mountains that are distant from them.

However, what we observe is the exact opposite: springs are generally more numerous, more abundant, and less deep in mountainous regions than near the sea, and a great number of wells that have been dug there, even at several dozens of meters below its level, have never encountered the least trickle of water. I have said that these small channels, although flowing near each other, must never flow into each other because if that happened, the one whose outlet was lowest would receive all the water and the other would remain dry, as would its spring. It can be seen, it is true, that some springs disappear but no one has ever seen a spring suddenly double its volume. These innumerable trickles of water that start at the sea and travel through the Earth to each supply its own spring are not proven by any fact; they are pure imagination.

Authors who have maintained that seawater is piped through land in broad channels have cited swallowing chasms [Fr. *gouffres absorbants*] such as Scylla on the coast of Calabria and the Maelstrom near the Norwegian coast. As conductor channels the authors have cited caves in which streams can be observed and also about a hundred caves that have always been dry.

Scylla is a nothing more than a rather large cave above the water level that extends underground 160 meters horizontally, into which seawater enters very noisily whenever wind pushes the water there and from which water exits again when the wind ceases.

The Maelstrom is not an abyss that absorbs seawater and pipes it through the Earth; it is a simple eddy or whirlpool (1) of water seven or eight leagues in diameter and of considerable depth. Every time the northwest wind blows opposite the current formed by the rising tide, the water mass between the islands of Wero and Laffouren begins to circulate rapidly, forms an open abyss near the middle into which all ships that have the misfortune to enter into the circle of this whirlpool are irresistibly pulled, engulfed, and wrecked. As the tide subsides, the swirling ceases, the sea flattens, boats cross it peaceably, and one can see the floating debris of objects it has swallowed.

For the streams that are observed in some caverns to support the opinion of the partisans of underground circulation, they would have to prove: 1st) their continuity to the sea, even when they are hundreds of leagues distant because their known length is always much shorter if it is compared to what it should be to extend to the sea; 2nd) that these streams and caverns exist in all regions where springs are present; however, they are found only in limestone and marly rocks, which are precisely the ones that lack visible springs; 3rd) that they all are directed toward the sea and do not have, as they do, all different directions; 4th) that they cannot come from higher mountains; 5th) that they are below sea level, so that seawater can descend there, and it is this that they can never prove by authentic facts.

As for caverns that are dry and that are incomparably more numerous than those filled or crossed by underground streams (2), their sole condition of dryness provides evidence that they do not conduct seawater into the Earth. It is just as certain that caverns that are occasionally discovered, that are terminated at both ends by solid rocks and that lack any outlet have never been able to serve as a passage for a watercourse.

If the sea provided water to springs, the springs would invariably have the same quantity of water because the sea neither rises nor falls depending on the season. However, all springs increase in times of rainfall and diminish in times of drought. There is not a single one that does not undergo some slight increase or decrease. There are even many that dry up; the sea could not supply these springs and even less those that dry up.

Second Question. Can water from the sea rise to springs that issue from the ground at heights that range from one to several thousand meters?

After accumulating assumption upon assumption to establish the existence of these innumerable channels to carry seawater onto land, the partisans of underground circulation have been no happier than when they have tried to explain how this water can rise underground up to the highest springs that one finds in the mountains. Some proponents, as we have just seen, have said that these waters rise through underground channels by the flux of the sea --- but at the highest tides, the flux raises ocean water only about ten meters and raises sea water that is on land, such as the Mediterranean, the Baltic Sea, the Black Sea, the Caspian Sea, etc. by decimeters only. Others have claimed that the Earth's core is composed of pure sand that has large capillarity and can thus lift the water that impregnates it up to the springs; ---- in the best-constructed capillary tubes, water never rises 32 feet and it has never flowed out the upper orifices. Others have claimed that winds enter into underground channels and push the water found there toward the ground surface; --- if the channels start below the sea, as they say, winds cannot penetrate the channels to make the water rise and as many underground air currents as water currents would be necessary; these air currents would have to be continuous and their action powerful enough to push columns of water to a height of several thousand meters. Other have imagined that the Earth exercises pressure on the water contained in the underground channels and that this pressure forces the water to rise and issue forth on the Earth; ---- the roofs of these channels, however slow their downward movement, would have caved in long ago. Others have maintained that underground water currents are pushed out of the Earth by the internal heat of the globe; --- according to this assumption all springs should be thermal.

One of the most incontestable principles of hydrostatics, which alone would destroy all these hypotheses if they were not already refuted by a lack of proof, is that *all portions of the same liquid are in equilibrium among themselves whether they are in a single vessel or in several vessels that are in communication among themselves*. By considering the sea as a vast basin and assuming all underground channels to be basins in communication with the sea, the water of these channels could well be in equilibrium with those of the sea but it cannot rise above its level; finally, others have assumed that groundwater was first converted to vapor and then pushed high by the internal heat of the Earth, and because water can neither be reduced to vapor without a space capable of containing at least 800 times its volume, they have assumed immense caverns to be present under all continents and that vapors attach to the roofs of these caverns, cool, and condense as in the heads of our stills [Fr. *alambics*] and the water spreads outward as springs.

The springs of Vaucluse, Loiret, Touvre near Angoulème, and the L'Ouysse near Souillac (Lot) each form a river of running water twenty meters [wide]; these seem to be something other than simple vents, each exhaling the vapors of a cave that can be no less than ten to twelve leagues in diameter. What capacity these innumerable stills! What regularity of all the heads (of the stills) and spouts that lead all this water outward! All these vast stills, the heat that does the work, the cold that condenses the vapors, the perfect regularity of all the heads and their outlets, are nothing other than pure assumptions, imagined to explain how seawater can rise up to springs that are all above sea level [See Translator's Notes - alambics].

One sees, it is true, a certain number of springs that issue from the ground by a rising movement. The largest rise from the bottom of a natural and almost vertical well, such as the springs of Gourg near Souillac, Lantoy near Cajarc, Touzac near Puy-l'Evêque (Lot), etc., and those that are weak issue from the earth bubbling and bringing sand; but it is easy to convince oneself that this type of spring does not only rise from bottom to top, because they come from higher ground, and that from their departure point, their channel always descends to the bottom of the cavity where they begin their rising movement to pour forth to the outside; this movement is, like that of spraying fountains, determined by the pressure the descending column of water exerts laterally on the rising column of water. Everywhere that someone has tried to follow the path of one of these springs by digging a trench upstream, it has been found that the water comes from higher ground and that its conduit follows a rising trajectory. It is notable that a rock or an impermeable layer always forms a dam and stops these springs, requiring them to flow upward to flow out of the earth.

When a spring is found and channeled outside and far from its natural channel, the spring located below it often dries up because the spring is intercepted higher and can no longer spring forth lower; but no one has ever seen a spring flowing out of the ground from an overlying rock unit stop flowing because someone has cut the spring in the lower rock unit. Thousands of tunnels have been dug underground to extract metals, coal, salt, rock, etc.; they have penetrated to a depth of several thousand meters (3) and extend horizontally to much greater distances; people have dug from one side to the other of numerous thick mountains to build railroad tunnels, canals, roads; we have dug millions of ordinary wells. In these various excavations, we have often encountered watercourses, sometimes very powerful, but no one has ever intercepted a single one that had a rising motion that flowed upward and that has caused springs in higher rock units to dry up.

The belief that all springs come from higher rock units and that they descend in the same direction as the ground surface is so generally accepted that, guided by simple common sense, all peasants who want to intercept a known spring look for it in a higher rock unit and never excavate in a lower rock unit. To believe that underground watercourses move upward, we have needed systems builders such as Cardan, Papin, Davity, and other authors cited in the previous chapter.

To support the position that seawater creates the innumerable visible and invisible springs that are present on all continents, the inventors of underground channels are forced to assume that a vast underground network of rivers, streams, and water trickles starts at the sea, splits up and branches to infinity to spread water everywhere; that these water currents are almost as broad, as long, and as branched as those observed on the ground surface, with the difference that on the land surface the small currents contribute their water into large ones while underground the large discharge into the smaller ones. Because water cannot move on a totally horizontal surface, the proponents of these ideas are forced to admit that underground rivers and streams slope from the seashores to beneath the mountains. Supposing that this slope is almost the same as that of surface watercourses, it follows that seawater is has flowed under the mountains, where for example springs are visible at 2,000 meters above sea level, the underground watercourses are located at depths of 4,000 meters below these springs and according to the authors who suppose that underground rivers begin at the bottom of the sea, the last branches, arriving under high mountains, are found at a depth of seven to eight thousand meters (4). The water must thus rise as much to be able to reach our springs.

Third Question. Given that seawater is salty, how can it get rid of its salts underground and produce fresh water springs?

We cannot admit the obviously false opinion of those who maintain that all springs are salty and that their saltiness increases the closer they are to the sea because on the margins of the sea, all springs that issue above sea level are as fresh as those located far away; the water-filled basins that are found in the mountains have no indication of communication with the sea; the water they contain is fresh and one sees water arriving continually from higher ground. Nor can one admit the opinion of those who claim that seawater deposits all its salts as it moves through the land; because it is proven by numerous experiments that repeated filtration through different sandy materials have reduced its bitterness but has not at all removed its salt; one is also forced to reject the opinion of those who wish that salty water, rising in vapors from the bottom of underground conduits leaves all its salt there; because the transport of salt from the sea within the land would have the following effects: 1st) desalting all seas gradually; however, for several centuries observations have been made on the salinity of seawater and no reduction has been noted; 2nd) spreading this salt everywhere springs are present; however, in all of France, where springs are very common, and where numerous deep excavations have been made, only four or five rock salt or saline rock units have been found, all of them very extensive and located in the Franche-Comté and Lorraine; 3) salt deposits that are taken from seawater either by distillation or by filtration would have long ago obstructed all the channels, filled up all the underground stills, and as a result, dried up all the springs.

The experiments of Marsigly, Halley, and Hales have established that a pound of sea water contains in dissolution four "*gros*" of salt [See Translator's Notes], that is, one thirty-second of its weight; thus 32 pounds of water produce a pound of salt; 64 would produce two. For a cubic foot of water weighing 70 pounds (to facilitate the calculation, counting only two pounds of salt in this 70 pounds), each cubic foot of fresh water arriving at a spring would deposit two pounds of salt underground; thus if according to Mariotte's calculation, 288,000,000 cubic feet of water moves under the Pont Royal in Paris in twenty-four hours, this quantity of water would have deposited 576,000,000 pounds of salt underground; however, because many of those who support the internal circulation of seawater agree that rain increases the water of a river, we can reduce this product to half. The water of the Seine would still leave 288,000,000 pounds of salt in the entrails of the earth every day, and we will have more than one hundred billion pounds per year. And what is the Seine compared to all the rivers of Europe and finally, of the whole world! What a prodigious amount of salt would have formed in underground channels, given the immense mass of water that rivers have discharged into the sea for so many centuries!

Seeing all these authors and several others imbued with such erroneous systems on the origin of springs, it is not astonishing that none of them thought of looking for ways to *find* springs to serve the needs of mankind. Knowing that the sea sends watercourses under all the continents through underground channels located at frightful depths and much deeper with distance from the sea and that these waters when reduced to vapors rise vertically from these channels to the ground surface, these authors should believe that to reach these watercourses, it would be necessary to dig to these channels and that at lesser depths, one can find only the rising vapors that come from depths of several thousand feet.

Notes

1. Those who have not seen a similar whirlpool in the sea can get an idea of a maelstrom from the small whirlpools that form in many places in our watercourses. "One often sees," says Buffon, tome II, page 44, "in fast rivers at waterfalls, past the downstream sides of bridge pilings, that small abysses or whirls of water form, of which the middle seems to be empty and to form a type of cylindrical cavity, around which the water swirls with rapidity; this apparent cylindrical cavity is produced by centrifugal force, which causes the water to try to get away and move away from the center of the whirlpool caused by the whirling."

2. "There are very few caves that form these long galleries that give passage to underground springs" De Malbos, *Bulletin de la Société géologique*, volume X, page 354.

3. At Kuttemberg, in Bohemia; at Kitzpuhl in the Tyrol; at Freyberg, in Saxony, etc.

4. The maximum depth of the sea, according to Mr. Rivière (*Géol*., chap. III) is about 4,000 meters. According to Mr. de Labèche (*Manuel géol*., sect. I) and Mr. Baudrimont (*Géol*., notions géner.), it is 3,200 to 4,800 meters.

### 2.4.13. Chapter XIII. The True Origin of Springs

Vapors rise every day from the sea, from all stagnant and running water, and even from the top layer of the land surface. These vapors form clouds in the air that the wind condenses, rarifies, transports, and disperses at will. These clouds fall back to earth as rain, snow, hoarfrost [Fr. *frimas*], fog, and dew. These various types of precipitation events [Fr. *météores*] turn into water, penetrate and infiltrate the land surface to various depths, and produce springs. By proving each of these assertions, I will establish the true origin of springs.

*Vapors* are water particles vesicular and hollow in shape, very small in size and very light; heat dissolves vapors and forces them to rise in the atmosphere. Those particles that rise above water are called vapors and those that come out of solid bodies such as land, wood, etc., are called *exhalations*. When the latter enter the atmosphere, they mix with vapors, properly speaking, and take the same name. These aqueous emanations are visible only when the air that receives them is already saturated and cannot dissolve them; they then form a type of steam that tends to be carried upward.

The upward movement of vapors is determined by the density difference of the various layers of atmospheric air. Vapors in the layers at the earth's surface are denser; those immediately higher are a bit less so, and this density decreases with height. The lowest layers of air, being specifically heavier than vapors, exert on them a pressure that forces them to rise until they reach a layer of air that is lighter than they are.

This decrease in air density and consequently of pressure that the vapors experience as they rise in the atmosphere causes them to slow down as they rise and to come to rest at different heights where they come together to form clouds.

When two liquids of different densities mix, the entire mass of the lighter one moves from the bottom of the receptacle to rise above the heavier one; in the same way, because vapors are ordinarily lighter than lower layers of the atmosphere, vapors rise until they end up above all the layers that are heavier than they are. This process always occurs when the atmospheric air is nearly calm, but when the air is churned up by the wind, the respective density of the different layers is inverted and vapors float wherever the currents carry them.

## Quantity of water that rises as vapor

The amount of water that evaporates depends on: 1st) the degree of heat that dissolves the water and converts it into vapors; 2nd) the degree of dryness of the air that receives the vapor: the dryer the air, the quicker and more abundant the evaporation; 3rd) the agitation of the atmosphere: an air current that carries vapor as it forms continuously puts the evaporating surface in contact with dryer air. Dalton noted that all other things being equal, evaporation by a very strong wind is more than double the evaporation that occurs in calm air.

To determine the amount of water that evaporates each year, an *evaporating basin* or *atmometer* [Fr. *atmidomètre*] can be used; this is a simple cylindrical vessel about 60 centimeters in diameter and one meter 30 centimeters tall. This container is placed in the open air in a location exposed to the sun all day; it is covered with a small metal roof to prevent rain from falling into it and it is completely filled with water. After a year has gone by, the portion of the basin that is empty shows the thickness of water of the original water mass that was exposed to the sun and to the wind and that has evaporated during this time.

Physicists have done repeated experiments to determine the approximate quantity of water that turns into vapor and rises continuously from all bodies of stagnant and running water. Halley found that the average thickness of the water layer that evaporates is one tenth of an inch per day or 36 and one half inches per year. Muschenbroek showed that in an average year, the water contained in a lead basin lost 28 inches of height through evaporation only (1). Sédilau found that in Paris during the years 1688 and 1689, evaporation was 32 inches 7 lignes [See Translator's Notes] per year. Carefully conducted observations show us that in Paris, the thickness of the water layer evaporated from a water mass by evaporation in a year is about 88 centimeters (32 and a half inches). The slight difference shown by these results may come from inexactitudes of the experiments or may be due to the different temperature of the years or even to the diversity of climates in which they were made because as we know, the activity of evaporation diminishes from the Equator to the poles.

## Clouds

After rising into the atmosphere, air currents push vapors and exhalations horizontally against each other; the vapors and exhalations mix, condense, and form floating masses called clouds [Fr. *nues, nuées, nuages*]. Because various kinds of clouds and also atmospheric layers have different densities, each cloud forms and swims above all the air layers that are heavier than it. Their different heights can be observed every time clouds move in the same direction and it can be noted that their speed is obviously not equal. This is even easier when the winds change direction; then the clouds stack up on top of each other with directions that cross and others that move in the opposite direction. Some clouds move very slowly and others so rapidly that they travel two to three leagues in an hour (2). The height to which the highest clouds drift hardly exceeds seven or eight thousand meters above depressions [Fr. *bas-fonds*]; clouds that produce rain and other aqueous precipitation [Fr. *météores aqueux*] are generally only several hundred meters above the ground. The air in which the clouds are suspended is never perfectly calm so clouds intermingle, condense, separate, rarify, take on all sorts of shapes, continually change in volume and color, and sometimes dissipate entirely. Clouds can be very small, middle size, or as large as hundreds of feet thick and they can extend several leagues in all directions. Their color ranges from snow white to dark brown, and sometimes the color is fire red.

The clouds that vapors form in the atmosphere do not remain stationary for an instant. Air or wind currents, either slow or fast that are continuously in control, push the clouds and drag them to considerable distances, until they turn into water and fall back to earth as *rain*, *drizzle* [Fr. *bruine*], *fog* [Fr. *brouillard*], *mist* [Fr. *serein*], *dew* [Fr. *rosée*], *snow, hail* [Fr. grêle], *fine hail* [Fr. *grésil*], or *hoarfrost* [Fr. *givre, frimas*]. Many readers who have little knowledge of these various weather events, will no doubt appreciate several words on the how they form and how they fall.

## Rain [Fr. *pluie*]

When clouds are pushed up against each other by the wind, they compress or interpenetrate and increase their density. Inside a cloud condensed in this way, countless small droplets form that begin to fall as soon as they acquire enough density to overcome the air's resistance to their fall. As they fall, they encounter numerous other drops and aqueous molecules that they join up with and carry along; they increase in size and they end up forming the raindrops that we see fall to earth. Clouds thus turn into and fall as rain whenever they become more compact and consequently heavier than the air that supports them or when they are pushed down by winds.

Because incomparably more clouds form over the sea than over land, the winds that come from the sea are ordinarily accompanied by rain; for this reason in France the wind from the west, coming from the ocean, is the one that brings the longest and strongest rains and winds from the north and east produce rain only when they meet clouds loaded with water and coming from the west as they move. The south wind produces only weak rains or rain of short duration because of the narrowness of the Mediterranean. We have noted that the farther the distance from the seashore, the less rain there is; thus the western coast of England averages 95 centimeters of rainfall per year whereas the eastern coast receives only 65 centimeters. It rarely rains during high winds unless the wind is moving downward.

The size of raindrops depends on the density, thickness, and height of the clouds that produce them, and is thus highly variable. The most common diameter is two or three lignes [See Translator's Notes]. When several drops coalesce while falling, the resistance of the air immediately breaks them up and reduces them to ordinary size. Raindrops are usually bigger and fall farther from each other in summer than in winter because in summer the air is more rarefied by the heat and the raindrops that fall through it experience less resistance as they fall, whereas in winter the air is denser, causes more resistance to the fall of raindrops, and breaks them up more. Raindrops rarely fall in a perpendicular direction; they commonly fall along on oblique trajectory in the air following the direction toward which the wind is blowing.

### Drizzle [Fr. *bruine*]

*Drizzle* or fine mist is very fine rain that falls slowly and in very small drops. When a thin cloud dissolves equally everywhere, the aqueous particles that comprise it do not combine to a great extent; they form only very small drops, of which the specific gravity is almost the same as air. These small drops form what is called *drizzle*, which may sometimes last for entire days. Drizzle also occurs when the dissolution of a cloud begins at the bottom and continues to the top. In this case, the small water drops forming at the bottom of the cloud do not grow as they fall because they do not encounter other drops; they arrive on the ground with the same volume as when they left they cloud. Drops of drizzle fall slowly, with an almost uniform speed, following rather sinuous trajectories; they almost never fall perpendicularly. Droplets of drizzle are sometimes big enough that they can be seen individually as they fall; other times one can only see them when there is a black body or a dark void behind them.

### Fog [Fr. *brouillards*]

*Fog* is just a cloud suspended in a very low region of the air or rolling very slowly along the ground. Fog sometimes forms as vapors and exhalations that rise imperceptibly from the ground, sometimes as thick clouds that descend from higher regions of the atmosphere, and often as a mixture of the two. In fog, the air is perceptibly calm; fog dissipates when the wind starts to blow. The most common movement of fog masses is horizontal and their different parts seem to move indifferently upward or downward. Fog appears more frequently in the evening and in the morning than during the rest of the day; fog occurs more in winter than in other seasons. The objects seen through fog seem larger and more distant than they really are.

### Dew [Fr. *rosée*]

*Dew* consists of very fine and unbound drops of water that fall from the atmosphere during warm periods from sunset to sunrise the next day. For dew to fall during the night the preceding day has to have been hot and the atmosphere must be cool and lack clouds and strong wind, because when the wind is strong, all aqueous particles that could make dew are carried away and dissipated. Most vapors and exhalations that move upward from the land surface during the hot seasons rise, as I have already said, into the upper regions of the atmosphere and form clouds; but those that leave only at the end of the day and have reached only a small height when the sun disappears, stop rising; they cool, condense, become specifically denser than air, and fall back to earth as dew, moistening all the bodies on which they fall and wetting the clothing of people who are outdoors. Dew floats in the air like fog; it seems to rise or fall haphazardly. Dew falls most abundantly during the morning twilight because at this time the atmosphere is the coolest, which makes it easier for vapors to fall. The first dew that falls as night begins, called mist [Fr. *serein*], is more abundant than the dew that falls during the rest of the night. More dew falls in the month of May than in any other month; more dew falls in spring and fall than in summer because the excessive heat of summer causes more vapor to rise to the clouds; in the country than in cities; in regions near the sea, a river, or a lake than in areas far from them; in wet regions than in arid ones.

Dew produces much more water than is commonly believed. Some observers have collected three inches per year, others four, and Dalton estimates about five inches of dew annually in Manchester.

Another type of dew does not come from the atmosphere but from secretions from the land that are taken up by plant roots, rise through their stems and branches, and are secreted by leaves on which the secretions pause and are mixed with the falling dew. To convince oneself of this fact, one has only to cover a plant with a glass bell in the evening; the next morning the plant will be covered with dew, but in a lesser quantity than neighboring plants that have received the falling dew and the secreted dew.

There is a new opinion that explains dew formation in a different way, and Mr. Arago (1835 *Annuaire*) [1835 *Yearbook*] explained it in these terms: "We know that dew does not fall, that air deposits it on surfaces previously cooled by their radiating loss [Fr. *rayonnant communication*] into celestial spaces; that the nature of bodies and their exposure and the pureness of the sky have the greatest influence on this phenomenon."

Water that falls from the atmosphere is transformed by cold, either during its fall and or after it has fallen.

Snow [Fr. *neige*]

*Snow* is frozen water that falls to the earth from clouds as a multitude of very light flakes separated from each other, of various sizes, ordinarily having the shape of a star with six complicated radii, and of a famous perfect whiteness. A snowflake is composed of small elongate pieces of ice or filaments of frozen ice that coalesce as they fall, and because they touch at only several points on their surfaces, the aggregation is always very imperfect. The flakes are smaller at colder temperatures; some fall almost perpendicularly and others, lighter, whirl as they fall. Snow can occur only in air cooled to a suitable temperature and when water particles spread out in the air are affected by freezing prior to coalescing as large drops. Newly fallen snow has a volume ten to twelve times greater than the volume of the water it will produce upon melting; as it melts snow provides a large quantity of water to streams and rivers and it often causes large floods if it melts rapidly.

### Hail [Fr. *grêle*]

*Hail* is rainwater that freezes in the middle region of the atmosphere and falls to the land surface as ice droplets; these droplets are usually spheroidal or ovoid with a compact and tight fabric. They ordinarily have a snowy and opaque nucleus and are covered with a layer of diaphanous ice. Hail stones form in clouds from very small raindrops and are very small at first; but because they are heavier and move faster than drops and particles of water they encounter as they fall, they freeze them, appropriate them and enlarge as they fall after leaving the cloud. In some storms, numerous hail stones, still hardly solidified, can agglutinate together and the raindrops they encounter and freeze will fill their interstices and envelop them, covering them with fine layers of ice; they end up forming hailstones that sometimes weigh a quarter of a pound, a half-pound, and even more than a pound each (3). Large hailstones formed in this way are almost always angular in shape and do not have a uniform density. The most common size of the hailstones is about that of a hazelnut; their size depends on the thickness of the cloud and the height from which the hailstones fall; those that fall on mountains are larger than those that fall on valleys. All hailstones that fall during the same storm have about the same shape and size. The most common season for hail begins in the month of June and ends in the month of September. Hail is almost never preceded by, but often occurs with and is ordinarily followed by rain. When hail is just about ready to fall and during its fall, people hear a loud noise in the air caused by the banging of hailstones that the wind pushes into each other with great force. After hail hits the earth it turns into water very quickly.

There is a type of small hail known as fine hail [Fr. *grésil*], which is as white as snow. Its grains are composed of very fine filaments rolled and stuck together. This small hail falls in various seasons of the year, but principally in the first days of spring; this hail is called April showers [Fr. *giboulée*].

## Frost [Fr. *gelée blanche*]

*Frost* is frozen dew. On some autumn, winter, and sometimes spring mornings, frost can appear on plant leaves and on the roofs of buildings and other structures where it forms a very light layer similar to snow, differing from it only in that snow forms in the air and frost forms concretions only on the surfaces of structures on the ground. Because the water particles that form dew exist as vapor in the atmosphere, they are invisible and do not freeze but when the droplets of dew encounter very cold surfaces of solid structures, the droplets lose their liquidity and turn into many small flakes of ice. The first drops deposited are the first to freeze; those that come afterward are deposited and freeze in the same way layer after layer. When the sun begins to make its warmth felt, the frost melts quickly; a part goes into the ground, the other is reduced as vapor and rises into the air.

## Hoar Frost [Fr. *givres* or *frimas*]

*Hoar frost* is a type of white frost that attaches strongly to various structures in winter when the air is cold and wet at the same time. Hoar frost and white frost form in the same way and look exactly alike. However, we usually note a difference between them; we give the name of *white frost* to the frozen morning dew, whereas *hoar frost* owes its origin not only to the morning dew but also to all the aqueous vapors that fall and freeze on the earth at any time of day or night.

When a large fog spreads in the air, wets everything that is exposed, and when the temperature is at the freezing point or below, the aqueous particles that the fog spreads are deposited on certain structures as visible, distinct, very slender molecules that freeze as soon as they are deposited. On top of these first ice particles, new aqueous molecules are progressively deposited; they freeze in the same way and increase the thickness of the layer. Frost attaches in great quantities to trees and often forms hanging ice that fatigues tree branches by its weight and breaks some branches. Frost also attaches frequently to hair, to the chin and clothing of travelers, to the hair of horses, etc.

## Quantity of water produced by precipitation events

The quantity of water produced annually by all precipitation events varies from year to year and from place to place, sometimes as much as doubling. The principal causes of the difference between one place and another are: the proximity or distance of the sea, lakes, or rivers; the environment of places, whether they are high or low; near mountains or the setting of certain mountains; temperature, because in warm climates rain is more abundant than in cold countries, etc.

To determine the quantity of water that falls in a year, an apparatus called a *udometer* or *hydrometer* is used, which is composed of a funnel, a container, and a pipe, all made of metal. The funnel is a cylindrical container 20 to 40 centimeters in diameter and a half-meter deep at least, so that raindrops that fall into it cannot splash out. The receptacle is another cylindrical container a meter and 30 centimeters tall, which has exactly the same diameter as the funnel and is closed from top to bottom. The funnel is placed outside on the roof of a building and the container in an apartment located below. The bottom of the funnel and the top of the container both have a small opening in which a pipe that goes through the roof carries falling rainwater from the funnel into the container. The pipe must have a diameter of at least one centimeter and the apartment must have a minimum amount of heat so that evaporation cannot remove water from the container. At the end of the year, the height of the water in the container is measured and noted and the container is emptied.

This experiment, like that of the evaporating pan discussed above, must be repeated over a number of years because one or two years do not suffice to determine the quantity of water that evaporates, nor that which falls in one place, given that no two years produce exactly the same quantities; this is why these experiments are commonly repeated for a period of ten to twenty years. The quantities of water taken up or fallen each year is added up and by dividing the total by the number of years that the experiment has been done, the average thickness of the layer of water that rises or falls annually in the region can be determined.

Here are results of some observations that were done on this subject at different times and places.

Perrault was the first to use the udometer to verify the quantity of water that precipitation events dump on the earth every year. He determined that the average quantity that fell in Paris during 1668, 1669, and 1670 was 19 inches and 2 1/3 lignes. According to careful observations Poléni conducted at Padua over a period of ten years, the average quantity was 45 inches [Fr. *pouces*] for this city and 43 for Pisa. At Lyon, the average was 37 inches; in London, 37; in Rome, 28; in Algiers, 27; in Uppsala 15; in Geneva, 24; at the Grand-Saint-Bernard convent, 59; in Figeac (Lot) 19; in Paris in 1711, 26 inches of water, and in 1723, 7 1/2 inches; in Toulouse, 32 inches of water during rainy years and 15 inches in dry years. Mr. Cotte, having collected one hundred forty-seven observations on the amount of rain that falls annually in our climate, concluded that the average was 35 inches, a quantity almost equal to the amount that evaporates annually.

But admitting the exactness of these observations, the question arises if it is possible to prove that enough water falls each year to provide for the flow of springs, streams, and rivers that send such prodigious quantities of water to the sea.

Perrault and Mariotte, members of the *Académie des sciences* under Louis XIV, found that water that flows in the channel of the Seine is only a small part of the rain that falls in its basin; here is how they determined this:

Perrault examined and measured the basin of the Seine from its source to Aignay-le-Duc in Burgundy. This basin is about three leagues long and two wide, which gives a surface of six square leagues, or 31,245,140 square *toises* [See Translator's Notes]. If for one year all rainwater that falls on this basin accumulates there, stays in place and is not lost to evaporation or any other cause, on the last day of the year this surface would be covered with a water layer 19 inches, 2 1/3 lignes thick, which would be 224,899,942 *muids* (4) of water [See Translator's Notes].

One sixth of this quantity would be sufficient to provide the ordinary flow of the Seine for the entire next year at Aignay-le-Duc, even assuming that the basin did not receive a single new drop of water because in this place the river has on average about 1,200 inches of running water which gives 99,600 muids of water in 24 hours and 36,453,600 in a year. Thus, the quantity of water contained in this basin, assumed to be 224,899,942 muids and the amount flowing in a year being only 36,453,600 muids, it follows that the water that passes through the channel of the Seine at Aignay-le-Duc in a year is only about one sixth of the amount that falls on its basin during this period.

Repeating Perrault's experiment, Mariotte measured the entire portion of the Seine basin above Paris, and deducting for the numerous curves made by its perimeter, he estimated its surface at 60 leagues long and 50 leagues wide, which equals 3,000 square leagues. Leaving aside the advantageous quantities that previous observations had already provided, he contented himself with assuming that 15 inches of water fall on this basin each year, which equals 45 cubic feet of water per square *toise* [See Translator's Notes]. A league is 2,300 toises long, a square league contains 5,290,000 surface toises [square toises], which when multiplied by 45, gives 238,050,000 cubic feet of water per year, and the 3,000 leagues of surface area produce 714,150,000,000 cubic feet of water per year.

To verify the amount of water that passes through the Seine channel at Paris every year and to compare it to what falls in its basin, Mariotte verified that the water of this river at its average elevation is 400 feet wide and 5 feet deep. By throwing into the water an object light enough to float, such as a small block of cork, dry wood, wax, etc., he determined after numerous experiments that the floating object and consequently the river water flowed on average 100 feet per minute, which means 6,000 feet per hour. Multiplying these 400 feet wide by 5 feet deep, one has a section of running water of 2000 [square] feet, which when multiplied by the 100 feet that it flows each minute, gives 200,000 cubic feet per minute, 12,000,000 per hour, 288,000,000 per twenty-four hours, and 105,120,000,000 per year, which is not, he concluded, one sixth of the water that falls in a year on the land that provides water to the Seine at Paris. If in place of the 15 inches he used in this calculation, he had used 18, he would have had 856,980,000,000 cubic feet for the whole year, which gives eight times more water than the river carries through Paris.

The way to determine approximately the amount that falls annually on a river basin and that which flows in its channel during the same time being thus revealed by these two academicians, other French and foreign observers have followed their example and have done the same measurements on other rivers.  The results some of our engineers have recently obtained are different from the two we have just discussed and there is even less agreement among them. Thus Mr. de Gasparin (5) estimates at one seventh the average ratio between the quantity of water that flows in rivers and the quantity that falls in their basins. Mr. Minard (6) found that the amount of water that flows in the bed of the Rhône, as compared to that of precipitation that falls on its basin, is 25 out of 100. Mr. Baumgarten (7) is of the opinion that the water that flows into the Garonne channel is 34 out of 100; and Mr. Dausse (8) puts the amount of water in the Saône riverbed at 45 out of 100 (45%).

Results that differ this widely should not be surprising when it is known that the absorptive capability of the land surface varies to infinity because some land absorbs absolutely all the rainwater that falls whereas other land absorbs almost none; that the activity of evaporation and that the quantity of rainwater that falls each year varies from one year to the next and that from one location to another it can double. All the measurements done to ascertain the amount of water that falls annually on various river basins and that which flows in their channels must thus end up at as many different results as the measurements that have been done, both on the same river and on different rivers. Although these results are not concordant, they all establish the important fact that *precipitation dumps on each basin much more water than flows in the channel of their watercourses where the water is found*; because by taking the average of the results obtained by the last four observers, we find that the quantity of water that flows in rivers is about one fourth of the precipitation that falls on their basins, and if one accepts the average of the results obtained by these eight observers just cited, water that flows in rivers is only one fifth of what falls in their basins. In the following chapter we will account for these three quarters or four fifths of rainwater that is held in the ground, part of which serves to supply springs.

To support my ideas on the origin of springs, I could cite the authors who have supported the true cause of their origin; they are: Vitruvius, *Architecture*; Gassendi, *Commentaire sur Diogène de Laerce*; Palissy, *de la Nature des Eaux et des Fontaines*; Le P. François, *La Science des Eaux*; Pluche, *Entretiens XX et XXI*; Vallisneri, *Annot.*; Buffon, art. *Génésie des Minéraux*; *l'Encyclopédie*, art. *Fontaine*; Nollet, *Physique expérimentale*, XIIe leçon; Bordeu, *Eaux minérales du Béarn*; Brisson, *Physique*, n° 1044; Héricart de Thury, §

191; Degousée, *Guide du sondeur*, chap. I, and a number of other recent physicists and naturalists. But, as text citations would prolong even more so a discussion that is already too long, I will limit myself to indicating some of them for persons who consider it suitable to read them. That being said, the remainder of this treatise seems to me to suffice to prove that *springs do not originate from the sea through subterranean conduits but from rain, drizzle, fine mist, fog, dew, snow, hail, white frost, fine hail, and frost that provide to the land all the water that it sends to the sea and that it produces as springs*.

Notes

1. Musch., *Ess. de Phys*., § 4455.

2. The speed of an isolated cloud can often be determined by going to a high place and observing how much time its shadow takes to cross a known or measured distance on land.

3. The history of the *Académie des sciences* contains stories of several extraordinary hailstorms. It speaks of a hailstorm that ravaged the Perche in 1703, in which the smallest hailstones were as large as nuts, the medium as large as hens' eggs, and the largest as big as a fist. On 11 July 1753, a monstrous hailstorm hit Toul. It was monstrous for the size of the hailstones; one hailstone was twenty-four lignes long, eighteen wide and fourteen thick; another was almost three inches in all directions. The large grains were few in number, fortunately, and the storm did not last long; however, several persons and many domestic animals were killed or hurt. On 12 September 1768, a prodigious amount of hail fell near Saint-Gilles in the Bas Poitou; most of the hailstones were two inches long and one inch thick.

In 1811 in Hanover, Muncke found a large number of hailstones that weighed 120 grams. On 7 May 1822, Noeggerath collected hailstones that weighed 190 grams. On 15 June 1829, in Cazorta, Spain, blocks of hail weighed up to 2 kilograms. On 13 August 1832, during a hailstorm that ravaged the banks of the Rhine, the heaviest hailstone, found by Voget at Heinsberg, weighed 90 grams; at Elberfeld, hailstones were as large as a hen's egg and at Randerath, they weighed between 120 and 240 grams.

4. A *muid* is a measure of 8 cubic feet, such that a container 2 feet tall, long, and wide contains one muid.

5. *Cours d'agriculture*, t. I, p. 485. [For complete citation, see Appendix C: Adrien Etienne Pierre de Gasparin]

6. C*ours de construction*, p. 317. [For complete citation, see Appendix C, Charles Joseph Minard]

7. *Annales des ponts et chaussées*, 2° série, t. XII. [Baumgarten, date unknown, tr. note]

8. *Annales des ponts et chaussées*, 1842, t. III, p. 201. [For complete citation, see Appendix C: Dausse]

### 2.4.14. Chapter XIV. How Springs Form

When heavy rains fall for short durations, thick snowfall melts, or when the ground is impermeable, short-lived water currents form on the land surface. The land cannot instantaneously absorb all the water spread on its surface in these three cases; the part that cannot be absorbed trickles across the land, flows into streams and rivers, and causes them to overflow and return to the sea without contributing to wetting the land.

The amount of water that returns to the sea in this way, without having infiltrated the land at any location, is always very little if we compare it to all the water that flows into the sea after having infiltrated the earth, because snowmelt and heavy rains usually last only several days. Assuming that for two or three days a river has its ordinary volume of water multiplied tenfold, these days of flooding would equal only twenty or thirty days of ordinary flow; they do not produce one-twelfth of the water that a river carries to the sea the rest of the year. Eleven-twelfths of this water is thus provided by ordinary rain or by the numerous springs that are disseminated throughout the river basin.

Large storms that suddenly transform all depressions into streams and all streams into rivers are only local and momentary; they send none or almost none of their water to the sea. Almost all the water that is not absorbed in place spreads out on lower ground located outside of the storm and here the water is progressively absorbed.

That water then reaches the channel of a neighboring stream and if the stream is dry, the water is slowly absorbed, and if it happens that a portion of the water reaches a river, most often it causes a flood that is hardly noticeable and is of short duration.

Except in the cases we have just seen, all water that rain (1), fog, mist, dew, snow, hail, fine hail, white frost, and frost deposit on the land infiltrates to varying depths, and comes back out in three different forms: part of the water rises as vapor, another portion nourishes plants; and the third creates and maintains springs.

1st. The ground loses a considerable portion of the water it has absorbed through a mechanism that few people pay attention to: water that rises by exhalation. Water that is held near the soil surface, and this is ordinarily water that has fallen most recently, ascends, rising into the atmosphere with an activity proportional to the porosity of the land and the heat of the sun, and builds up in clouds. If on sunny summer days we turn our gaze toward a blackish or dark object located on the horizon, we can see water molecules or exhalations continually leaving the earth; these molecules rise rapidly and in rapid spurts. It is impossible to determine or even approximately evaluate the quantity of water that ascends from the earth in a given period. We observe only that it decreases daily from one rain to another.

2nd. A portion of the water the land absorbs is used for the growth and nutrition of plants. Few people have an idea of the quantity of water that roots pump and that the trunk, branches, and especially the leaves of plants and trees exhale through transpiration. The learned investigator of nature, Hales, on the basis of repeated experiments that he conducted with all possible care, found that during twelve hours of a very dry and hot day, the average transpiration of a sunflower was 20 ounces (1 ¼ pound) and three ounces during a hot dry night without dew; a dwarf apple tree exhaled 15 pounds of water in ten daylight hours and a foot of hops exhaled four ounces in a day. Mr. Monestier Savignat (2) says that a square meter of leaves can evaporate up to 27 kilograms of water in six months of growth, etc. If these experiments and a large number of others done to determine the *maximum* amount of water secreted by the pores of certain plants within a given time, cannot tell us how much they exhale during the ordinary course of vegetation, they at least give us an idea of the large amount of water that the land must lose in this way; a quantity that is as difficult to evaluate as to count all plants and measure all their surfaces.

Although we cannot know the quantity of water exhaled from the land or the amount used in plant nutrition, in any case we know the total portion that it amounts to because Dalton, Dickinson, and Charnock managed through experiments to determine that 35 percent of the average amount of rainwater is absorbed by the land surface; it follows that about two-thirds of rainwater that gets stopped by rock units leaves by exhalation or is used for plant nutrition.

3rd. After considering the amount of rainwater that only flows across the ground and the amount that penetrates without contributing to springs, we shall now talk about the portion of this water that, after infiltrating into the land, serves to form and maintain springs.

The depth to which the ground is wetted during each rain is highly variable; this variation depends on the amount of rain that falls, its duration, and the porosity and slope of the land. Everyone has observed that given an equal duration a heavy rain penetrates the land less deeply than a mild rain but a weak rain that falls for ten hours for example penetrates the land more than a heavy rain that lasts only an hour, assuming that during these two periods the two rains release the same amount of water. Different degrees of porosity of the rock units contribute considerably to allowing rainwater to move downward to various depths. Thus all the observations and experiments that have been done on this subject have resulted only in verifying the impossibility of determining exactly how far rainwater descends into the earth. After heavy rains, some people have found the ground wetted to a depth of only a few centimeters, whereas others have found it wetted to several meters (3). The disagreement between these authors regarding the depth to which rainwater penetrates comes from the degree of porosity of the land on which each of them did their experiments or the time that fell between the rain and the experiment. It should be noted that these observers and several others speak only of the depth to which they had found water immediately or shortly after rainstorms; they do not tell us that over time large quantities of rainwater descend into the earth to all types of depths (4) or that water has been able to reach the bottom of certain mines and caves by moving through rock masses several hundreds of feet thick. "It is a constant observation of miners, those of Cornwall especially, that in mines located in certain limestones, water increases in the deepest galleries a few hours after the beginning of rain on the land surface. The force of springs that issue from the earth at the bottom of vertical faces of chalky limestone grows considerably immediately after a rain." (Arago, *Notice sur les Puits artésiens* [*Note on Artesian Wells*])

All that can be said in general on this subject is that every time rainstorms deposit water on land, the water penetrates only to a very small depth during the first hours. The first layer is the most saturated, the second less so, and the third even less so, in such a way that the layers of earth are less wet with depth.

The amount of water that a given rock mass can receive internally is also highly variable; it can only be compared to the quantity that another mass of the same dimensions can contain, this other mass being more or less porous. For example, a cubic meter of rock that is very spongy can absorb one hundred, one thousand times more water than a very compact cubic meter; thus it is often seen that of two mountains that have almost the same height and extent, one can produce twenty times, one hundred times, or one thousand times more spring water than the other.

There is also an external reason that can cause inequality between springs produced by two plots of ground of same type and equal in extent; one of them is wooded and the other is not. Thus the surface, the constitution, the configuration of the ground, and the amount of rainwater that falls on the two plots can be almost the same but the volume of springs that they produce is different because any wooded area produces more abundant or more numerous springs than an area that is denuded (5). This cause is real but secondary and its effects are exaggerated, so that one should not believe that an area lacks springs because it is not wooded. Deforesting no doubt impoverishes springs but it does not destroy them or it destroys only springs that are extremely small.

Rain and other precipitation that falls on the land encounter impermeable rocks in some localities and permeable rocks in other places.

*Impermeable rocks* are those that water cannot penetrate and on which water either runs off or enters into cavities it encounters. The principal rocks of this type are massive rocks, some aggregated rocks, clays, and clayey soils. These two latter types, when mixed in a certain quantity with naturally permeable rocks, make them impermeable.

All massive rocks, stratified or not, that cover a large area and that lack vertical and oblique fissures or that have such tight fissures that water cannot penetrate them are impermeable rocks. In this category are granites, porphyries, gneiss, micaschists, quartz, syenites, sandstones, rocks formed from magma, etc. A thorough knowledge of this small number of rocks can put us in a position to discern other impermeable rocks. Because these rocks are impenetrable to rainwater, they can never produce springs by themselves; however when they are covered or intermixed with permeable layers that alone can receive, filter, and yield rainwater, the impermeable layers add powerfully to spring formation in that they prevent water from descending to too great a depth. These layers receive water, support it, and transmit it out of the earth.

*Permeable rocks* allow rainwater to penetrate to some depth. There are three types of permeable rocks. One is composed of unstratified rocks, divided into blocks and fragments of all shapes, separated from each other by cracks or crevices that extend in all directions; another is composed of rocks whose strata are almost horizontal, broken up by vertical fissures into prismatic blocks of small size; and the third is unconsolidated rock or detrital deposits. Rainwater penetrates each of these three rock types in different ways.

1st. The principal rocks types composed of unstratified rocks that are fractured in all directions and broken up enough to allow the passage of water are some layers of gneiss, micaceous schist, slates, serpentine, traprock, some chalks, gypsum, etc. Rainwater that falls on these rocks cannot penetrate into the interior of the blocks of solid fragments that compose them; rainwater wets only the surfaces and the contours of the blocks and seeps into all vertical and oblique cracks that it encounters, no matter how bizarre their directions, moving downward constantly and slowly to the impermeable layer that is always found below these rocks at some highly variable depth.

2nd. When rainwater falls on rocks that have almost horizontal stratification and that are broken up into small blocks by vertical fissures, it cannot wet the interior of these blocks; the rainwater can wet only the surface and the sides. Because almost no layer is perfectly level and because all layers that have the same stratification are ordinarily concordant, water flows along the slope of the blocks until it encounters a vertical fissure that lets it move downward to a lower stratum. Each vertical fissure in an upper stratum ordinarily falls into the middle of the lower stratum, and water follows the slope of the new blocks to their lower extremity where it finds a new vertical fissure that allows it to move downward to a lower stratum, and so on, from stratum to stratum to the impermeable layer that supports the entire stratified mass. The principal permeable stratified rocks are: sandstones, limestones, solid chalks, etc.

People are too often convinced that unknown springs lie at extraordinary depths, and this error has been substantiated in many places by the depth to which people have had to dig certain wells whose locations were chosen haphazardly. However, by choosing the location of an excavation with care and according to rules that will be spelled out, people will generally find that water circulating within the ground does not penetrate to great depths without encountering one or even several impermeable layers that prevent the water from descending indefinitely. Although these layers do not reveal themselves everywhere at the ground surface, their presence at shallow depth is no less probable, since according to Buffon:

> Clayey soil forms an envelope over the entire mass of the globe. The first beds are located immediately under the layer of topsoil just as they form a base under limestone benches. It is on this firm and compact soil that all water trickles gather to infiltrate through cracks in rocks or to infiltrate through the soil. The layers of clayey soil compressed by the weight of overlying layers and itself being very thick become impermeable to water that can wet only the top surface; water that reaches this argillaceous layer cannot penetrate it, it follows the first slope it encounters, and exits as springs between the last rock bench and the first bed of clayey soil. (Buffon, *Min., argiles et glaises*.)

This learned man expresses the same sentiment in seven other places in his works. Wallerius shares the same opinion, since he says (§ 19): *Argilla maximam constituit partem terrarum.* Clay holds up the greatest part of the earth [Edwin Robert, Latin-English translator, personal communication, 2016].

3rd. *Detrital sediments* are composed of debris from rocks and fossils. It forms a disaggregated and ordinarily very thin surface layer that covers the entire surface of the globe; it is the layer in which all plants grow. Some geologists call this *topsoil* [Fr. *terre végétale*] but the name detritus suits it better because in many places absolutely no plant life is present. The composition of this rock is not at all constant; it depends primarily on the nature of the rocks it covers or that surround it. Its composition varies from place to place as the covering or surrounding rocks do because the debris of the covering or surrounding rocks determines its composition. When these rocks decompose and are reduced to sand, this material is called *sandy soil* [Fr. *terre sablonneuse*]. If the rocks are limestone, it takes the name *limestone soil* [Fr. *terre calcaire*], etc. This material also exhibits an infinite number of modifications due to movement and mixture caused by agriculture, by fertilizers that are applied to it, and debris that running water deposits on it. It also contains abundant debris from animals, plants, and objects produced by humans.

When rainwater falls on disaggregated or detrital material, which is very porous and spongy, each drop is absorbed at the exact spot where it touches the ground. This water penetrates the topmost layers of the earth, where it is called *wetness*, *humidity* and the water mixes together intimately with the first layer, fills all the pores, and seems to exhibit no movement. However, all water that escapes by evaporation and by plant suction is not immobile for an instant. By virtue of its liquidity and its gravity, the water moves continually downward. The movement is slow, imperceptible, and is directed by the interstices of the material that it encounters. Water particles, moving downward with unequal speed, encounter each other, associate with each other, form first innumerable and imperceptible veinlets that grow little by little and become perceptible trickles. The water trickles, continuing to move downward, join up with other water at various intervals and encounter impermeable layers that force it to take an oblique direction, less and less inclined, and end up forming underground watercourses whose volume increases with distance from their place of origin. When looking at the place where water pours out of the ground, a person should not, as do a large number of people, represent it as forming a single horizontal watercourse of the same volume along its entire length. All springs are the product of an infinite number of veinlets and small water trickles that are interspersed and that increase in volume as they advance and form the watercourse that we see at the land surface.

The formation of a spring and its underground circulation are similar to the movement of sap in the crawling root of a tree. This root grows longer and extends mostly horizontally, divides and subdivides into new branches as it grows longer, and grows countless small filaments called *hairs* [Fr. *chevelu*] along its entire length and extremities whose function is to pump vapor out of the earth. As soon as this vapor is trapped by the filaments, it is called sap and it passes progressively, always concentrating more and more from the hairs to small roots, from these to middle-sized roots, and from middle-sized roots to the big root that transmits them to the foot of the tree; in the same way, the wetness that enters the ground during rainfall events condenses and flows imperceptibly through pores and interstices opened by previously infiltrating water and forms small trickles; these trickles, obeying the laws of gravity, move downward, continue to link up with other water along their paths, and combine in this way until the trickles encounter a compact layer that prevents them from sinking further, forcing them to move along a slightly inclined slope, and most often causing them to flow out of the ground.

The underground formation of a spring is better represented by the formation and circulation of streams and rivers that flow on land. A very correct idea can be obtained by looking at a map that correctly shows all the branches of a watercourse. A river that flows into the ocean is made up of rivers, rivers form from a number of streams, and streams form from countless rivulets and springs. Just as a major river receives not only rivers and large streams but also countless springs and small veins of water along its entire path, in the same way a spring collects water as it moves, not only from other springs that have almost the same volume or a lesser volume but also countless veins and veinlets of water that help it grow continuously (6).

This way of explaining the formation and the flow of springs underground is much more natural and better confirmed by all the excavations conducted every day than the supposition of *lakes, reservoirs, basins, and underground water masses* that no one has ever seen function and that are described by a large number of authors (7) who do not cite examples. While admitting that rainwater produces springs, these authors have not been able to conceive of the formation and flow of springs without imagining a reservoir full of water located within a mountain to supply the spring. They represent these *reservoirs* to us as filling during rainfall events, with holes at the bottom to allow the water they contain to drain little by little, and each maintain its spring until it goes dry. The abundance and duration of each spring is, according to them, proportional to the capacity of its basin and the diameter of the orifice by which it escapes. Others, seeing many springs pour forth around a certain mountain, have imagined that a unique reservoir at the center of each mountain provides water to all these springs; others, without questioning how this could happen, believe that a big spring, which they call the mother-spring [Fr. *source-mère*] is present at the center of each mountain, that it divides and subdivides as it moves downward and provides water to all the springs that flow in the vicinity. Thus in many localities I have seen people imbued with these false ideas who try to reach the supposed mother-spring by digging deep long trenches to increase the volume of a spring they see flowing from the earth. They began at the outlet of the spring and followed the conduit upstream but the more they pursued it the less abundant it became, as it had to be. All these lakes, reservoirs, water masses, and all these mother-springs that they have assumed to be at the center of mountains to supply springs should be relegated to the category of illusions (8).

I do not deny, that undoubtedly springs in their underground pathways can sometimes flow through basins filled with water; this happens primarily in cavernous rocks. Nor do I deny that a spring leaving one of these basins can be stronger than when it entered, because the basin can receive other springs on other sides; this is how many visible watercourses cross lakes and increase by lateral tributaries. But it is far from these two hypotheses, which I can easily admit, to the existence of these innumerable basins that fill suddenly during rainstorms and empty slowly to supply springs. One might as well say that Lake Geneva provides water to the Rhone, Lake Constance provides water to the Rhine, etc.

Notes

1. So as not to repeat the nomenclature of all this aqueous precipitation that drops water onto the ground, and whose description we have seen in the preceding chapter, I will most often call it only rain, given that rain provides the largest amount and that all other precipitation events, when they are turned into water, wet and infiltrate the land in the same manner as rain.

2. Monestier-Savignat, *Traité des inondations*, [*Treatise on floods*] p. 42.

3. *Ego vinearum diligens fossor affirmo nullam pluviam esse tam magnam quae terram ultra decem pedes madefaciat* [English: I as an attentive digger of vineyards assert that no rain is so great that it soaks beyond ten feet (Edwin Robert, Latin-English translator, personal communication, 2016)] says Seneca; *Pluvia non ultra decem pedum profinditatem humectat terram* [English: Rain does not moisten the earth deeper than ten feet. (Edwin Robert, Latin-English translator, personal communication, 2016)] says Varenius, *Géog*. Book 1 Chap 16; "I have had the land opened on mountains, on the slope of hills, in low places on the plains, and in cultivated gardens after large and long rains, and I have never found the land wetted more than a foot and a half or two feet" Perrault, page 167. "After a very heavy rain that lasted almost an hour, in several places I found the ground wetted a half foot at the most; almost everywhere it was much less." Pluche, *Spect. de la nat., Entr. XX*.

Mariotte claims that cultivated land allows the heavy rains of summer to penetrate only six inches.

Lahire recognized that through ground covered by grass, penetration never reached two feet.

"While examining large heaps of garden soil eight to ten feet thick that had not been turned for several years and of which the tops were almost level, I noted that rainwater never penetrated to a depth of more than three or four feet." Buffon, *Théorie de la terre*, 2e *Discours*.

4. Pluche, in one of those asides that our simple writers sometimes find it possible to guard against, advances without any reservation that rainwater that penetrates the ground heads for the sea far below its level. Soon thereafter he repeats the same assertion in different terms and cites some underground watercourses that discharge their water below sea level. (*Spectacle de la nature, Entretien XXI*) [*Spectacle of nature, Discourse XXI*]. If this naturalist had observed things close up, he would have seen, as I did, that rainwater that falls on continents and that saturates the ground will not go farther than neighboring streams or the nearest rivers and that it is only rainwater that falls on land near the sea that travels underground into the marine basin.

5. "Proximity to a forest exerts a major influence on the state of the atmosphere, just as forests exercise a great influence on springs located in their soil. The destruction of forests facilitates the evaporation of water, suspends water infiltration, and as a result causes springs to dry up ..." (Héricart de Thury, § 199.)

"It can be observed in places where there are small clearings that stream volume decreases because after the grass was disrupted, loose soil carried into depressions has left naked the rock layers that form the mountains. Rain causes it to go faster to enlarge rivers whereas water that was received by grassy land on the surface of mountain chains moves only little by little and slowly so that it left their flanks slowly, forming springs that spread gradually, and supplied streams all year long. What seems best verified is that springs dry up earlier than previously in the districts where the mountains are bare as a result of clearing. (*Statistique du département du Lot*, by Delpon, Vol. I, p. 117 and 121.)

6. "The same processes that one sees at the surface occur within the earth; small currents always flow into larger currents. Thus, these enormous springs can be regarded as true underground rivers that result from the joining of countless streams." *Nouveau Dict. d'Hist. nat.*, art. *Source*.

7. See Seneca, *Quest. nat.*, liv. III; Buffon, - *Théorie de la terre*, 11th discourse; Richard, *Hist. nat. de l'air*, VIIIth discourse, § 5; d'Aubuisson, Volume I, note 7; Demerson, *Géol*., p. 74; Héricart de Thury, *Consid. géol*., §§ 330, 343 et 344; Boué, chap. IV, § 3; Cuvier, *Rech*., Vol. IV, p. 556; Huot, *Géol*., chap. VIII; Rivière, *Géol*., chap. III etc.

(8) "At Bex, in Switzerland, they followed a saline spring for more than a league in the mountain, without finding a reservoir. La Métherie, § 1246.

### 2.4.15. Chapter XV. Underground Pathways that Groundwater Follows

The numerous trickles and veinlets of water that form in permeable mountains and hills and fall on impermeable layers do not move randomly. These trickles diverge underground just as rainwater does on the surface; thus a divide located above the ground indicates and follows exactly the line that divides groundwater. Each of the two hillslopes directs the small underground watercourses that form there into the vale toward which it is inclined.

These trickles move toward the bottoms of the vales because in stratified rocks the strata that make up the two escarpments are often inclined in the same direction as the surfaces of the escarpments and both sides [Fr. *côtés*] plunge toward the thalweg (1). When the two escarpments are composed of unstratified rocks, the water rivulets still tend to go from the inside to the outside because the void formed by the vale offers no resistance to their flow and thus they find it easier to move from the inside to the outside through conduits previously formed by water than to dig through solid and impermeable masses of unstratified rock.

The width of hills is generally so minor that water rivulets that flow down each side to the bottom of the vale are generally insignificant but the thalweg of the vale receives all the water trickles sent to it by plateaus, escarpments, and the two sections of the plain that form the basin, and thus the thalweg may host a significant water course. And so, springs almost always flow out of the ground into the bottom of the vale and along the thalweg line; when springs are not apparent, they are hidden there and flow beneath transported material. Based on the knowledge of several thousand natural springs I have observed and on the large number of excavations that have been done as a result of my indications, I can suggest that, aside from a few exceptions to be pointed out later, *in every valley, vale, defile [narrow gorge* – tr. note*], gorge, and depression, there is an apparent or hidden watercourse*. The one that is visible moves along the ground surface because an impermeable layer supports it; the hidden one also moves along an impermeable layer but it is covered by permeable rock that cannot support it at the ground surface. A person who understands the laws that govern visible watercourses can thus understand and follow on foot a hidden watercourse because the two follow the same laws and flow in the same way.

I say that the watercourse present in each vale is apparent or hidden. In fact, some vales have permanent and visible watercourses along their entire length; in others the watercourse flows only during rainfall or shortly thereafter and remains dry the rest of the year; in others the watercourse is visible only near the origin, then it flows externally a certain distance and disappears absolutely or reappears only near the edge of a neighboring river; in others the highest part is absolutely dry and after a certain distance the watercourse flows as one or several large springs that continue to flow at the surface to the mouth of the river; in others the watercourse appears and disappears several times; and finally in others no visible watercourse ever forms and, no matter how hard it rains, they remain permanently dry along their entire length.

Almost everything that was said in Chapter IX about visible watercourses can be applied to invisible watercourses; the point of departure of an invisible watercourse or spring is either on an elevated dry slightly depressed and slightly inclined plain or in a vale shaped rather like a cirque.

When a watercourse starts on an elevated plain [Fr. *plage élevée*] composed of a single depression [Fr. *pli de terrain*], the first water rivulets converge toward a common center that occupies the lowest point. If this plain is composed of several depressions, the depressions are not all equal; one always extends farther or is deeper than the others and each of the shallower depressions will direct the water rivulets they carry into the one that extends farther or is deeper. To get an exact idea of the way watercourse forms underground in a depression, one has only to look during a hard rain and carefully observe how runoff [Fr. *eaux sauvages*] (2) flows and comes together to form a momentary water current at the surface; we can be sure that the small permanent and hidden watercourse forms and moves underground in the same way and that the veinlets and veins follow the same lines underground as water does on the surface (3). When it is not raining, it is still possible to imagine the formation, movement, and collection point of rainwater to determine the formation and flow of the hidden watercourse.

When a watercourse forms at the end of a cirque-shaped vale, all water rivulets that the plateaus and surrounding hillsides can produce converge like the radii of a semi-circle toward the center of the cirque and come together to form the watercourse. The central point of a cirque is always at the foot of the steep and semi-circular slope that forms the walls.

Starting at the bottom of the depression or of the center of the cirque, the thalweg begins to take shape, the slope of the bottom of the vale becomes less steep, the water, which already has a certain volume, always follows the thalweg of the vale, whether it forms a straight or tortuous line. This is how watercourses form in all vales, both principal and secondary. A watercourse located in a principal vale receives other watercourses of different sizes at various distances, which are brought there by vales and toward the mouth of which it [the principal stream] inflects to receive them (4). The larger the tributary stream, the more the principal stream deviates from its straight line. The feet of cliffs and non-undulating escarpments provide some water rivulets, which are normally small, and toward which the principal stream does not make any inflection.

It would be impossible to give an idea of the prodigious number of small and large watercourses that each underground and visible watercourse receives on its two sides along its length, the existence of which has never been suspected, because each vale, gorge, and depression brings one. Any recess, even if it forms a small reentrant or a semi-circle at the foot of a cliff whose base forms the margin of a low plain, ordinarily harbors a spring; this always happens where a vale is present on a plateau or even a series of sinkholes that line up in the direction of this recess.

Wherever the rock unit that makes up the bottom of the vale is solid enough for a watercourse to form at the surface during heavy rains, the underground and permanent watercourse follows nearly exactly the same line as the surface and temporary watercourse everywhere that the bases of the two escarpments are contiguous. This happens even in low plains when the two lateral slopes [Fr. *pentes latérales*] are inclined toward the channel of the temporary watercourse.

However, this concordance of the two watercourses moving on top of each other during rains is often disturbed by either 1st) the stratification of escarpments, or by 2nd) human construction, or by 3rd) visible watercourses left to themselves on the plains. Here is where a hydroscope must be attentive.

1st. The visible thalweg does not coincide with the invisible thalweg when the rocks that make up the two escarpments have concordant/parallel stratification and when the gently dipping strata of the escarpment plunge underneath the strata of opposite escarpment, which is steeper. In this case, the watercourse passes along the foot of the steeper escarpment, and sometimes even, although rarely, it abandons the thalweg formed by the two escarpments and moves under the strata of the steeper slope. This deviation may continue over a part or over the entire length of the vale. Consequently, sometimes this watercourse flows out of the ground on the edge of the river, not across from [Fr. *vis-à-vis*] the middle of the vale that brought it; instead it pours out at the base of a cliff, either upstream or downstream of the outlet of the vale, depending on whether the stratification of the two escarpments is inclined toward one side or the other. Other times, the watercourse deviated in this way pours out from the flanks of the steepest escarpment and even above the level formed by the alluvial deposits in the valley; and the person who did not notice that the watercourse follows concordant stratifications of the two slopes would believe that it came from the center of the hill from which it flows.

There are also some places where the underground watercourse leaves the vale in which it formed and flows into the neighboring vale. It may happen: 1st) when the hill that separates the two vales is completely disaggregated and the water has a much easier time flowing though it than in the transported material [Fr. *terrain de transport*] that occupies the bottom of the vale, 2nd) when the strata that make up the hill have been uplifted or dropped down, and 3rd) when the strata are vertical across the vale and form a dam that continues into the neighboring vale. A change of vale by underground watercourses is very rare. I know only five or six examples of it. An attentive examination of a vale makes it possible to recognize if one of these situations is present and as a result, to recognize if a deviation has occurred.

2nd. It is often noted that in dry vales, property owners fill the channel and dig another at some distance from the real one to connect two fields separated by a stream that flows only briefly or temporarily; others, to have more land, dig a straight channel to replace a sinuous one that follows the stream; others have moved the bed of the stream by constructing dikes along their property, causing banks on the opposite side to erode. But the former streambed is almost always easy to recognize.

3rd. On plains, temporary and ephemeral streams left to themselves deposit terraces along their borders that build up over time during storms. After a certain period of time, the channel is at a higher elevation than the rest of the plain and is located on a type of high point; the stream then abandons the high place to dig another channel in the lowest part.

The underground watercourse, which is never disturbed by human construction or by levees present at the ground surface, always follows the true thalweg and in none of these cases can a stream that flows temporarily at the surface serve as a guide to the location of the underground watercourse. A search for traces of the old channel must be conducted, assuming that agriculture or levees have not totally erased them, or the following methods can be used.

When it becomes apparent that in the place where one wants to dig to find water, the visible thalweg does not coincide with the invisible thalweg, which happens only in parts of vales that are on plains, it is necessary to observe attentively the two inclined planes that form the two opposite escarpments and to know that the watercourse follows their line of intersection underground. Thus if the slope of the two escarpments is equal, the underground watercourse moves at an equal distance from two foot-of-slope lines; if the slope of the two escarpments is unequal, for example, if the slope of one is a third, a quarter, a fifth, etc. steeper than that of the other, the watercourse will flow near the steeper escarpment proportional to its steepness, and if one of the escarpments is a cliff, the underground watercourse passes along its base.

The underground thalweg is still indicated by temporary water flows. In many places they flow along the thalweg line and in boulders there is always a watercourse each time it rains heavily (5); in others, scarce or short-duration rains establish the same flows. This watercourse flows out onto the ground only when it rains because its ordinary volume increases and its conduit is then insufficient to provide passage. The entire portion of the watercourse that cannot pass through the conduit flows outside during rains and even some time afterward. In some places, this flow occurs through a passageway or vertical conduit that remains open constantly; in others, the water rises through loose stones or detrital material that hides the opening in the rock by which the water escapes. To be sure of finding a permanent watercourse, often at shallow depth, all one has to do is dig along this passageway, unless it is one of those [passageways - tr. note] that does not go far enough or because the channel is too inclined so that it flows only during each rain and soon dries up. *Thus in any dry vale several hundred meters long, at the rocky bottom or covered by sediment, which may be shallow or deep, there is a watercourse that follows the underground thalweg*, and one can almost everywhere recognize exactly the straight or sinuous line that it follows and follow it step by step.

Knowledge of the lines that watercourses follow underground serves not only to find them but also provides a method to avoid them when necessary. Everyone knows that groundwater is a scourge in coal mines and that water drowns miners from time to time, that its drainage costs several millions every year, that it has caused the abandonment of many mines known to be rich, some from the beginning and some in full exploitation, and that the losses caused by these abandoned enterprises cost millions or hundreds of thousands of francs. From now on, mining engineers who want to study the lines that groundwater follows will be able to direct their galleries in such a way as to avoid them. At the very most, they will be able to intercept small trickles of water that would otherwise join larger groundwater flows or even groundwater whose course has been diverted, but the latter case is extremely rare. When miners excavate to extract rock, salt, plaster, etc., this same study will prevent them from opening quarries and galleries into underground watercourses and will prevent the invasion of water.

Notes

1. *When the strata of a mountain are inclined toward the horizon, they rise on one side and descend on the other*. Saussure, § 281. *The beds plunge from the two sides toward the bottom of the thalweg. Mém. géol*. of Mr. Boué, p. 3. These assertions, which are true in the majority of cases, are subject to numerous exceptions; thus Buffon (in an addition to the article on earthquakes) expresses the same idea but with the restriction: *Between two neighboring hills, one often finds*, he says, *strata that dip along the first and rise along the second after having crossed the valley.*

2. *Runoff* [Fr. *eaux sauvages*] is water that flows at the surface only during rainfall and the melting of snow and ice.

3. This principle was known to Seneca and all my observations and experiments have confirmed it entirely; generally speaking, watercourses follow underground the same laws as above: *Sunt et sub terra minus nota nobis jura naturae, sed non minus certa; crede infra quidquid vides supra.* [There are under the earth laws of nature less known to us, but they are not less valid; trust that underneath is whatever you see above. (Edwin Robert, Latin-English translator, personal communication, 2016)] Sen., book. III, *Quest. nat*.

4. As a result of this observation and what was said in Chapter IX about the inflection a stream makes to receive another large stream, each time I have looked at a Cassini map representing a region I have never seen, I have been able to indicate the precise point where each important spring flows from the ground along a river or a stream. Knowing that every time a permanent and visible watercourse makes an elbow toward a dry vale, which is always very exactly represented on these maps, I have announced to the great astonishment of those who are familiar with these localities that at the outlet of such vales there is a visible or hidden spring and of such volume, because the volume of a spring is always proportional to the length of the vale and this spring is almost always visible.

At the end of August 1835, the day after my arrival in Poitiers, the directors of the seminary held a dinner for the members of the chapter of this town and they graciously invited me. At the end of the meal, these gentlemen, who had heard that I indicated springs based on Cassini maps, had the map of their region brought to the table. Mr. Samayault, vicar general, placed a map before me and said: *Sir, I have been the priest of this parish here*, which he showed me with the end of his finger. In this area*, there is only one known spring. Can you point it out to me*? After examining the map for several seconds, I responded: *The spring is about 120 meters west of this house*. Gentlemen, said the completely astonished grand vicar, addressing his assistants, *this designation is perfectly correct; the spring is exactly at the point where the gentleman has placed the point of his pocket knife and at about 120 meters west of this isolated house. However, there is no indication of this fountain or stream on this map*. The other chapter members asked me similar questions, which were all answered in the same way.

5. At the foot of the slope of Chatagna in the Jura, there is a crack in the rock through which water shoots a large jet almost four meters high in winter. In summer, this spring is

entirely dry. -- The Black Well and the White Well, near the ruins of the former city of Antres in the same department, are types of very deep abysses from which water flows in torrents after heavy rains and snowmelts. --The Ornans well (Doubs) shows the same phenomenon and during periods of overflow, it expels a large quantity of fish. --The Loule well, located in the thalweg of a vale in the commune of Saint-Jean-de-Laur (Lot) is dry all year, but during heavy rains it ejects such a large quantity of water that it forms a large stream.

### 2.4.16. Chapter XVI. Where to Dig for Water

Not all points along the line that an underground watercourse follows are equally advantageous for bringing it to the surface. At some points along its path, the water is quite close to the ground surface and at others it is very deep, and often so deep that it cannot be exploited; in some places, it is quite abundant and at others it is not; in one place its passage is certain and in others uncertain; in some places, it can be found by digging, such as in very friable rock units whereas in others it would be necessary to dig through hard rock, sometimes rock that cannot be broken. Thus, just knowing the path that an underground watercourse follows is not enough information for finding it; it is also necessary to know the most advantageous and the least disadvantageous locations for digging along its path; this is what I will try to make known by pointing out places where an underground watercourse is most shallow and where it is most abundant.

Places where an underground watercourse is most shallow

If an underground watercourse flowed parallel to the land surface everywhere, a person who drilled at any location along its path would feel sure of finding water at the same depth but that is not the way it is. The invisible thalweg where the underground watercourse flows often has no similarity to the thalweg at the surface; the slope of one corresponds only fortuitously and over short distances with the slopes of the other. Where a plain is visible at the surface, the watercourse it conceals may have a rather steep slope and where the ground surface has a significant slope, the hidden watercourse is often almost not at all inclined.

The points where an underground watercourse is most shallow are: 1st) the central point of the first depression where all water trickles coalesce on the high section [Fr. *plage élevée*] to form its beginning; 2nd) the center of the cirque [Fr. *cirque*] where the watercourse begins; 3rd) the bottom of each slope of the visible thalweg; 4th) the approach to its outlet or mouth.

1st. When an underground watercourse begins on an elevated plain, the shallowest point is the one toward which the water converges or where the first water trickles of the mass coalesce. This point is recognizable because it is toward the middle of the depression and the place where the thalweg begins to be visible. If a person departs from this point and digs farther downstream in the thalweg, the underground watercourse will be found there and even more abundantly if another depression discharges its water there; but the water will be deeper because the two small hillslopes of the depression are becoming steeper, and on top of the underground watercourse, agriculture and runoff deposit material whose thickness increases with distance from the origin of the thalweg.

2nd. When an underground watercourse forms at one end of a cirque-shaped vale, the shallowest point is the center of the cirque. If a person digs downstream in the thalweg, he will find water but it will be deeper.

3rd. Along the underground pathway of the watercourse, its shallowest points are at the foot of drop-offs. The longitudinal slopes [Fr. *pentes longitudinales*] of vales are normally composed of sections [Fr. *plages*] with gentle slopes alternating with steep slopes or slope breaks [Fr. *chutes de terrain*]; these two slope types are similar to those seen at the surface of watercourses, which are called *rapids* and *slack zones*. Every time a bank of rock, a layer of hard soil, or even a wall is placed across a vale to form a dam, a section [Fr. *plage*] with a shallow slope is formed above the dam by transported material and at each dam is a steep slope or a cascade. A person who digs above the steep slope will have to dig through the excess depth of the entire difference between the top and the bottom of the drop-off and in addition he will have to drill through a bank of rock that he could avoid by digging at the bottom of the slope. To find water at a lesser depth, a person should also always dig at the foot of a wall or the talus that crosses the vale. The proof that a watercourse is less deep at the foot of steep slopes than everywhere else is that this is the location where almost all springs that flow on their own emerge from the ground and in addition, this is the place where in all my experience, underground watercourses are closest to the ground surface.

It is true that a spring sometimes flows to the surface at the top of a steep slope or on a steep slope itself because a rock or impermeable clay layer conveys the water out of the ground; but whenever the spring does not reveal itself, it follows that the layer of rock or hard ground that makes a dam and forms the steep slope is pierced or cracked and that it lets the water move downward deeper than the base of the steep slope; thus one should never look for a watercourse at the top of a slope nor on the slope itself.

4th. When a spring flows into a visible and permanent watercourse and when the bottom of the vale in which it flows has a gentle slope, by digging not far from its mouth a person can count on finding it at a shallow depth, because it can never be below the level of the watercourse into which it flows.

Although the water of an underground watercourse found near a visible watercourse rises and falls at the same time as the latter, it should not be assumed (as people who are ignorant of underground hydrography do) that the water comes from the visible watercourse. All underground watercourses move from mountains to a visible watercourse. It is only during floods in the surface stream that they are momentarily stopped and held back because the two types of water, which are then in communication, come into equilibrium; but when the flood ends, the underground watercourse continues its normal flow.

When the thalweg of a vale is not cultivated and willows, poplars, alders, osiers, rushes, reeds and other aquatic trees or plants are growing there naturally, it must be presumed that the watercourse is not deep in this location. However, because these plants grow in all ground that retains moisture, they can serve to indicate the presence of a hidden watercourse only if they are on a thalweg or at the bottom of a recess. Pliny himself (1) observed that exploration for springs by looking for certain plants that grow only in humid places involves much uncertainty and he call these signs erroneous indications, *augurium fallax*.

### Places where an underground watercourse has the most abundant water

An underground watercourse grows as it advances; we cannot here compare its volume near the origin to the volume near the outlet; I want to talk only about the difference in volume that a person finds, for example, sampling the water about ten meters more upstream or more downstream.

The places where underground watercourses are most abundant and at shallowest depth are the bases of drop-offs. In fact, water ordinarily crosses layers of rock or hard ground through a single conduit that conveys it underground to the foot of a steep slope or cascade. From this point, the underground watercourse flows under a new plain cluttered with transported material where the water spreads out to form a wide water layer or separates into currents or numerous trickles that leave islands between them. He who is not the owner of the foot of the steep slope or who is too far from it or who does not need the entire watercourse can dig in the thalweg of the plain, always being careful to approach the foot of a steep slope as closely as possible to spare himself some of the depth and to find a large quantity of water.

Some gently and uniformly sloping plains overlie layers of shallow flowing water that extend from one foot-of-slope line to the other; in these places the art of finding springs is totally unnecessary. Once it is known that several holes have been dug here and there with complete success, a person can dig there at leisure with the certainty of finding water at the same depth as his neighbors. For this to be the case, the plain must meet three conditions: 1st) receive one or more large watercourses from a small vale or vales that discharge there; 2nd) consist of pebbles, gravel, and sand to a certain depth that allows the water to spread out; 3rd) have an impermeable layer beneath the disaggregated rock and this layer must be parallel to the surface and extend over a large area.

On plains composed of transported material interspersed with alternating permeable and impermeable layers, an underground watercourse not only spreads out farther but also he who digs deeply can find several water-bearing layers superimposed one on top of another, each flowing within its permeable layer. If a person has dug and already reached a water layer he finds sufficient, he has only to continue digging until he finds another or more that will furnish all the water he wants because generally speaking, the deeper a person digs in this type of rock, the more abundant water layers he finds (2).

In low-gradient plains that have a visible watercourse, permanent or temporary, the [visible] watercourse is ordinarily much more sinuous than the invisible thalweg where the underground watercourse flows. By zigzagging from the foot of one escarpment to the other, a person crosses and re-crosses the invisible thalweg many times and he is on top of it only for short distances. (Refer to what was said in the previous chapter.) To find the underground watercourse, a person must dig in the channel of the visible watercourse after first digging an additional channel several meters from the excavation and perhaps also constructing a dike along the new channel high enough to prevent flooding the watercourse and the hole that was dug to find it. To reduce the cost of the diversion canal, if the person owns one of the bends of the visible watercourse, it is preferable to excavate toward the middle of the space in the river bend so that it is located at the maximum distance possible from the edges of the visible watercourse and so that its water can never mix with that of the underground watercourse, either by flooding or by infiltration.

On some very wide and long low plains, it is not possible to dig on the longitudinal and principal thalweg because a permanent watercourse is present there. Even when there is no visible watercourse, it often happens that this thalweg is outside the property of the person who wants the underground watercourse or that it is too far from his house. In these three cases, it is necessary to excavate on lateral thalwegs. Although the vales, gorges, and depressions all end when they reach the plain, the underground watercourses that they bring do not end there; they continue to flow under the plain toward the principal watercourse. The thalweg that each of these lateral watercourses follows under the plain is ordinarily recognizable because in this unconsolidated material [Fr. *terrain incohérent*] the hidden watercourse continuously erodes the walls of its conduit and carries materials toward its outlet, often producing a small depression on the ground that very clearly indicates the line it follows underground. If the thalweg is entirely obliterated, it is at least visible at the outlet of the vale and at the point where this thalweg meets the principal thalweg, a point ordinarily marked by an indentation, and these two points suffice to indicate the line it follows on the part of the plain where it is entirely obliterated. A person can even make use of the axis of the lateral vale that has carried the underground watercourse and excavate on the line indicated by this axis and based on what was said regarding the laws that govern visible watercourses.

## Underground watercourses on mountains

Underground watercourses are found not only in the thalwegs of every valley, vale, gorge, etc.; they are also found on mountains and hills of all heights and on their hillslopes. In these two cases, their discovery requires several special observations.

All mountains and hills have a sharp summit, a rounded dome-shaped summit, a long and rather sharp watershed divide, or a plateau.

When a sharp ridge or a sharp or dome-shaped summit tops a mountain or hill, no underground watercourse will be present on the ridge or summit, absolutely speaking (3). If the rock type is impermeable and if a cavity is present, it is undoubtedly possible to find there a puddle of water or even a lake full of rainwater but this cavity is never supplied by a spring. Curious to verify a fact that had always seemed impossible to me, I visited more than one hundred mountains, large and small, at whose summits people have assured me of the existence of a spring right at the summit. I have not found a single case in which it was true; in each location, a plot of ground several meters thick and of an area proportional to the volume of the spring towered above the spring.

Everything that modern hydrographers have spouted about supposed *reverse siphons* that originate in the highest mountains, cross numerous deep valleys, all to flow out as a small spring at the top of a smaller mountain has no supporting evidence. No one has ever intercepted an underground watercourse that has dried up a spring located on the top of a mountain, and no one has ever seen a spring pour forth from the highest point.

In mountain chains a peak sometimes pours out a spring on the ridge of a pass but the spring has not formed on the ridge of the pass; rather it comes from the land mass that makes up the neighboring peak, which would itself form a veritable mountain that pours its water onto the pass because its strata are inclined toward this side.

If a spacious plateau is present at the top of a mountain and the plateau is slightly inclined and covered with several meters of permeable ground resting on an impermeable layer, it is rare that an underground watercourse does not form in the middle or at the lowest point of the plateau. The rain that falls more frequently on mountains than on low plains, the large size of plateaus, and the usually favorable composition of the surface rocks sometimes forms large underground watercourses that are only a few meters of rock above their outlets. One even sees lakes that receive underground watercourses from upstream and from two sides; the watercourses contribute their product into permanent streams. Several meters of rock are all that towers above the outlets of these springs, which has caused many people, more avid of miracles than inclined to make exact observations, to infer that these springs are located exactly at the summit of mountains and that the water can come only from higher mountains via a reverse siphon.

If the plateaus are sufficiently wide, for example five to six hundred meters and of suitable rock type, they can provide springs proportional to their size, which is not the case for narrow plateaus that are only about fifty meters across; here no springs are present, even if the composition and distribution of the rocks are favorable because there is not enough space for them to form.

Conical and isolated mountains that have a basal diameter of less than four or five hundred meters, whatever their height and composition, can produce only very weak springs in their vicinity, and most often they produce none at all. The same is true of elongate hills that are only four or five hundred meters wide at the base. If the stratification and the waters divide along the axis of a hill, no matter how high it is, it can produce only a few small springs; often if the rock units are unfavorable it produces none at all; but if the stratification of a hill directs all the water to one side, this space may suffice to form voluminous springs.

### Underground watercourses on hillslopes

It is possible to find significant underground watercourses on hillslopes of mountains and hills that are several kilometers wide. Prior to indicating the most favorable locations for finding them, one observation precedes and dominates all others: the inclination of the strata present in these mountains or hills.

When a long mountain or a hill has a plateau at the top and it is located between two vales, the plateau is ordinarily inclined to one side rather than the other and the strata, if there are any, are parallel to the surface of the plateau. When the drainage divide is located near the middle of the plateau, the strata of the two hillslopes are inclined in different directions, their slopes are almost equal and they carry the same amount of water to their vales; and if the ridge is on or near one side, the underlying escarpment is steeper and sometimes very steep. On this escarpment, the tops of the strata [bedding planes – tr. note] form stair steps, sometimes cropping out and sometimes covered by detrital material. All rain that falls on the plateau follows the hillslope with the most reduced slope and flows into the vale farthest from the ridge. Thus, a person should never look for springs on the steepest escarpment because the strata, instead of carrying water from inside the hill to the outside, collect water that falls on the plateau and also rain that falls on the stair steps formed by the outcrops, and these strata direct the water across the mountain to the foot of the escarpment with the gentle slope. Thus knowing that water that falls on a plateau infiltrates between strata and follows the slope, from as far away as a person can see he can announce the dip direction of the strata that make up the mountain, the side where springs occur, and the side that will have no springs (4).

It may happen, undoubtedly, and I have seen examples where the rock strata that should regularly carry water toward a valley are vertically fractured down to an impermeable layer on which they rest, and the slope of the impermeable layer is opposite that of the [overlying] strata; then the watercourse, instead of continuing its path along the strata, falls into cracks, descending to an impermeable layer that has a different slope, and reverses direction to flow out at the foot of the steepest escarpment, but these are exceptions and should not be taken as the rule.

When escarpments with steep slopes are tall, for example two or three hundred meters high, when the permeable rock that covers them is only several meters thick, and when all the rest of the escarpment is composed of rock types favorable to springs, watercourses may form there and descend to the base of these escarpments but the watercourses are neither large nor numerous.

Mountains and hills that are composed entirely of clay, topped with a plateau of jurassic limestone [Fr. *calcaire jurassique*; not Jurassic age limestone, but limestone present in the Jura region] sufficiently extensive and from eight to about fifteen meters thick, ordinarily produce numerous springs at the foot of the cliff that forms the lower edge of the plateau. This occurs very commonly when a layer of marly limestone is present between the limestone deposit and the clay. Some of these springs are visible but most are hidden. Springs are found hidden in recesses in the cliff and in slight depressions or hollows formed by clay in front of this recess. This depression is often filled with rock debris from the recess and with a sprinkling of aquatic plants or bushes. A springs-seeker should never neglect to go up on the limestone plateau to determine its extent and to see if it is smooth or folded. When the surface is folded, each fold that leads right to the recess announces the underground watercourse it brings. These springs, always of good quality, are mostly small and they are only abundant when the part of the plateau that produces them is very extensive. Springs are thus found on top of escarpments when the rock conditions that have just been discussed are present, but this is far from being the ordinary case.

In many locations, very abundant springs pour forth from the feet of steep and high escarpments composed of accumulations of unconsolidated rocks [Fr. *terrains désagrégés*]. Most landowners who have built their homes toward the top of these escarpments believe that they can reach this water without digging too deeply; this is an error. For it to be so, the underground watercourse would have to flow under the plateau parallel to the surface and at a shallow depth, and when it reaches the ledge, cascade toward the foot of the escarpment, but this is does not happen; because I have verified numerous times that underground watercourses have only the ordinary slope of visible watercourses and that cascades are as rare in one as in the other; from this it follows that a person who wants to dig near the top [Fr. *corniche*] of an escarpment to intercept a spring that comes out of the ground at its base would choose precisely the most unfavorable point of its entire course and would be obliged to excavate to a depth equal to the height of the escarpment.

Starting at the top, the slope of the escarpment is sometimes smooth and has no detectable ridge and is sometimes composed of a single depression; in addition, depressions and areas of positive relief, which may be pronounced, furrow the slope. Some furrows extend from top to bottom, others disappear into the slope; others begin there and continue to the base.

When the escarpment slope is absolutely smooth and has no ridges, which is very rare, there is no reason to dig at one place rather than another other than distance from the drainage divide, because we know that the farther from the drainage divide the larger the watercourse. Thus if the point where a person wants to dig is far, for example two to three hundred meters from the crest, if the stratification of the rocks leads water toward the surface and if the water-bearing strata are shallow, a large number of water trickles may be found there descending from the escarpment and flowing close to each other, but because they lack a vale or depression to concentrate them, none of them is large. When there is no other way of getting water, a horizontal trench should be cut across an escarpment; the length of the trench should be proportional to the desired amount of water. (Chapter XXVII contains information on the shape of the trench and aqueduct to be built.) These trickles of water, thus intercepted and collected, will together form a considerable watercourse and in my explorations, they have often provided the means of supplying healthy and permanent water to a large number of populous villages that would not have had water without these long trenches.

If the escarpment has the shape of a narrow and rounded hilltop from top to bottom, even if only slightly convex, there is no reason to look for water there because only a small amount will be found; but if the hilltop is large, if it is more than five hundred meters wide, for example, it thus forms a real escarpment and water can be found there, as we shall see.

If the middle of an escarpment is slightly depressed in comparison to its two sides, one should not look for water on the margins; rather the trench should be placed in the middle, where a type of wide thalweg is present and the trench should extend across its entire width.

When an escarpment is furrowed from top to bottom by several depressions, the trench should be dug in the thalweg of one of them, and if the thalweg has a steeper slope near the top than at the bottom, the trench should be placed precisely at the bottom of the steep slope and at the point where the reduced slope begins.

If a depression begins at the ledge at the top of the escarpment and completely disappears before reaching the bottom, the excavation should be made at the foot of the ledge or at least as close to it as possible, because at the end of the depression, the watercourse goes deeper as it infiltrates.

One of the most favorable signs of the presence of an underground watercourse on an escarpment is a depression that starts there and continues to its base. In fact, wherever there is a visible spring on an escarpment, it pours forth into the middle of a small circular depression that forms the beginning of a depression and it continues to flow outside to its base. The place to look for a hidden spring is thus the bottom of a similar hollow or an analogous point.

The points of a hillslope where hidden springs are most numerous, most abundant, shallowest and where their presence is best characterized is on the foot-of-slope line. This does not mean that a person should dig randomly at all points along this line; rather, the favorable points are located only in certain places, at intervals that may be short or long. It is thus important to learn to detect these points.

First of all, digging should be avoided at any point where the foot-of-slope line turns around a salient because the rounded tops of mountains, hills, foothills, and spurs lack underground watercourses. Digging should also be avoided as much as possible on sections [Fr. *trajets*] where the foot-of-slope line follows the foot of a smooth or very short escarpment because with an ordinary trench it is possible to find only insignificant water trickles and most often none at all, unless a long trench is dug. Although all field characteristics may be favorable, one should still avoid digging on this line in places covered with thick rubble [Fr. *éboulis*] (5), because the height of the fill makes the underground watercourse deeper by the amount of its thickness; but digging should be done along the foot-of-slope line at whichever of the following points is easiest: 1st) at the top of a reentrant, in other words, at its most concealed end; 2nd) at the most concealed end of a recess at the level of the plain and at the foot of a cliff; 3rd) at the base of a depression or at the bottom of a gully, at the point where the thalweg crosses the foot-of-slope line; 4th) at points chosen by preference where watercourses appear during heavy rains and places where shrubs or aquatic plants are growing.

Because some escarpments are composed entirely of rocks, in choosing the point along the foot-of-slope line for digging, care must be taken to avoid placing the excavation too close to the visible base of the rock because ordinarily its surface slope continues under the transported material. If after beginning to dig, it becomes obvious that bedrock has been encountered, the digger should step back from the excavation several times if necessary until he can ensure that the excavation is exactly at the foot of the underground slope of the rock and that it is located on rock or soil strata that are almost horizontal.

## Optical illusions to avoid

*We have*, says Brisson (*Phys*. No. 1211) *countless optical illusions, errors of viewing that we cannot avoid*. As a result of one of these errors, a person in a boat in the middle of a pond imagines that the water surface rises around him, rather than viewing the surface as horizontal as it really is. If a person stands next to a pond, the water surface seems to form a vale whose axis begins at his feet and this vale seems to follow his footsteps.

The same error hounds the hydroscope when he works in the middle of a smooth and entirely open plain. He must pay close attention to this optical error which causes him to see the point where he is standing as the lowest point and the surrounding ground as rising on all sides to the extent that he will be led to believe he is at the center of a vast, very wide crater: what frees him from this belief is that he sees that this center moves with him. When he is working in a very shallow depression with a large plain extending several tens of meters in which runoff has left no trace of a thalweg, if he looks at the two small hillslopes in turn, they will seem more steep than they really are and it will seem to him that their two planes meet under his feet; if he looks upstream or downstream in the depression, it will seem more depressed that it really is and he will think he is seeing a long vale whose thalweg always passes under his feet; when he crosses this small plain, the thalweg will seem to come and go as he moves. It is impossible to avoid these illusions.

To protect oneself from errors into which he may be led by these false appearances, to find the real thalweg, the hydroscope must in this case go upstream of the depression until he sees a point where the thalweg is indicated by runoff and there he must plant a marker, then go downstream to find traces of the thalweg and plant another marker there. Traces of the thalweg are most often found nearby. The line created by the two markers is the line that the underground watercourse follows, and as a result, the place where one should dig.

## Examination of Springs

After studying the theory, the best method for learning to recognize the most favorable places for revealing underground watercourses is to spend several months visiting a large number of springs that flow naturally from the earth. Every time the student hydroscope sees a spring, he should examine the volume of water produced, the permeable layers that lie atop it, the impermeable layer that causes it to flow out onto the land, the nature of these layers and their dip. He should walk slowly across the entire upstream part of the vale or depression that produces the spring, examine the perimeter, the thalweg, the transported material, the composition, stratification, the slopes of the two escarpments; in a word, he should try to account for all the field circumstances in which each spring forms, moves, and flows to the surface. After examining the upstream area he should walk down along the thalweg of the vale to see if the spring water, after having flowed on the land surface for a certain distance, returns underground by infiltration or through an opening and reappears farther downstream to form a new spring there. If this occurs, he will observe how many times the same water appears and disappears before arriving at the surface and the permanent watercourse into which it flows.

When the student has examined several thousand springs, he will draw the general conclusion that they form, travel, and occur in various rock types and that within each rock type, there will be some uniformity. He will see, for example that in primitive rocks, springs are generally numerous, shallow, rarely deflect from their trajectory, and have a small volume; in secondary rocks, they are much rarer, deeper, more abundant and their underground course is often disrupted. Finally, he will remain convinced that to dig successfully it is necessary to imitate nature and to excavate in rock types analogous to those in which springs occur naturally.

The student who lives in one of the departments I have explored or who is near one of these departments would do well to go examine the largest number possible of the indications I have made, to observe all the rock characteristics involved, to ask in each area what quantity of water and at what depth I stated, also to visit the location where I said there was no underground watercourse, so as to see how the theory is applied. This examination will prepare a student to indicate at first glance not only springs found nearby but also those located far away. To be able to find underground watercourses, it is not enough to study theory in the office, or even to learn it by heart; it is necessary to gain a thorough knowledge of rock types, a knowledge that can only be obtained in the field.

Only after studying for a long time the occurrence of rock types in which springs occur and the numerous places where they occur, was I able to do something I had never expected, that is, to be able in any place I went to designate immediately and exactly on any land surface within my field of vision, the point where each spring would appear and even to predict the volume every time, once I had seen the area of its watershed. I did not make these designations just a few times; during the twenty years I traveled, at a distance of a half-league and even a league distant from a hillside that I was seeing for the first time, at the request of the curious observers who were following me, almost every day I had the opportunity to indicate with precision all the springs that occur there. I would say for example: At so many feet to the east or to the west, to the north or to the south of such and such house, tree, or bush there is a visible spring that has such and such volume. Each inhabitant of the area asked: *That's true, sir, it's very true. How did you know?* The simple application of the ideas contained in this book was a marvel to them. Here are some of the newspaper comments about some of these designations, which I cite as encouragement for young hydroscopes.

*La Gazette du Périgord*, 16 November 1833: "Arriving for the first time in Périgueux, in the middle of a dozen spectators gathered on the terrace of the city mayor, and in the presence of this magistrate, the learned hydrognost designated with a finger, with the greatest precision and at a great distance, seven springs that he declared to be the only ones at this location; out of the seven designations, five springs were already known to the spectators. From the height of the Caesar's Camp, and still followed by the same cortege, to the great surprise of his assistants, Mr. Paramelle also indicated the precise point where four underground watercourses should well up on the right bank of the Isle, near Périgueux: that of Toulon, another near the property of M. Raynaud, the springs of Arceau and the Tourny well, of which he could have had no prior knowledge. In Thiviers, in the presence of the justice of the peace, he also designated all the surrounding springs. We can multiply to infinity the citations of similar experiences, which are ordinarily the prelude to Mr. Paramelle's research. Wherever our geognost appears, he immediately designates all the springs found there, both hidden and visible.

"Mr. Paramelle repeatedly says, with modesty, that his theory is not infallible because out of forty-seven attempts, three have failed and that his discovery method still needs improvement."

*Le Courrier du Midi*, newspaper of Hérault, 24 April 1841: "We have news from Bedarieux from April 19:

"Mr. (Father) Paramelle spent a week with us. This man, whose great geologic research has rendered him eminently capable, was the subject of lively curiosity. Those who followed him watched his face carefully. He began his excursions the day after he arrived. It was really remarkable to see him across a field followed by an escort of 40 to 50 men, and point out to this column which was eager to hear him, the presence of water most often at a distance of 300 paces, analyze the nature of the land surface, indicate the depth of each underground watercourse, and all this with such precision that one is forced to recognize in him an instinctive faculty that is developed to a high degree."

*L'Êcho des Cevennes*, 29 May 1841: "What are the geologic processes used by this astonishing man in the discovery of underground watercourses? What is the particular method he has created in this science? We do not know; but we think he may be the first, perhaps the only, who in ancient as well as modern times has possessed to such an eminent degree this very special faculty.

"What is certain is that without preoccupation, without apparent effort, and at considerable distances, he designates springs located in neighboring localities.

"As soon as he arrived in Vigan, he was taken to a property located above the rock of Bourque. From there, with the naked eye, in the presence of eight or ten persons, of which we were party, he indicated about ten or twelve springs within a circuit of a league; all the springs were known by the participants. His indications could not have been more precise and those who surrounded him attested to the exactness and the truth and could not cease to admire this prodigious man."

*Le Courrier du Gard*, 1 April 1842: "Everyone was able to see him indicate from far away the location of known springs based on the general appearance of the land; he was the only one who had not seen them and he had not been able to approach them."

*Le Nouvelliste de Pontarlier*, 17 November 1844: "Although he was still a quarter hour distant from the spring and unable to see it because of the dense ground cover of beech trees and thick brush, he indicated the spring with astonishing precision: "It is across from this pine, preserve it," he said, "to try to augment it will ruin it." Then, without ever seeing it, he depicted the Orbe spring that flows near the *Dent-du-Vaulion*. Looking at *Mont-Tendre*, he said to those around him: "The northwest hillslope has no spring; the other hillslope has all of them; and the people familiar with this area knew that the judgment expressed by Mr. Paramelle was exactly correct. Mr. Paramelle had proven his knowledge and had astonished the inhabitants by indicating exactly, at a distance, springs and watercourses and the good or bad quality of their waters.”

Same journal, 27 October 1844: "The knowledgeable hydroscope followed the spring and went straight to a cavity that he had never seen, where it springs from the ground. At Hôpitaux-Neufs he indicated with a finger the sole spring that exists there.”

*La Sentinelle du Jura*, 12 November 1844: "Father Paramelle, from the chalet of Mr. Frédéric Gauthier, examined the hills that encircle the north side of the basin where Lons-le-Saulnier sits, and from this point he indicated, with a wisdom and precision truly inconceivable, the location and size of several springs known to the audience but that he had never visited.”

*Le Journal de l'Ain*, 14 April 1845: "During his exploration, he always travels by horse. This is how he operates when he goes to a locality set by his invariable itinerary: from as far as he can see, he sizes up the geologic setting. When he stops on his horse and directs his scrutinizing gaze, luminous rays shoot from his eyes that seem to penetrate the entrails of the earth. Then addressing the persons in his party, he indicates from a distance of several kilometers springs that to him as a stranger are marked only by the summit of a tree, the indentation of a hill, a road, or a rock. Checking of these remarks, which is done instantly by people of the area, always shows precise exactitude.”

*Le Journal de Saône-et-Loire*, 10 October 1846: "The day before yesterday, Father Paramelle, accompanied by the prefect and his assistants, several members of the municipal council, M. Vinsac, borough surveyor of the district, Mr. Giùllemin, city architect, and several curious onlookers, explored the territory on the northwest edge of Mâcon. The famous hydroscope astonished everyone in attendance with the extraordinary precision with which at considerable distances he designated known and unknown springs within the scope of his travel.”

Same newspaper, November 4, 1846: "Last Monday October 6, Father Paramelle, accompanied by the mayor's assistants, several members of the municipal council and a large audience, visited the vicinity of Charolles for the goal of discovering underground water courses to satisfy the needs of the city. After pointing out all the already-known springs with surprising precision and rapidity, he discovered two new large-volume underground watercourses. Mr. Paramelle pointed out numerous underground watercourses that had not been discovered.”

*L’Espérance de Nancy*, 18 May 1847: "One of the most striking moments was when Father Paramelle, from the top of a hill with a vast horizon, began to indicate all the hidden and known springs in the area, without regard for distance. We witnessed this magnificent and marvelous spectacle on the hillslope of Aufremont. The geologist was there surrounded by notables of the county seat of Vosges; without having traveled the countryside, but with only a simple inspection of the place, he designated all the springs that should exist far off in the area. Nothing is more curious than the astonishment of all the spectators, who knowing the area, know that his calculations are true.”

*La Tribune de Beaune*, 4 April 1849: "He indicates the locations where people should dig to find underground watercourses with unbelievable speed and precision and in places where they are known only to the inhabitants of the region, he goes straight there, without any indication; or if the underground watercourses are far away or if they are separated by an obstacle, the priest indicates them with his finger, to the great amazement of the winegrowers in the crowd of followers. Father Paramelle is a practical scientist who renders immense service to the regions he crosses; we respect his character as much as we admire his science."

Notes

1. *Hist. nat*., Book XXVI, c. 3.

2. Found in a report published by Nadault on a well dug during Buffon's time in a small vale near Montbard, "At a depth of eight feet, we saw a small amount of water. At a depth of 16 feet the water spread out in the hole and it seemed to come out through the entire circumference through small springs that provided ten to eleven inches of water throughout the night. The water continued to flow and the project was discontinued for eight days. The hole was 36 feet deep and the water rose to a height of ten feet. When it was emptied to continue working, the workers found a little more than a foot in the morning, which fell throughout the

night to the bottom of the hole. At this depth (50 feet) we stopped digging and the water rose slowly to a height of 30 feet.

Héricart de Thury (*3rd Notice*) reports that in 1829, Mr. Flachat dug a 66-meter deep artesian well at Saint-Ouen near Paris; he found six different water layers. The first was located three meters under the ground; the second at 35 meters; the third, at 45 meters; the fourth, at 50 meters; the fifth, at 59 meters; and the sixth at 66 meters.

"In the Arques forest near Dieppe (Seine-Inférieure), an artesian well encountered seven water layers, as follows: the first at a depth of 30 meters, the second at 100 meters, the third at 180 meters, the fourth at 215 meters, the fifth at 250 meters, the sixth at 285 meters, and the seventh at 333 meters. Mr. Dégousée, *Guide du fondeur*, p. 458.

I have experienced the same result at a number of locations; I will cite one: On 21 September 1831 while indicating a spring for Mr. Malès, adviser to the *Cour des comptes*, at his country house in the commune of Chasteaux (Corrèze), I announced that at a depth of 12 feet there would be a small underground watercourse the thickness of a writing pen and that at 39 feet he would find one the thickness of a finger. When the digging was done, he confirmed the exactness of the two statements.

3. *Nulli umquam fones in summon montis vertice erumpunt, aut adeo prope cacumen quin semper superemineat portio aliqua superior*. [English: No springs ever rush forth on the highest peak of a mountain, nor indeed do ones near the top because there is always some higher portion above it. Edwin Robert Latin-English translator.] Robertum Plot, *De origine fontium* [*The Origin of Springs*].

*A spring cannot, says Pluche, flow from the height of a mountain if there are not at least several toises of higher land. Entr.* [Discourse] XXI. *There is no spring*, say Mentelle and Malte-Brun (*Géogr*. book vi), *that does not have some higher ground above it*.

It seems that these authorities and many others that I could cite, plus the sheer implausibility of the belief that springs could exist at the summits of certain mountains and that they arrive there by way of reverse siphons, should have encouraged educated men to verify the facts for themselves prior to including them in their writings and to not to lay themselves open to inserting assertions that lack proof. To inspire confidence, they should have designated each spring that exhibits the supposed phenomenon, made known the size of the plateau, the elevation of the land that dominates it, the soil type, inclination of the layers, etc. The following shows how serious authors, whom I chose at random, have reported these marvels, for the sole reason that they had found them recorded in other written documents.

"One often sees," says Saintignon (*Phys*., 3° part., sect. 2, chap I) “springs on the summit of isolated sugar loaf-shaped mountains whose upper surface is too small to support these springs; they come from higher mountains, often very far away, sometimes separated by broad valleys and by large rivers; the waters that collect on the highest mountains are brought there by a sand bed between two beds of compacted clay [Fr. *terre forte*], without interruption along the slope of these mountains, under the plain and under riverbeds, to the mountain summits where these springs are located. The higher spring forces the water to rise to reach equilibrium with it or flow through openings.”

According to Nollet (*Phys*., 7th Lesson) "A spring that gives rise to or that maintains a large pond on a high mountain should not be regarded as an inexplicable phenomenon; it comes from someplace even higher, although it is impossible to say if it is from 40 or 50 leagues away."

According to Héricart de Thury (§ 206), "springs and even very abundant springs are present on plateaus and on mounds higher than all the places that surround them, as for example, the Feyolles spring at the top of Mont Ventoux at an elevation of more than 1800 meters, an abundant and constant level spring. These springs result from reservoirs located in distant mountains whose water flows underground and is present under these mountains and in their interior, the outlets by which they maintain their level and rise and spring forth at their summit following the progress of the siphon.”

"The springs found in very high places," says Mr. Beudant (*Phys*., liv. m, 2e sect, art. iv) and around which no higher places are seen, can be produced by crevices that communicate from one mountain to another and through which this liquid seeks to become level.”

To support these assertions, people have cited, as we have just seen, Mont Ventoux (Vaucluse) where *la Font-Feyolles* is claimed to be at the top but the summit of the mountain is 200 meters higher than the spring.

People have more often cited the small spring on the butte of Montmartre near Paris, which is only 50 feet below the highest part. No water, they say, can constantly supply a spring located there unless it comes from a higher mountain or unless it comes from below and rises as vapor. However, measurements conducted of the part of the plateau that is higher than the spring and that could consequently transmit its water by interior flow show that this area is 585 meters long and 195 meters wide, equivalent to 11 hectares, 40 ares, 75 centiares; thus the average volume of annual rain that falls in Paris on a parcel this size greatly exceeds the quantity of water that supplies the little spring in question.

4. After attentively observing this arrangement of strata for several years and having practiced the other observation stated in Chapter 1: *Every peak of a mountain ridge is the departure point for two ridges that go in opposite directions, and each pass is the point of departure of two opposite valleys*, everywhere that I have looked at a hillslope of a mountain, I have been able, based on the side I was looking at, describe almost exactly the opposite hillslope, which I had never seen, and to announce the following: "From the top of this peak, a ridge or hill takes off in this direction toward a slope that we do not see; a vale departs from that pass, it has more or less this slope and it goes in this direction on the other side of the mountain" and when the rock types were favorable for springs, I said: "Leaving from this pass and following the bottom of the vale that goes from the other side of the mountain, after walking so many meters you should find a spring of about this volume and beginning at this spring the slope changes and becomes less steep." In all the departments where I have worked, thousands of people will attest to these facts. Now that the reader knows the data on which these announcements are based, he should find that they were quite easy; however, the spectators found them extraordinary.

This is how newspaper writers described them:

*La Gazette du Périgord*, 16 November 1833. "Ordinarily, upon seeing the hillslope of a hill, he (Mr. Paramelle) describes, as if he had already seen them, the depressions present on the opposite hillslope."

*La Gazette du Berri*, 27 September 1834. "Everyone involved in agriculture has heard of the success of Mr. Paramelle in exploring for water ... His knowledge has reached a high degree of certainty and precision to the extent that, located on the one side of a hillslope, he can correctly describe depressions on the opposite side and indicate the underground watercourses that they conceal. In places entirely new to him, Mr. Paramelle always travels alone; the river courses, the layout of the land are the indications he uses to orient himself and find his route."

The *Nouvelliste de Pontarlier*, 17 November 1844. "From the hamlet of the Sarrazins, commune of Montlebon, Mr. Paramelle declared it useless to cross to the other side of the mountain to visit farms located on the opposite side from where he was because “there are no springs there,” he said, “but farther on they are abundant.” In fact they were found seven kilometers from the location where he announced them, and they are so abundant that they power a sawmill."

5. See the discussion of rubble [Fr. *éboulis*], Chapter VII.

### 2.4.17. Chapter XVII. How to Determine the Depth of an Underground Watercourse

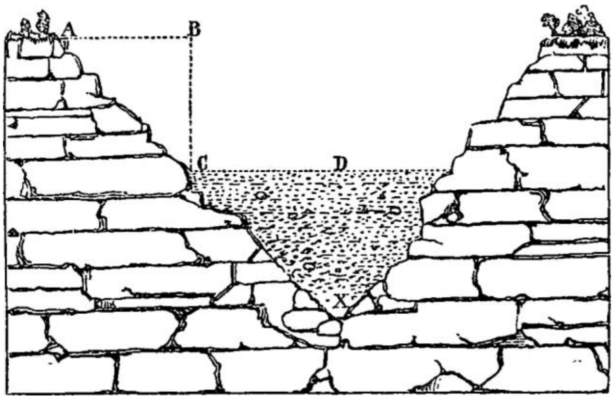
To reach an underground watercourse, as we have just said, a person should dig in the thalweg of a vale, on the foot-of-slope line, on an escarpment, at the top of an escarpment, or on a plateau.

1. When digging in the thalweg of a vale, it is necessary to determine if the underground watercourse is already visible in one or several places, either naturally or in a man-made trench, and especially if water is visible below and not far from the place where one plans to dig. Each appearance of a spring is a reference point that can be surveyed to determine the height of the excavation point above the spring outlet. The elevation difference between these two points is the depth of the underground watercourse less some amount, because the underground watercourse has an unknown slope and this slope guarantees that one will have to dig only to the level of its discharge [Fr. *dégorgement*]. However, if the spring comes out of the ground by moving upward and if one can probe the depth of the column of ascending water, it will be necessary to survey not from the surface of the spring water but from the bottom of the vertical conduit.

If the location selected for digging is only a few hundred meters from a river or stream whose flow is continuous, and if the underground watercourse does not flow out onto the plain, the water seeker should find out, by himself or by asking others, if during low water the underground watercourse does not issue along the bank or at the bottom of the channel of the visible watercourse through a conduit coming from below. In one or the other case all that's necessary is to survey, as just explained, either from the spring outlet along the bank or from the bottom of the vertical conduit, and the person can feel sure that it will not be necessary to go to the level of the bottom of the conduit or to the bottom of the river or stream to draw water, because the water from the spring will rise and will remain in the new trench, at least at the level of the visible watercourse.

2. When the underground watercourse that follows a vale is nowhere visible or if the point where it is observed is too far away or if it is at a too low a level compared to the point selected for digging, it is possible to determine its depth in the following way: almost all vale bottoms are filled with transported material, except in gorges, and thousands of experiences

have shown me that the line of intersection of the two escarpments is generally the greatest depth at which an underground watercourse will be found under these materials, the chosen excavation location on the thalweg can be determined as just discussed and a marker placed there, the distance between this marker and the base of one of the escarpments is measured; the escarpment is surveyed to determine its height and the horizontal distance between its top and a vertical line that rises from the base of the escarpment. This height and this distance are made up of the heights and partial distances found at the monitoring stations. When the operation is finished, the spring seeker sets up the following proportion:




Cross-section of a vale whose bottom is filled with transported material

The distance between the top of the slope and the vertical line from the foot of the escarpment is the height of the escarpment, just as the horizontal distance between the foot of the escarpment and the point where one wants to dig is at the depth of the underground watercourse. Thus, AB is to BC as CD is to DX. By multiplying the height BC by the distance CD and dividing the product by the distance AB, one will find in the quotient the depth between D and X, which is the point where the underground watercourse flows.

When the escarpment slope is uniform, it is not necessary to survey to the top; it possible to, for example, survey only to one third or one quarter of the height and the remainder of the operation will be the same.

In a vale that widens and narrows, this method of determining the depth to the underground watercourse should not be done in narrow areas; rather this operation should be done in a wide part upstream or downstream, in an area where the bases of the two hillslopes are farthest apart.

It is true that in certain vales the underground watercourse is not present along the line of intersection and instead it flows at greater depth; this happens primarily when the strata of the two sides are highly inclined and plunge toward the thalweg. The two stratifications, being thus broken apart, leave a vertical crevasse between them that cannot support the underground watercourse at the juncture of their surfaces; but this chance of finding an underground watercourse a little deeper than expected is rare, and it is more than compensated by the incomparably more likely chance of finding it at a shallower depth; because whenever the strata of the two hillsides are horizontal and impermeable, it is rare that continuous strata are not located before the line of intersection formed by the two hillslopes. The transported material that fills the valley bottom is often composed of alternating permeable and impermeable layers that support the underground watercourse much closer to the ground surface than one might expect from the inclination of the escarpments.

When the underground watercourse runs along the base of a cliff or an extremely steep escarpment, the surveying is done on the opposite escarpment.

These two methods of determining the depth of an underground watercourse are applicable not only to watercourses that follow the underground thalweg but also to those that circulate on the same plain and to those located along foot-of-slope lines, because in both hidden and visible watercourses the level of each additional current [Fr. *courant*] becomes similar to the level of the principal current as it approaches its outlet.

3. The two methods just discussed are applicable only to underground watercourses on low-lying plains, whereas to determine the depth of those located on escarpments or on plateaus, the process is different. Here everything is reduced to the knowledge of permeable and impermeable layers, knowledge that can be gained only by studying books on geognosy and by many hours of field observation. When person has decided on a location to excavate on a slope or at the top of a hillslope, he should walk downhill at most several tens of paces. While descending, he should attentively examine the inclination and composition of each rock or earth layer. On these types of slopes, bedding plane surfaces are almost always visible; when

they are not visible in the thalweg itself, they are ordinarily visible next to it, on a cliff or on a steeper slope, in a gully or a man-made cavity. If the inclination of the layers is opposite that of the surface slope of the escarpment, and rather than bringing water out of the mountain or hill, the beds lead water toward the interior, no excavation should be done because, as we saw in Chapter XVI, any escarpment whose stratification is arranged in this way has no underground watercourse. If the layers are horizontal, or inclined in the same direction as the escarpment surface, the water seeker should not stop at any permeable layers while descending but should stop at the first impermeable layer observed in outcrop because that is the layer that carries the underground watercourse. By surveying from this layer to the point where the person wants to dig, the water seeker will determine the true depth of the underground watercourse. However, he must deduct the total thickness of the impermeable layer from its outcrop to this point. This height may be very easily determined by surveying the small part of the layer that appears in outcrop; if for example this portion is inclined a decimeter over a meter, and if the point chosen for digging is at a horizontal distance of 20 meters, the layer and the spring will be about 20 decimeters higher at the point where he plans to dig.

The same method is followed for determining the depth of an underground watercourse located on a plateau. After marking the point chosen for the excavation, the water seeker follows the thalweg and goes to the foot of the cliff or the steep slope that forms the top of the escarpment, where he surveys from the highest impermeable layer he sees and proceeds as just described for finding underground watercourses on the escarpments.

4. There is another simple method of determining the depth of an underground watercourse but it is applicable only to low-lying plains; it was explained in the preceding chapter. If on the plain where a person wants to find water there are already several trenches that have reached the water table at the same depth or nearly the same depth, provided that the rock is of the same type, he can count on finding the underground watercourse at the same depth as the neighboring wells.

These four methods of determining the depth of an underground watercourse are the only ones that thirty-three years of research and experiment have led me to discover. If they cannot help determine the depth in a rigorously exact way in all cases, at least they almost always resolve the important question, which is to determine the *maximum* depth to an underground watercourse in a location where one is thinking of digging, and as a result, the *maximum* cost of reaching it. He who wants to bring water to his house can figure out by simple surveying if the water is high enough to reach the desired point.

### 2.4.18. Chapter XVIII. How to Determine the Volume of an Underground Watercourse

Some land surfaces [Fr. *terrains*] absorb much more rainwater than others, and during rainy periods springs flow much more abundantly than during droughts; therefore, their product will vary greatly from one area to another and from one season to another. After each rain springs increase and then decrease daily until the next rain; thus, probably no spring produces the same amount of water two days in a row. One should not expect to find here rigorous calculations according to which one can demonstrate that for a given plot of land [Fr. *étendue du terrain*], a hidden spring will discharge a certain quantity of water in such a period of time, because for that result a person would have to know the time of each rainfall in advance and the amount of water it would deliver to the basin that produces the watercourse. This question thus can be resolved only by estimates that approach exactness in an approximate way.

In some cases, there is a great interest in knowing, at least approximately, the *minimum* amount of water that a spring would be able to produce. So as to obtain as exact knowledge as possible on this subject, I have spent a long time observing the amounts of water produced by plateaus located on mountains or isolated hills where it has been easy for me to measure the volume of water of each spring and to measure the surface of the basin that produces it. Here is the general result of these observations: In basins on plateaus that are covered with a layer of detrital sediments [Fr. *terrain détritique*] two to seven or eight meters thick overlying a suitably inclined impermeable layer, I have found that during a period of ordinary dryness, each five-hectare surface produces an underground watercourse about one centimeter in diameter (1) and discharges about four liters of water per minute.

This quantity is the ordinary product of rock types [Fr. *terrains*] that are most favorable to underground watercourses; according to their location, rocks produce quantities of water ranging from one centimeter per five hectares to zero depending on their porosity, layout, or compactness. Some rock types are so compact and so impenetrable to water that even an area of 20 or 100 hectares would produce no watercourse. Permeable and impermeable rocks are intermingled amongst themselves in thousands of different ways, so it is impossible to establish rules to use to determine the quantity of water of each combination; however, the study of different rock types and numerous observations on the quantity of water that each combination produces can help the hydroscope estimate rather exactly the quantity of water that each hidden watercourse will provide. After nine years of theoretical studies and observation of springs, I spent almost every day of the following twenty-five years indicating underground watercourses of all volumes. I would declare, in a document prepared for the landowner, the quantity of water each underground watercourse would produce and in the great majority of attempts, the estimated quantity was found. It rarely happened that a notably greater or lesser amount was found.

During the first years, at each field location I surveyed the land surface to determine the depth of the spring and I measured the surface of the watershed to determine the volume. Seeing that springs do not observe laws so constant that they can be subject to rigorous calculations, and besides, geologic data, which is true in the vast majority of cases, almost always presents exceptions, I have become accustomed to surveying and measuring the land by sight, and I have not noticed that my forecasts have been farther from exact than if I had used instruments.

Note

1. A *fountain-maker's* centimeter of water is the quantity produced by a circular and lateral orifice one centimeter in diameter, while maintaining the water surface constant at 6 millimeters above the center of this orifice.

### 2.4.19. Chapter XIX. Rock Types Favorable for the Discovery of Underground Watercourses

For a rock type to be favorable for the discovery of an underground watercourse, two primary conditions are necessary: a permeable layer several meters thick at the surface and a suitably inclined impermeable layer underlying the permeable layer. If this arrangement of rock layers [Fr. *terrain*] is repeated several times, that is, if there are multiple sequences of permeable layers superimposed on impermeable layers and if all of them are suitably inclined, an underground watercourse flows on each impermeable layer; in this case, it can happen that by drilling an artesian well or digging an ordinary well to great depth, water can often be found at each stage that is crossed (1).

All things being equal, more rain falls on mountains than in surrounding valleys because clouds that generally float horizontally and at great heights often melt into rain against the peaks they encounter, whereas they spill only a little or no water at all on lowlands [Fr. *bas-fonds*], and this is what causes mountains to be more favorable for the production of springs. Besides, trees and plants usually cover these areas and the coolness they provide protects the ground from the intense heat of the sun, considerably reducing evaporation and giving rainwater time to infiltrate into the land where it forms springs.

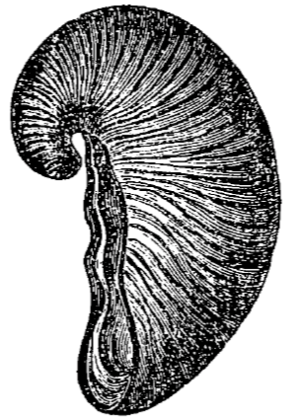
Primitive rocks are not very permeable by nature but when their plateaus are covered with detrital sediments or rocks with numerous vertical fissures, this rock type may host multiple springs located near each other and all of small volume. When these rocks occur as various formations superimposed one on another, such as gneiss, phyllite, eurite [fine-grained porphyritic igneous rock containing quartz phenocrysts – tr. note], diabase, primitive limestones, etc., springs are abundant. Springs are not generally found on plateaus and hillslopes in primitive rocks that are smooth or that lack depressions and that are not covered by permeable rock units.

Intermediate or transitional rocks [See Translator's Notes] are somewhat permeable to water when they directly overlie primitive rock; in this environment, infiltration generally moves downward to the surface of the latter, follows slopes, and issues to the outside through cracks separating the two. These rock types are: puddingstone, arkose, greywacke, red sandstone, coal-bearing sandstone, psammite [layered sandstone –tr. note], molasse, slate, argillaceous shale, marble, bituminous limestone, etc.

In secondary rocks [See Translator's Notes], visible springs are not as numerous as in primitive rocks but they are larger; it is a general rule applicable to all rock units that *the rarer the springs, the larger they are and vice versa.* When a traveler encounters a spring with extraordinary volume, he can state without fear of making a mistake that all the surrounding area that is at higher elevation will be devoid of visible springs. The largest springs flow from secondary rocks and consequently this is where one finds the largest springs.

Because not all secondary rocks are suitable for the discovery of springs, I will indicate the ones that generally have the best constitution and arrangement for the discovery of springs; they are oolitic, compact, saccharoidal, siliceous, shelly, marly, and coarse limestones. Descriptions of these rocks are found in Chapter V, and the reader is invited to re-read them. Limestones that contain cerithium [Fr. *calcaire à cérites*] [cerithium is a gastropod- tr. note], [Fr. *calcaire à trochytes*] trochite-bearing limestone [trochite = wheel-shaped joint of the stem of a fossil crinoid - tr. note], crinoid-bearing limestone [Fr. *calcaire à encrinites*], fresh-water limestones, and clays interbedded with sand layers are rock types favorable for springs.

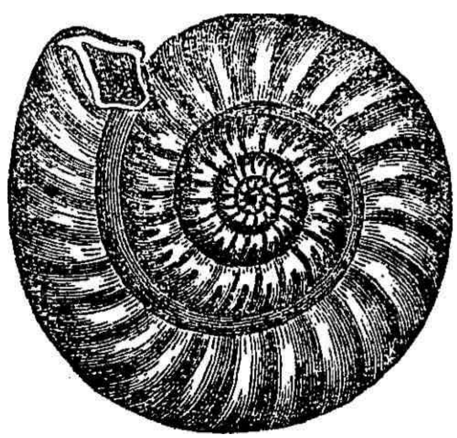
To these rock types we should add limestones and marls with *Gryphaea* and limestones with ammonites and belemnites (2). Each of these rock types has been named on the basis of the type of shell that predominates and characterizes it; I am thus required to introduce these three types of shells. Although the rock they designate includes many other fossils and although these fossils are found in many other rocks, it is the convention to give the rock the name of these shells because the shells are found there in large numbers.



*Gryphaea*

*Gryphaea* is a shell whose valves are very unequal. The lower valve is large, arched on the outside, concave inside and terminated by a salient curved hook with an involute spiral. The upper valve is small and flat. The ordinary length of *Gryphaea* is one to two inches, and they are about an inch wide.

There are about five or six species of *Gryphaea*, including the *Gryphaea colombe, Gryphaea virgule, Gryphaea dilatata, Gryphaea undulata,* and *Gryphaea arcuata* but the differences between them are not important to our subject. It is enough to know their general characteristics so as to be able to identify them when they are found in a rock unit.



Ammonites

*Ammonites*, which were called "*the horns of Ammon*" [Fr. *cornes d'Ammon*] until recently, are disc-shaped shells rolled in a circle along a horizontal plane; they have multiple coils; some have only two or three and other have six or seven; sometimes they are involute and sometimes simply evolute and entirely visible on two sides. Some species have convex, rounded, or cylindrical coils; others have depressed and more or less flattened ones; some are dentate, striated, and others completely smooth and even. They range from a millimeter to a meter in diameter; they are found only in hardened layers of secondary rocks and lie in parallel layers. Their shells are quite thin; it is rare to find entire specimens. The opening, which is extremely fragile, is the part most often missing. The animals that inhabited these shells, which were so abundant in the past, are no longer found in our seas; they are known to us only by their remains.

Belemnites

*Belemnites*, which the naturalists of the previous century called *dactyles* or *lightning bolt rocks* [Fr. *pierres de la foudre*], are shells whose shape is ordinarily conical, sometimes cylindrical, with a blunt point; sometimes they bulge at the center in which case they are called *fusolites*; they are two to six or seven inches long and about two *lignes* in diameter. They are ordinarily brown; however, their color depends to some extent on the rock that contains them. They can be white, yellow, etc.; their texture is crystalline, fibrous, and the fibers radiate from the center to the circumference. At the base is a conical cavity of variable depth. A striation extends from the base to the point, and the recess diminishes in this direction, causing them to split lengthwise.

### *Tufa* [Fr. *terrain tuffeau*]

There is a rock type that is not only favorable to springs, but indicates their presence with certainty when they are hidden; this is *tufa*. This rock, which is also called *tuff* or *travertine*, occurs only as isolated and small deposits, sometimes stratified, and sometimes as unshaped masses; it is white or yellowish in color and is ordinarily covered with green moss. It is produced by springs that come from limestone rocks. As watercourses travel underground, they carry in solution calcareous, siliceous, or ferruginous material, and when they flow to the surface, these materials precipitate, solidify gradually, and become more solid with age. If this precipitation occurs in a basin full of water, it forms layers like sedimentary rock formed in basins, but if the deposit forms in air it is impossible to distinguish any vestige of stratification. It is full of pores, fistula, tubercules, and cavities of all shapes. These holes are left by mosses and other plants on which the encrusting material was deposited and concretioned and the mosses and other plants have been completely destroyed. Tufa's solidity, lightness, and the ability of tufa to take mortar make it highly suitable for certain construction elements such as arches and chimneys. This rock type has formed continuously over geognostic time and continues to form every day. Some springs that produce it are so charged with encrusting material that if an item is plunged into it for several weeks it will be entirely covered with a tufa crust; *objets d'art* are often found there such as pottery, glass, iron; animal bones, fluvial terrestrial shells, all belonging to the species that currently live in these places, plus wood and plant fragments. The regions where this rock type is most abundant are between Rome and Tivoli; also around Larzac (Aveyron), in Auvergne, in Burgundy, in the Cévennes, etc. Because each travertine deposit is the product of a spring that often is no longer visible, it is the most definite sign of a hidden spring that has covered its outlet and needs to open another outlet from time to time.

### Molasse

*Molasse*, also called *nagelflue* or *macigno*, is a rock composed of sand, limestone, clay, and sometimes mica, mixed together and cemented by limestone cement. Its texture is coarse and often similar to sandstone found in transitional rocks [See Translator’s Notes]. It is usually soft and even friable, which has given it its name; sometimes it is competent enough to be used as building stone. Its stratification is generally indistinct and the most common color is gray, greenish, or yellowish. It is most often covered by puddingstone and overlies shelly sandstone, fetid limestone, or argillaceous marls; sometimes it is intercalated with these formations or alternates with them. Marine and fresh water shells, lignite, and mammal remains are found in molasse. This rock is found in Aiguillon (Lot-et-Garonne), in the strait of Mirabeau (Vaucluse), in the valley of Saint-Laurent-du-Pont (Isere), in Alsace, especially in Switzerland, etc.

Because rainwater can easily penetrate detrital layers (3), molasse absorbs the greatest amount of rain, and rain drains from it slowly. Almost everywhere this rock overlies a layer of clay or impermeable rock that has almost the same dip and often a lesser dip; these circumstances make it very suitable for the discovery of groundwater.

Sandstones and green sands, millstone grit, spathic limestone, cerithoid limestone, freshwater limestone, and green marls are also favorable rock types for finding underground watercourses when the rocks occur in suitable positions. Alluvial and terrace materials contain numerous and thick water-bearing layers and currents, especially when they are interspersed with impermeable and slightly inclined layers.

Notes

1. See note 2 of Chapter 15.

2. *Coquilles caractéristiques des terrains*, by Deshayes.

3. See the description of this rock in Chapter 14.

## 2.4.20. Chapter XX. Rock Types Unfavorable for the Discovery of Underground Watercourses

A thorough knowledge of rock types where underground watercourses are unlikely to be found is as necessary to the hydroscope as that of favorable rock types. During each field excursion, a springs-seeker must have in mind all the characteristics that distinguish one type from the other so as to indicate with certainty if the probability of success is high or, if not, to refrain from looking. I will thus briefly describe the principal rock types unfavorable for the discovery of springs, while continuing to recommend both an assiduous study of the geological literature because its broad extent can provide more complete notions on this subject and especially the study of these rock types in the field.

Some rock types are unfavorable because of their constitution, including: some limestone rocks, volcanic rocks, and some friable rocks. Others are unsuitable because of their location, such as subsided hills, landslides and slumps [Fr. *éboulements and glissements*], escarpments where the strata rest on their sides, those with exposed bedding plane surfaces, and those that dip more than 45 degrees.

Limestones where a person should generally abstain from indicating underground watercourses are: limestones with swallow holes, cavernous limestones, cellular limestones, and dolomites.

Limestone with Swallow Holes [Fr. *calcaires à bétoires*]

In many limestone rocks, sometimes in Liassic, gypsum and Keuper formations, circular or elliptical holes are present; they are shaped like cirques or funnels. In northern France, they are called *bethunes*; in Normandy they are called *bétoires*, *boitouts*, or *boitards*; in Franche-Comté, they are called *garagais*, and in the south, they are called *cloups*. These sorts of cavities have a generally accepted name in French. I will call them *bétoires* [English: swallow holes].

Some of these cavities formed during the retreat of seawater and others formed later and at various times. They continue to be discovered almost every day. Either under the feet of an animal, or under the weight of a tree, and most often during heavy rains, the ground suddenly caves in, forming a narrow pit [Fr. *puits*] that is sometimes only several meters deep but is sometimes more than a hundred feet deep. Little by little, the pits crack along their margins, the opening widens, and debris falls into fill the bottom. When two pits form at almost the same time and very close to each other, the ground between them collapses and the swallow hole assumes an elliptical shape. When after several centuries landslides stop filling these cavities and the slope approaches approximately 45 degrees, their diameter and depth remain stationary. In this condition, some are only two or three meters in diameter and others range up to 20 or 30 and sometimes a lot more. The diameter is usually twice the depth.

Some swallow holes have a gaping hole at the surface and form abysses [Fr. *gouffres*]; others become obstructed by landslides. Others are only a few decimeters deep and are hardly perceptible and others are entirely filled by gullies or by crops.

In some places, the swallow holes are dispersed on plateaus where they absorb only the rainwater that falls on their surfaces; in other places, they occupy the bottoms of vales, of which some are always dry and the others carry streams or rivers that fall into the first swallow holes they encounter (1); in other places, swallow holes are located at the bottom of a large basin where they absorb water and would otherwise form a lake several kilometers across.

Swallow holes are not randomly scattered, as some people believe who have not observed them attentively or who have no knowledge of underground hydrography; on the contrary, they are arranged in a rather regular order. If a plateau has a principal vale, even if it is only very slightly depressed, a series of swallow holes will be located along the line of its thalweg. They can be followed from the mouth of the vale to its head. If, while walking up the thalweg of the vale, a person notices other vales on the right or left that flow into it, he will see in each of these secondary vales a series of swallow holes located one after another and all of them will be located in the thalweg (2). If along the principal vale or a secondary vale, an isolated swallow hole is found, it is because the depression or tributary it represents is very short. As for swallow holes located on the summits or crests of hills, they must have formed during the retreat of seawater.

The regularity with which swallow holes are aligned in the thalweg of each vale proves that under each line of swallow holes, there is a permanent or temporary watercourse that has progressively produced them because 1st) all underground watercourses in narrow or rapid passages abrade and erode the walls of their conduits and when the roof supports are removed and they finally have no support, they collapse, dragging down the overlying rock (3), causing subsidence at the ground surface, which is the pit that we have been talking about; 2nd) in some vales during heavy rains the underground conduit that I contend is present under these swallow holes can no longer support the flow of the watercourse, and water columns can be seen flowing out the swallow holes and sometimes shooting upward out of the ground to a height of several meters; 3rd) by leaning an ear on the orifice of some swallow holes, the watercourse can be heard murmuring as it flows below (4); and 4th) when after an extraordinary storm a temporary watercourse forms at the surface of a vale with swallow holes, if the water is not absorbed by the first swallow holes, it continues along the line the swallow holes form on the hillslope, pouring into each hole a portion of the water until it is entirely absorbed; thus underground and under the line formed by the swallow holes there is a conduit that progressively receives the various portions of the watercourse that flows at the surface; 5th) some landowners have filled these holes where they are present in the middle of their fields but almost always during the first heavy rain the disappearances happen again; the underground watercourse has thus eroded from the base of the column of subsided rock as much soil as the landowner has deposited above.

Although undoubtedly an underground watercourse is present under each series of swallow holes and the size of the watercourse increases with the length and number of tributaries, I still regard all rock units with swallow holes to be unfavorable for the discovery of underground watercourses because the water is too deep. Near the origin of vales and near where springs flow into a river, by digging in the swallow holes themselves, watercourses can be reached at depths of five, ten or fifteen meters; but along most of their pathway, they are at much greater depths. A person often has to dig to the level of the river into which the watercourse flows, less the height created by the slope of the watercourse, which is almost the same as that of streams that flow at the surface. Therefore, in view of the considerable expense of such deep wells and the great difficulty of getting water out of them, they are constructed in only a few places.

## Cavernous Limestones

*Caverns* or *caves* [Fr. *grottes*] are underground cavities that are large and elongate. A vertical excavation formed by nature is called a *natural well* or *abyss*, depending on its depth. Caverns are ordinarily horizontal and disregarding the slight deviations observed along their length, they deviate only a little from a straight and horizontal line. If a cavity does not penetrate far enough into a mountain to be called a cavern and if it is only several meters long and wide, it is called a *lair* or *den* [Fr. *antre*]. If it has a small diameter, large enough for a man to walk in freely, and it has no notable cavity, it is called a *conduit* [Fr. *galérie*]. If it has a very small diameter it is called an *underground channel* [Fr. *boyau souterrain*].

The name of cavern or cave is ordinarily applied only to cavities that are longer than twenty meters and that have considerable width and height. Some are twenty or thirty thousand meters long and have rooms 30 to 40 meters tall; these rooms are larger than our largest cathedrals. Some have parallel sides, a roof that parallels the ground, and regular corridors, but they are few in number. Almost all are sinuous and neither their sides nor the roof and floor are parallel; the two sides, the roof and the ground alternately become distant and close, such that a cavern is composed of a series of rooms located one after another and linked by hallways, sometimes so narrow that the only way to get through them is to crawl. Each room is ordinarily elongate in the same direction as the cave; the roof is arched, and from the middle the roof decreases in height to the openings of the two corridors that are at each end of the room; the two sides also approach each other toward these openings. Almost all caverns have several branches that veer off the principal one and form other series of rooms of all dimensions.

Caves ignite the curiosity of the public because of the admirable concretions that decorate them, because of the animal debris that they contain, and the currents of air that people experience there; but these features have no influence on underground watercourses, so it is unnecessary to talk about them here.

Primitive rocks and those of recent formations very rarely contain natural caverns. Caverns are abundant in the limestone of the Jura, in large chalk deposits, in basalts and other volcanic rocks. In the Department of Lot, where limestone like that of the Jura is the predominant rock type, there are 155 remarkable caves.

Some caves were produced by subsidence or uplift of one of the two rocks that form the sides; others by the erosive action of underground water currents that have slowly removed and carried away the soft and soluble portions of the limestone masses; others by volcanoes, by explosion of underground gas and earthquakes that have broken up the rocks; others by the retreat of the rocks as they changed from a liquid to a solid state. Most have been produced by a combination of these processes.

The number of known caverns is nothing compared to those that are unknown. In fact, a person has only to imagine that each large underground watercourse that flows from limestone rock and whose volume is more than a half meter in diameter can form and travel underground only via caverns; that its starting point is several leagues distant; that along its pathway it receives a large number of accessory watercourses each brought to it by a cave that has several branches. Because the water that travels in caves does not issue at any point in the basin that provides the underground watercourse, not even during heavy rainstorms and snowmelt, it follows that all caves that carry underground watercourses are large enough to allow the water to flow freely and without risk. For this reason, one can conjecture that unknown caves are generally like known caves.

The presence and direction of caverns are indicated by: 1st) the innumerable series of swallow holes we have talked about; 2nd) the aqueous vapor that many swallow holes exhale from time to time; 3rd) land subsidence and new swallow holes that form from time to time; 4th) the air currents that some very large caves inhale and exhale loudly through narrow windows or cracks in the rock (5). He who walks the land and attentively examines regions where swallow holes are present will find a prodigious number of caverns! On how many abysses, covered with thin vaults, will he walk!

Entrances to caves ordinarily occur on cliffs or on very steep escarpments and at all elevations. Caves located high above neighboring rivers are dry or contain only masses of non-moving water; on the contrary, those located at the level of rivers or very slightly above them ordinarily contain lakes, pools, or watercourses; some of these follow the caverns along their entire length, others only a portion, and others only cross them.

These remarks, along with those I made on the subject of swallow holes, make it clear that in cavernous rock units, underground watercourses are at very great depths (6) and that instead of underground watercourses, one often finds only abysses of immeasurable depth.

## Cellular Limestone [Fr. *Calcaire cellulaire*]

*Cellular limestone* takes its name from the numerous pipes or vacuoles the rock contains. This limestone is mixed with silica of great hardness and is often stratified. All its cavities are round in shape. Some of them are almost cylindrical, perpendicular to the bedding surfaces that they cross and showing traces of gas bubbles as it escaped from viscous material. Many cavities are tortuous, sinuous, and cross only a part of a layer, move in all directions and join or intersect. They also form simple spheroidal, ovoid, and amygdaloidal geodes. The diameters of the same pipe and from pipe to pipe range from a millimeter to a meter and sometimes more. Some of these rocks are so decayed that the voids have removed more than half of their weight. This rock is whitish or grayish, with an uneven fracture; it is located principally on the summits of limestone hills and in places it covers extensive plateaus.

This simple description of cellular limestone will give the student geologist the premonition that no groundwater will be found (7) unless after examining the perimeter of this deposit or having dug a test pit, he recognizes that it overlies an aquifer layer that can be reached without digging too deep.

## Dolomite

*Dolomite* is a rock with a simple appearance, composed of calcium and magnesium carbonate. Over geognostic time, limestone rocks that contain magnesium change completely in nature and structure. Stratification, bedding planes, and all the fossil debris that characterizes limestone disappear; new rocks produced by this transformation are dolomites. They form very thick masses, even in mountains that are 300 meters high and have steep slopes. Here and there the masses are separated by wide vertical fractures and sprinkled with pipes and cavities that have no orderly shape, position, or direction. The texture of this rock is lamellar, granular, or saccharoidal; its color is ordinarily a very pronounced white. In England, however, it is yellowish. It is sometimes solid and even very hard, sometimes friable; it effervesces in acid but much more weakly and slowly than ordinary limestone.

The absolute impermeability of dolomitic masses and the arrangement of their vertical cracks mean that rainwater cannot penetrate them, not even the water that trenches can carry to these masses; rainwater can only seep into this rock, sink into cracks, and stop when it reaches the level of the neighboring river.

Notes

1. Numerous watercourses in France sink into swallow holes or disappear under loose stones or gravels, including the *Dromme* and the *Aure* that disappear into Fosse-Souci in the commune of Maisons, 6 kilometers north of Bayeux (Calvados) and pour out at the seashore in the communes of Commes and Port-en-Bessin. The *Rille* disappears in the canton of Beaumont-le-Roger (Eure) and after a certain distance, reappears in the same valley. The *Iton* disappears at Villalet (Eure) and reappears at Bonneville. The *Unain*, after turning several mills, is lost in swallow holes near Montachet (Yonne), and reappears at a distance of three leagues at Lorrez-le-Bocage. At Châtillon-sur-Seine (Côte-d'Or) the Seine, after travelling underground several leagues, reappears at Courcelles. In the same department, the rivers of the *Tille* and the *Ignon* come together at Thil-le-Châtel, fall into a large swallow hole, meet up underground with the stream that

comes from Selongey, and after traveling underground a distance of three leagues, reappear at Bèze. The *Doubs* disappears imperceptibly as it crosses the canton of Montbenoît (Doubs) and reappears at several outlets above Morteau after an underground journey of three to four leagues. Between Langres and Chaumont (Haute-Marne), almost at the midpoint, the water of the *Marne* flows underground imperceptibly and reappears at Condes below Chaumont. A part of the water of the *Loire* is lost in gravels and pebbles of Guilly, follows the foot-of-slope line along this river, and after flowing underground for five leagues, forms the Loiret Spring near Orléans, one of the four largest springs of France. The *Meuse* falls into a vast abyss in its channel near Bazoilles and reappears at Neufchâteau (Vosges) after remaining hidden for the space of 10 kilometers. The streams around Saint-Martin-de-Londres (Hérault) that are lost above this village, come together along their underground pathways, and after a stretch of three leagues form the spring in the *Lez* River, which passes through Montpellier. We will see later (Chapter XXIII) the disappearance and reappearance of the Calavon (Vaucluse), of the Bandiat, and of the Tardoire (Charente), and of several rivers and streams in the Department of Lot.

Several of these rivers disappear completely and show no exterior vestige of a channel until they reappear; others preserve a regular channel at the ground surface where the part of their water that does not sink into the ground flows year round or only part of the year. In some regions the inhabitants are well aware of the disappearance and reappearance of these rivers; in others this relationship is suspected and in many others the inhabitants seem not to have asked themselves where the disappearing river will reappear, nor the source of the enormous spring that flows out of the ground among them. However, whoever will make the effort to follow the continuation of the vale in which the watercourse disappears, and if the vale fades away completely, continue walking in the direction of the visible watercourse and the general slope of the rock, that person can feel sure of finding nearby the outlet of the watercourse that disappeared and will see it considerably augmented. Sometimes, it pours forth at the end of a deep vale where it empties into a neighboring river and most often it flows out along the edge of the river or in the river itself.

The prodigious quantity of water that rivers and streams send underground has caused some hydroscopes who have never made the effort to go and search for these outflows to imagine that all this water returns to an immense abyss that exists at the center of the globe. See Vood-Vard [Perhaps Woodward? – tr. note], Kircher, Dickson, and others.

2. During my travels, when I arrived on a plateau with swallow holes that I had never visited, and I could see only two or three swallow holes in a row in a thalweg, either near the beginning or near the mouth of the vale, I would point out from afar and with precision all the swallow holes located in this vale that were invisible to me. This amazed educated and ignorant people alike.

3. "Groundwater that flows between layers toward a valley carries along parts of these earthy non-lithified layers, carries them along and as a result removes the support of overlying layers." De la Métherie, § 1,233.

4. In 1827, a child who was tending sheep fell asleep with an ear placed on a very small crack in a rock and heard a very faint noise produced underground near the Pech-de-Ligoussou spring in the commune of Livernon (Lot). The population of this commune, which previously had no water, came to verify the discovery and began to dig; at a depth of three and a half meters they found an excellent watercourse.

Near Gramat, in the same department, a city absolutely deprived of nearby potable water, for time immemorial people had heard the sound of an underground watercourse through a crack in a rock. In 1833, the commune finally broke open the rock and exposed a very abundant spring.

5. "Air reservoirs are found everywhere inside mountains and their eruptions produce wind that can be felt. This unusual phenomenon has no other cause than the alternating rarefaction and condensation of air. Air contained in caverns remains in a type of inertia unless it is put into motion by a foreign cause; the natural cold in these cavities decreases the volume and makes it smaller. One should thus not be astonished that during winter, the outside air enters through the orifices of wind channels, and moves in the direction of the side of the mountain where it exits in summer;

these are the variations of cold and heat that everywhere establish differences in the status of the air and in its movements. » *Histoire naturelle de l'air* [*Natural history of air*], by Richard, § XX.

One of these air currents, long known in the region, led to the discovery of the large Trieste cave and the underground watercourse that accompanies it. Here is how Mr. de Weyman reported this discovery to the Geological Society during the meeting of 7 May 1841 (*Bulletin*, volume XII, p. 263):

This city (Trieste) has no water for part of the year. The limestone mountains that surround it are dry and sterile; no stream of any size and no springs flow from them. In the karst at an elevation of 240 meters, a small river, the Recca, sinks and disappears suddenly into a cave near the village of Saint-Ganzien, not far from Nacle, and does not reappear until far from there under the name of Gimaro, near Duino, at a great distance from Trieste. A German engineer, Mr. Lindler, in hopes of using this water for Trieste, went down into the cavern where the water disappears to study its underground direction. Defying all obstacles, he penetrated 800 meters into the mountain, sometimes across vast caves, sometimes through tight and dangerous corridors. When he could go no further, he emerged from this place of darkness to attack the rock from the outside at the place closest to the end of the interior pathway he had followed. A lively air current escaped through a fissure and guided the workers in the direction of their objective. They enlarged this crack on the flank of the mountain to about twenty meters when all of a sudden, their tools were carried off along with rock fragments and fell into a void in front of them. Mr. Lindler, using a rope ladder, descended into this abyss last April 6 and by torchlight he found himself "filled with admiration in an immense chamber that measured no less than 40 meters high and 780 m long, dimensions that since then have ranked this chamber the largest known underground cave. The engineer's expectations were met; a beautiful river, about 3 meters deep and between 4 to 6 meters wide, flowed in this abyss. The clear water flowed from NW to SE on a bed of sand and limestone debris and its banks were incised into large deposits of alluvium of the same nature. Thus the problem is resolved; Trieste will have healthy and abundant water. With equally inexpensive work, the rocks were opened at their base and it was possible to bring the water to town through an aqueduct or canal that would not exceed three quarters of a league in length."

6. Many landowners who had no water because their houses are located on plateaus of cavernous limestones have asked me to indicate springs even at very great depths and to exploit them by expensive methods. The results that they have obtained have been similar to the expectations in other rock units. One of these is described in the newspaper *l'Estafette*, March 25, 1837, edition:

"Several Paris newspapers have already spoken of Father Paramelle and have admired his great talent in geology. Here is an anecdote, among many others, that shows the extent of his knowledge of this science.

"Called in 1835 to the Department of Vienne to find groundwater, which was badly needed in many parts of this department, Father Paramelle went to the canton of Saint-Savin and made several indications. One of them was a property called Le Breuil, near the little town of Saint-Savin. He announced to the landowner that a large underground watercourse was present but at very great depth. He said that after several feet of topsoil an irregularly stratified limestone rock would be found and at the base of this rock was a rather wide crack oriented from west to east; that this crack should be goal of the excavation, that it would end at the spring which would be further indicated by a massive rock layer without vertical fissures, under which a cave oriented from west to east would be found, in which a spring would flow.

"After having followed very exactly the indications made by Father Paramelle, at a depth of 134 feet the workers encountered the cave in which an abundant spring flowed. The diameter of the well is four feet two inches. It now contains 35 feet of water and the water continues to rise."

7. In May 1833, I stopped at the castle of Mr. Vialard-Vernhes, mayor of Carlus (Dordogne) and this magistrate told me: "Sir, I would like, if it is possible, to find an underground watercourse in my courtyard or in my garden; other than that I'm not interested." The courtyard and garden are halfway up the hill, surrounded by cellular limestone, which made up the whole hill. After examining the property, I told him: "Sir, there is no groundwater in the courtyard or

garden; the closest water to here will be found over there in the wheat field, fifteen feet from the apple tree." Mr. Vialard-Vernhes did not respond but he led me into a corner of his courtyard enclosed by walls and told me: "Sir, you do not find groundwater here, but look here.” I saw in fact a beautiful waterfall coming out of a pipe in the rock, forming a cascade and supporting a beautiful covering of fresh and green moss. Knowing that cellular limestone can neither produce nor conduct a watercourse, I responded: "Sir, this beautiful fountain does not come from this rock; I do not know where it comes from, but it was brought here by the hand of man." After these words, a dozen persons who had assisted in my field excursion began to clap their hands. "Sir," the landowner told me, until now everyone has been wrong and we let all strangers believe that this spring comes from this rock. But it does not come from this rock; it comes through a terra cotta aqueduct that starts right near the apple tree that you pointed out and arrives behind this rustic rock that we have not touched, to give this fountain the appearance of a natural spring. You are going to ask me why I called for you since I have such a beautiful fountain in my courtyard? It is because the aqueduct that brings the water is crumbling. If I had been able to find water here, I could have spared myself the considerable expense of the aqueduct repairs.”

### 2.4.21. Chapter XXI. Volcanic Rocks that are Unlikely to Contain Underground Watercourses

*Volcanoes* are openings through which vapors and incandescent material that make up the globe pour out.

We know that as water converts to a vapor, it occupies twelve to fourteen times its original volume and that when heat is held back by obstacles its pressure increases greatly; from this, it follows that sea and other water that descends through cracks and pores of the earth to the central fire are also converted to vapor. As long as these vapors are not present in too large a quantity in underground concavities, they spill out unnoticed and noiselessly through fissures and pores present on the continents and islands; but when vapors condense and ordinary outlets can no longer provide passage, they raise some parts of the ground and cause earthquakes that topple the most solid buildings and even sections of mountains, or they force a passage through the crust of the globe and form a volcano.

As volcanic openings form, large quantities of vapors escape and throw enormous blocks of rock, rocks of all dimensions, scoria, sand, and ash into the air. Currents of fluid and incandescent materials flow out of it and spread in all directions; these are called *flows* [Fr. *coulées*].

The material strewn around the opening mixes and piles up, slowly raising the sides and ending up forming a conical or dome-shaped mountain, at the summit of which the opening is always preserved, which is called a *crater*. These volcanic cones have various heights, from the humblest knoll to the highest mountain. The melted material that is ejected by volcanoes is generally called *lava*.

Active volcanoes continuously emit smoke, sometimes fire, and from time to time, at indeterminate intervals, glowing material. There are 205 of them, none located in France.

What has just been explained on the subject of active volcanoes is only for the understanding of what will be said about the rock units formed by extinct volcanoes.

Extinct volcanoes are those that in historic time have produced neither fire nor smoke. They are more numerous in France than in any other country and their products occupy vast expanses in the Department of Puy-de-Dôme, Cantal, Haute-Loire, and Ardèche. Isolated and small deposits are also found in other departments, such as those located at Drevain, near Autun; at Montbrison (Loire); at Ollioules and at Fréjus (Var); and at Saint-Thibéry and at Agde (Hérault), etc. Products of extinct volcanoes are the same as those of active volcanoes and they are thought to have formed recently. The crater from which they were ejected is ordinarily well preserved and it is possible, with few exceptions, to distinguish and follow each flow along its entire length.

The principal formations produced by volcanoes are ash, sand, flows, basalt, and trachytes.

### Ash and Sand

During eruptions, volcanoes expel immense clouds of ash and sand into the air that sometimes block out sunlight, extend over large distances, and fall back to earth. This ash, which is very fine, has the same composition as lava, and is often mixed with a large amount of sand that has the same composition as lava and makes up the majority of volcanic ejecta. These cinders and sands are greenish, blackish, or reddish in color.

### Flows

*Flows* are currents of material melted or altered by fire and ejected by the volcano. This material is black, sooty, partially scorified, and partially compact. As flows leave the crater, they go in different directions. Like all fluids they obey the law of gravity; they flow down valleys and other recesses they encounter. Some are stopped and solidified near the volcano; others extend tens of thousands of meters. The higher the mountain, the farther the flows travel. These currents pile up on top of each other around the volcanic mouths and they are smashed and broken up in a thousand ways; for this reason the lava has no obvious stratification or structure. Flows are accompanied by scoria, which are the bits of material melted in volcanic furnaces and spread around the crater.

## Basalt

*Basalt* is composed of an intimate mixture of pyroxene, feldspar, and iron, to which olivine is often added; its color is grayish or black. Basalt is composed of portions of flows deposited in basins that the flows encounter and that contract and separate into prisms or columns two to four decimeters in diameter as it cools. The sides and angles of the columns most often number five or six and sometimes number three or four, seven or eight. Most of them are vertical; others are inclined and others lie in a horizontal position.

In some places the basalt takes on a globular shape as it cools. The globules have widely ranging diameters, are often composed of concentric layers, and decompose very easily under the influence of atmospheric agents.

Basalt rock forms conical mountains and plateaus whose perimeters are limited by a cliff formed by numerous columns arranged symmetrically against each other.

## Trachytes

*Trachytes* are porphyritic rocks composed primarily of vitreous feldspar. They contain highly varying proportions of domite, eurite, perlite, phonolite, obsidian, volcanic breccia, opal, alunite, pumice, etc.; only rarely do they show indication of imperfect stratification and they are completely lacking in quartz, olivine, peridot, and organic debris. These rocks are rough to the touch, are whitish, grayish, blackish, reddish or yellowish in color, and have a texture that is sometimes compact, sometimes fissured, sometimes scoriaceous or cellular.

Trachytes are the first volcanic rock that erupts; they are usually covered with modern and more extensive ejecta. They usually occur in very thick masses, form very large plateaus, and are terminated on all sides by almost vertical cliffs; sometimes they make up conic mountains that have very high elevations. These mountains form groups rather than true chains.

Trachytes are well developed in the mountains of Cantal, of Mont-d'Or, and Puy-de-Dôme; they are also found on the coasts of Brittany and along the Rhine.

The lack of stratification, the disorder, and the extreme porosity that are common in all parts of volcanic rocks show that no underground or surface watercourses can develop in them.

This rock type conceals numerous and often large springs that move along underlying impermeable rock and flow out along its perimeter but the immense thickness of these deposits, especially around the craters they produce, can leave no hope of finding underground watercourses at ordinary depths; only on the extremities of these deposits, in places where they are the least thick, can there be any fruitful attempts.

## 2.4.22. Chapter XXII. Friable Rocks where Underground Watercourses are Not Likely to be Found

In this chapter I list various rock types that are unfavorable for the discovery of groundwater; the only characteristic they appear to have in common is friability.

### Clay

*Clay* [Fr. *argile*] or *clayey soil* [Fr. *glaise*] is sticky compact earth; its molecules are tightly linked to each other. As it dries it hardens and contracts. When wetted with water, its volume increases, its tenacity increases, and it becomes more ductile and unctuous. When molded it assumes all kinds of shapes; tiles, all types of vases and statues can be made with it and after firing, they preserve the shape they have been given. When subjected to fire, clay becomes fragile and rough to the touch; it can even take on enough hardness to spark when hit with steel.

All clay is primarily composed of quartz or flint [Fr. *silex*] and aluminum. The purest clay is white; but in nature it is never perfectly pure; it is always mixed with other minerals and it is classified by whatever mineral is present in largest quantity; thus it is called marly, chalky, ferruginous clay, etc. depending on whether marl, chalk, or iron predominates.

Some authors distinguish clay from clayey soil; according to them, when heterogeneous materials mixed with the clay are in low proportion, it is considered pure and is called clay; but when it is mixed with large quantities of foreign material, it is called clayey soil. Historically clays have been categorized as white, black, gray, brown, yellow and red colors but these different colors can be combined and varied infinitely; they are only accidental and establish no difference in their composition, and they are not distinctive characteristics that can be used to recognize the different types.

Clay covers the majority of the Earth's surface; it is found everywhere. In some places it is at the surface of large areas, such as the Department of Lot-et-Garonne, of Gers, of Tarn-et-Garonne, and Haute-Garonne, which are almost entirely covered with these deposits. It also occupies extensive areas in Champagne, Lorraine, Picardie, and in Normandy. Elsewhere, it is hidden under one or more layers that belong to rocks of a different type. It is everywhere at the base of stratified rocks. Some clay deposits form compact masses, thick and without any fractures; others are regularly stratified and the layers are separated from one another by horizontal layers of rolled pebbles, gravel, sand, silt, etc.

When the layers intercalated in the clay are permeable, shallow, and under the conditions that have been described, water can be successfully sought there and the water will always be found in the intercalated layers; but when clay forms a compact and homogeneous mass of great thickness that one cannot dig through without digging too deep a hole, one should abstain from digging there because no water current has ever been able to force a passage through such a mass, not even to become saturated enough so that the clay can collect drop by drop the quantity of water necessary to supply a well.

Chalk [Fr. *craie*]

*Chalk* is limestone composed of pulverized shells that the sea has deposited in some localities. Some of these deposits have remained in the pulverulent or very friable condition whereas over time others have become solid enough to be used for construction. If shells are reduced to powder the material will be completely similar to pulverized chalk. When hard and rocky chalk is heated, it changes into lime; it loses about a third of its weight by calcination but its volume does not diminish appreciably. When exposed to air and rain, this chalk lime gradually reclaims the characteristics that the fire took away, and in this new condition, it can be calcined a second time to make lime that is as good quality as the first.

Geologists have discovered more than 1100 fossils in this type of rock. I will limit myself to naming some of them, not as characteristics, but as those that are most commonly found: ammonites, belemnites, gryphaea, nummulites, cerithium, ampularia, hamites, turritellids, scaphites, terebratellids, nautilus, baculites, crinoids, madrepores, echinoids, etc.

When the chalk is almost pure, its color is ordinarily dull white. Other colors it may have, such as yellowish, reddish, brownish, are due to heterogeneous minerals that it contains such as sulfur, iron oxide, small deposits of lignite, and even coal. Rock salt and gypsum are also found in it.

Although chalk is a sedimentary formation, its stratification is sometimes muddled and uncharacterizable; however, it is generally stratified, its layers are horizontal and separated from each other by layers of flint [Fr. *silex pyromaques* (*pierres à fusil*)] or chert [Fr. *silex cornés*]. These flint or chert layers are thin and parallel to each other. The flint is always rounded, oblong, flattened into nodules and lying on its flat side. Some chalk layers are cut by thin veins of silica, which are extensive and have all strikes and dips. In all chalk masses there are also nodules of loose flint that have no positional relationship between them.

Chalk deposits are ordinary very thick, as proven by numerous ordinary wells that have been dug to 100 meters and artesian wells that have been dug to depths of 200 meters without encountering the bottom of the deposit. In England, chalk has been found to have a thickness of more than 600 meters in many places.

When it is possible to view a great thickness of this rock type in cross section, such as the cliffs of the English Channel, on escarpments with abrupt slopes, or in wells that are being dug, it can be seen that this deposit is divided into two types of chalk with different characteristics, one above and one below.

The upper chalk is purer and whiter; it is light, has no taste or odor, has no luster or transparency, and it effervesces with acid; it is soft to the touch, sticks slightly to the tongue, and stains the fingers; it is dusty or a very soft rock and is stronger at greater depth; chert nodules [Fr. *rognons de silex*] are abundant in it. This chalk, incorrectly called *marl* by the man in the street, is used to marl the land; the rock called Spanish white [Fr. *blanc d'Espagne*] is a variety.

The lower chalk, called *craie-tuffau* [name of French formation member – tr. note] is composed of essentially the same elements as the preceding; it also contains sand, limestone, and clay; it is sometimes dominated by one of these elements; it does not make a mark like white chalk and its base, always composed of hard marl and clay, rests on a layer of green sandstone.

Unevenness of the chalk rock type is generally minor; the high points are only slightly elevated, topped by plateaus that are often extensive and bounded by small cliffs, or they terminate as rounded domes. The valleys are shallow, narrow, and ordinarily begin at a basin shaped like a cirque. This rock type contains neither streams nor springs.

Among sedimentary rocks, chalk is the most extensive. Departments where it is most extensive, where it is the predominant rock type at the surface are: the Nord, Pas-de-Calais, Somme, Seine-Inférieure, Oise, Aisne, Marne, Aube, Haute-Marne, Yonne, Seine-et-Marne, Seine-et-Oise, Eure, Calvados, Orne, Eure-et-Loir, Sarthe, Loir-et-Cher, Cher, Indre, Vienne, Charente and Charente-Inférieure. Chalk covers an estimated 6,200,000 hectares of the surface of France.

The extreme permeability of chalk causes it to absorb each raindrop at the point where it touches the ground and lets it infiltrate straight down to the level of the neighboring river, makes it unfavorable for finding underground watercourses. People who live on high plateaus of this rock type can hope to obtain underground watercourse only by digging to extraordinary depths that are often impracticable. In Normandy, the ordinary depth of wells is 30 to 60 meters; a rather large number are 100 m deep and, what is worse, the locations of most of them have been randomly chosen and they do not provide enough water for a house. Even so, chalk formations conceal numerous and abundant springs, but as in cavernous limestones, they are at great depth.

For future projects, if well digging is restricted only to the deepest vales, after ensuring by prior surveying that drilling will not have to be too deep to reach the level of the neighboring river, an underground watercourse can be found that will not be below this level.

### *Marl [Fr. marne]*

*Marl* is not simple soil, but a combination of clay and chalk produced by nature. The proportions of the mixture are highly variable: when clay dominates, it is called *argillaceous marl*; when chalk dominates, it is called *clayey or chalky marl*. In places this deposit contains limestone, sand, ochre, dolomite, bitumen, etc., which causes it to be called calcareous, sandy, ochre, dolomitic, bituminous marl, etc. A small clod tossed into a glass full of water will identify it; it will swell and split up; if it is soft, the parts will come apart quickly; if hard, it will take longer to mix with the water. When it has just come out of the marl pit, sun and rain will quickly reduce it to powder. Marl is less sticky than clay and less friable than chalk; it effervesces in *aqua fortis* [Fr. *eau-forte*, En. nitric acid – tr. note], vinegar and other acids, hardens when heated, and vitrifies when it becomes incandescent. It sticks lightly to the tongue, and it is often solid enough to be used in buildings, either as freestone [Fr. *pierre de taille*] or as rubble stone [Fr. *moëllon*]. About forty fossils can be found disseminated in a disorderly way in marl: among others, scallops, crinoids, plagiostomes, trigoniid, helix, ammonites, terebratellids, belemnites, mastodon, ichthyosaur, and plesiosaur debris, etc.

Marls generally have few vestiges of regular stratification; those whose mass is interrupted by limestone layers, which are always thin and of limited extent, and those that are layered or schistose, are almost the only ones that can be considered stratified. Marls range in thickness from 10 to 150 meters.

Seven colors can be found in marl in various locations, but no marl is perfectly homogeneous. All are nuanced to a greater or lesser extent by different metallic oxides that are mixed with marl and combined in many ways; thus, rather than say such a marl is white, black, red, green, blue, yellow, or violet, geologists commonly say it is whitish, blackish, reddish, greenish, bluish, yellowish, or purplish. One type of marl has alternating whitish, reddish, greenish, bluish and purplish bands; it is called *iridescent marl* or *keuper*. It is compact, granular, laminated, slightly aggregated; in air, it breaks up into small cubic fragments and it contains few fossils. This marl contains masses of gypsum [and] rock salt, produces saline springs, and occupies almost all of the departments of Meurthe and Moselle; it is also found in small deposits in Salins, Lons-le-Saulnier, Alais, Anduze, Castellane, Avallon, Bayeux, Flize, at Mont-d'Or, etc.

When a hydroscope looks for water in marls, he must exercise all his wisdom to determine if they are stratified, the thickness of each layer, which layers are permeable and which are not, if the deposit is composed of an unstratified mass, if there are swallow holes or not. Without an attentive examination of the rock, he runs the danger of not being able to make an indication that will be useful and often very important, or of making an erroneous one.

When the marl deposit is stratified, if is composed primarily of chalk and as a result is permeable, and if the intercalated and horizontal beds are impermeable and are not very deep, one can dig with success; but if the deposit is not at all stratified, if it is composed primarily of clay and is, as a result, impermeable, and if the intercalated and horizontal beds are permeable or at too great a depth, no digging should be done.

If there are swallow holes in the marl that one is exploring, one must proceed as described in Chapter XX regarding limestone with swallow holes.

## Alluvial deposits

Alluvial deposits [Fr. *terrain clysmien ou diluvien*] [See Translator's Notes] were transported by seawater or large lakes and deposited in certain places. Wherever a person sees piles of pebbles or rounded gravel all around that could not have been carried by present-day watercourses, he can be sure they were brought there by floodwaters or by outflow from upland lakes that broke their dikes. These deposits are so numerous and so widespread on the globe that there is perhaps not a square league that does not possess a deposit of them.

This rock type can be distinguished from all others by eight principal characteristics: 1st) It is composed of pebbles, gravel, sands that are rounded to some extent and in valleys, on hillsides, on plateaus and even on high mountains, they occupy positions that present-day watercourses could never have reached during their largest floods. 2nd) It forms isolated deposits, sometimes restricted and sometimes extensive, almost always independent of each other. 3rd) From time to time, one sees rounded blocks of all sizes lying on this rock type, some of which are from 10 to 20 meters in diameter and are found on plains where the most powerful present-day watercourse could not move them. Some of them have no similar rock in the valley where they are located, and as a result, come from other hydrographic basins. 4th) This rock type is never covered by a layer of solid rock; 5th) It contains slightly altered marine shells. 6th) It contains debris of animals whose species no longer exist, such as mastodons, megatherium, megalonyx, trogontherium, etc., or debris of animals whose analogues live at latitudes or in climates very different from where the debris was found, including elephants, rhinoceros, hippopotamus, etc., which are today concentrated in the torrid zone. 7th) No human bones, nor any trace of human activity. 8th) In certain regions, this rock type, although absolutely devoid of watercourses, does have furrows or small vales that are elongate and parallel to each other and that could not have been dug by ocean currents.

The water-transported blocks, pebbles, gravels, and sands are sometimes unmixed with other substances, but most often they are contained in layers of clay, topsoil, or silt. Some parts of this rock are unconsolidated, others are agglutinated by limestone or ferruginous cement and constitute piles of puddingstone; others are divided into undulating layers or layers of small extent, which indicates successive deposits carried by water; but most commonly they have no semblance of stratification. Near the edges of rivers, alluvial rock ordinarily has several terraces with cliffs or steep slopes, rather elongate and almost parallel to the thalweg of the valley. Comparison of the thickness of one deposit to that of another, and even different thicknesses within the same deposit, shows wide variation. In some places, these deposits measure only a few decimeters; in others they range up to two hundred meters in thickness. As one gets farther from the places from which the rocky fragments of this rock have departed, the fragments are more rounded and less abundant. The deeper one digs in these deposits, the larger the blocks and pebbles.

The regions of France where this rock is most common are the banks of the Rhine, the Isère, the Durance, and especially the Rhône, at the mouth of which is the famous plain of the *Crau*, which is about two thousand five hundred meters wide in all directions (twenty square leagues) and which is composed solely of this rock type.

Water-transported deposits must be ranked among the least favorable rock for the discovery of underground watercourses because they are generally unconsolidated, lack stratification, are very thick, deposited in a disorderly way, and have few or no surface depressions. The porosity of this rock is such that rainwater and stream water that comes from other rocks is lost and sinks down to the level of neighboring rivers which, because of the great thickness of the deposit, are most often at a level well below that of the locations where a water supply is needed. It is true that it is possible to find a water-bearing layer of clay, marl or puddingstone there; but these sorts of layers are so rare, so small, and often so deep that the chances of failure exceed those of success.

Almost everywhere under this rock are water layers that occupy the entire lower surface, moving painfully slowly and almost horizontally across the gravels to pour into the neighboring river; thus in the low sections of this rock, along rivers and dominating them by only a few meters, a person can dig for his own use with the certitude of finding a water layer at shallow depth.

### 2.4.23. Chapter XXIII. Rock Types that Lack Water because of their Structure or Lack of Cohesion

Some rocks would by nature be likely to harbor groundwater but a person should not seek water in them because of the structure of their constituent strata. These rocks include:

1st. All stratified rocks where the strata [Fr. *assises*] rest on their sides and as a result are vertical or steeply inclined. Steeply inclined refers to all strata that dip more than 45 degrees. Experience has shown me that generally wherever stratification has a slope of 45 degrees or more, even if the strata carry water from the inside toward the outside of hills, one should not seek groundwater there because all watercourses that in principle are found at shallow depth have had every opportunity to develop and have carried away the little bit of ground that hid these springs and that they are now visible; however, underground watercourses that are located deeper were never able to come to the surface and are still very deep. Thus groundwater should be sought only in rocks with a slope less than 45°; the lower the slope, the more favorable the rock.

2nd. All unstratified rocks that are cut from top to bottom by crevices or vertical or almost vertical cracks such as masses of sandstone, porphyry, traprock, schist, rock units that overlie Jurassic limestone, marble, graywacke, anthracite, etc. In some sections of these rocks, the fissures are somewhat parallel to each other but for the most part, the fissures are sinuous, contorted, observe no parallelism, and are more nearly vertical than horizontal.

3rd. Some rocks that are regularly stratified contain strata that may have a gentle slope and may be arranged in a way so as to transmit water horizontally but because they are composed of large blocks that are not very rectangular and that are separated from each other by numerous wide vertical fissures, the water descends freely and almost vertically to their base, whether these fissures are connected or not, as for example, vertical fissures in an overlying stratum on top of an underlying stratum, as in a wall built of freestone.

It can be easily understood that all rainwater that falls on rock that has this structure, however extensive it may be, can never form a watercourse at its surface or in its interior and that all water must freely sink to the base of the rock by following the numerous vertical fissures and crevices that permeate the rock. Rocks that have this structure are ordinarily very thick. A person who needs to obtain water and decides to dig to the base of these rocks, can promise himself the discovery of a watercourse only to the extent that he has made sure by attentive examination that the rock rests on impermeable ground at a relatively shallow depth.

Rock types where one should not seek water because of their lack of consolidation include *subsidence* [Fr. *affaissements*], *landslides*, and *slumps*.

## Subsidence

*Subsidence* is the name given to a considerable mass of rock that was previously prominent or located at the ground surface that has suddenly or progressively sunk into a cavity existing under its base or a cavity that has been formed gradually by an underground watercourse.

1st. During the time seawater covered the continents or at the latest during its retreat there were limestone hills that crumbled and subsided and were reduced to blocks, scree [Fr. *pierrailles*], and detrital material [Fr. *terrain détritique*]. These blocks, scree, and detritus were reduced to such a state of disaggregation [Fr.] and thus to say, a state of fluidity, that they filled adjacent vales and brought them up to level to such a point that there remains almost no vestige of the old hills or vales that they have filled. In France we have three striking examples of these ancient catastrophes, and all three are found between swallow holes where rivers have been lost to form springs at distances of several kilometers: the Vaucluse, Touvre, and L'Ouysse springs.

The Calavon River, coming from the Basses-Alpes, below Apt (Vaucluse) is gradually lost into the plain, which is completely composed of unconsolidated material. Below Gordes it receives the underground Nesque River that comes from the district of Sault to form the famous Vaucluse spring, which on average provides 890 cubic meters of water per minute.

When the two rivers of Bandiat and Tardoire reach the district of Montbron (Charente) they disappear imperceptibly into the vast debris of the hill that previously existed between the two rivers and that now fills the two former valleys. The locations of the hill and the two valleys form only a plain, five leagues long and three leagues wide to the east and two to the west. It is completely covered by blocks of marly limestone, a few of them larger than a meter in diameter, loose stones, and topsoil mixed together is a disordered way with no vestige of stratification. The two rivers, now underground, reunite below La Rochefoucauld and after traveling underground the distance of about six leagues, provide the water for the magnificent Touvre Spring near Angoulême. The water of this spring forms a river that is about 40 meters wide and 1.5 meters deep.

All the streams of the Lacapelle-Marival district (Lot) form on granitic and schistose rocks; when they reach the villages of Thémines, Théminettes, and Issendolus where the ground is limestone, they sink into three caverns, unite underground, join up with a large number of hidden streams and, after a trajectory of 25 kilometers, form the L'Ouysse spring near Souillac (Lot). The volume of the L'Ouysse spring is almost equal to that of the two just mentioned. All the hills that separate the basins of these streams, which are at high elevation in the granitic and schistose rocks, drop suddenly and disappear when they reach the limestone rock. To the south of these three villages one finds only a vast plain two or three leagues long and about as wide, covered with immense debris that previously made up several hills of which there remain only traces. Here the Jurassic limestone, more coherent than that of La Rochefoucauld, has left numerous masses at the surface of the ground; they lie pell-mell with blocks of all sizes, scree, and topsoil.

These types of subsidence features or landslides are much more common in limestone formations than is commonly believed. In many locations I have seen former knolls, foothills, and spurs that have been broken up from bottom to top, have filled adjacent valleys, and their debris today lies in a state of *confusion* [Fr. *brouillage*]. Although less extensive and less well leveled than the three I have just cited, they are no less real and are easy for any attentive observer to distinguish.

One still frequently finds broad spaces on plateaus where the stratification is completely disturbed; these spaces are filled with disordered scree and topsoil that form dikes of indeterminable depth. These extensive piles or chaotic accumulations are due to the movement of seawater that pushed and piled up these materials into the intervals left by benches of broken up rocks; some result from explosions of underground gases that have opened and broken benches of rock to reach the surface, with or without earthquakes.

### Landslides and Slumps

Masses of rock detach and move down mountains during *landslides* or by *sliding*.

Rocks move downward by a *landslide* when the different parts of the detached mass separate from each other and roll downward in a disordered way.

Rock moves downward by *slumping* or by *rock fall* [Fr. *avalanche*] when all or almost all the detached mass moves down the inclined plane of the mountain without breaking up or turning over.

In large mountain chains one sees summits and sections of mountain that have suddenly fallen or have progressively moved downward toward their bases and have formed new mountains and hillocks at various elevations. Some of these new mountains have an elongate high point parallel to the ridge from which they fell; others form mountains or conical knolls that show no positional relationship between them or with the mountain that formed them. These new mountains can be easily distinguished from those that have remained in place because the latter are usually stratified and their strata extend over large distances whereas mountains that have formed by landslide show only disorder, upheaval, and confusion. If some that have come down as slumps contain rock masses that have preserved their stratification, these masses are always quite small and all the rock that supports them, like the rock that surrounds them, is broken up and not coherent. All these landslide and slump rocks have left voids at the ledge of the mountain where they detached; they form reentrants where the previous position of the stratified masses that have slid without breaking up can be seen.

Landslides and slumps that produced these mountains and knolls occurred while seawater or large lakes covered the land or as they retreated; others take place all the time, either by earthquakes or by water that penetrates into argillaceous layers, softens them, and makes them swell sometimes to the point that these masses, no longer being able to support themselves on the slopes they previously had, crumble under their own weight.

Among the former, we can consider the Ramonchamp valley (Vosges). The hillslopes of the two hills and the entire plain, which is about a kilometer wide, are studded with conical knolls, obviously transported, separated from each other, and randomly placed. They are composed of blocks of rock of all dimensions, of topsoil, confusedly mixed together, and each blister [Fr. *boursouflure*] is between three and eight meters tall. All these ridges and the surrounding slopes bear traces of old slumps and landslides that could have occurred only in water.

Since the retreat of the sea, large landslides and slumps have occurred and continue to occur frequently.

In the year 1249, half of Mount Grenier, near Chambéry (Savoie) collapsed during the night and crushed all the inhabitants of the small city of Myans and several surrounding villages, and the debris extended onto the plain over an area of about one league in all directions.

In 1618, an enormous portion of rocks that bordered the Chiavenna valley in the Valteline (Switzerland) collapsed and buried the small city of Pleurs and more than 2,000 of its inhabitants.

In 1714, the western part of Mount Diablerets, in the Valais, collapsed; its debris occupies more than a square league to a depth of about 100 meters.

In 1772, Mount Piz in the Marche de Trévise (State of Venice) cracked in two; one part turned over and covered three villages and their inhabitants. A stream, dammed up by the debris, formed a lake within three months. The remaining part of the mountain collapsed, the lake overflowed, and many people perished; several villages are still covered by water.

At Solutré near Macon after heavy rains, the argillaceous layers of the summit of the mountain slid down the limestone layers located below; they had already moved several hundred of meters and threatened to bury the village when the rains stopped and with it the progress of this shifting ground [Fr. *terrain mouvant*].

In a similar way, a part of Mount Goyéna in the State of Venice, broke apart in the night and carried several houses to the bottom of the neighboring valley. In the morning when the inhabitants, who had felt nothing, awoke they were quite astonished to find themselves in the valley. At first they believed that a supernatural power had transported them and it was only by examining their new location that they recognized the traces of the turmoil that had miraculously spared them.

On September 2, 1805, following a rainy period, a mass 4,000 meters long, 400 meters wide, and 30 meters thick detached from Mount Ruffiberg in Switzerland, rushed down the valley and buried several villages under its debris, taking the lives of 500 people and creating hills higher than 60 meters in the bottom of the valley.

Between June 22 and 23, 1837, part of the Perrier Mountain near Issoire on which the village of Pardines was built, slid to its base amidst roaring, taking trees and houses with it. An entire vineyard and a building were transported without any damage; the next day a basaltic rock 100 feet high suddenly rolled over, creating a frightening commotion.

In the night of September 27 and 28, 1853, part of Mount Duret near Alais crumbled without killing anyone, thanks to the wise precaution of local authorities who saw a crevice at the highest point enlarging daily and recommended a few days in advance that all the inhabitants of the valley in the path of the moving mass move without delay.

La Gazette de Coire (April 1856) says that in its district there is a mobile village and it explains this remarkable fact as follows: the houses and outbuildings are located on moving ground that from time to time slides downslope on the escarpment whose summit it used to occupy, without the buildings or trees that cover it suffering any notable change in position. This village is that of Iscliappina, near Tusis. For about six years, the ground has advanced almost a half league down the slope of the mountain; even so, the locality is still inhabited and the land is used for agriculture.

On May 30, 1856, following prolonged and heavy rains, the inhabitants of Barjac, near Mende, observed the flank of Mount Sennaret, which towers over the village at an elevation of about 250 meters, crack and move imperceptibly throughout the day; at the same time, they heard their houses crack and a dull and prolonged noise come from the mountain. After these unequivocal signs of imminent disaster, the inhabitants all took refuge in neighboring villages. At about eleven o'clock at night, a detonation much stronger than thunder was heard; an enormous rock fall ripped loose from the hillside, poured down into the plain with a frightening roar, crushed houses and covered or dragged everything found in its path to the foot of the opposite hillside. The Lot River, whose valley in this location is only a narrow gorge, was entirely blocked by a dam 100 meters tall and 500 meters thick and a vast lake formed upstream. Parts of buildings that were not engulfed, outer walls, hedges and trees that were on the hillside are now seen along this roadway, most having preserved their respective positions.

In addition to these overturned mountains, where history has preserved the tradition, there are many others that we do not know about that have contributed and been overturned in the unknown past. When a person travels in higher mountains such as the Alps, Jura, and Pyrenees, one finds proof at each step.

The reader senses that he should not seek groundwater with any hope of success in deposits [Fr. *terrain*] resulting from subsidence, landslides, and slumps. These deposits are often 100 meters thick; their extreme porosity, incoherence, and disorder of all their parts does not lead to any conjecture on their composition nor their internal structure; it is thus as difficult for a geologist to know the interior of this rock unit as it is for an anatomist to understand each part of a cadaver that has been chopped up.

Fuller's Earth [Fr. *Argile Wallérius*]

Independently of these enormous masses of rock that detach from large mountains and crumble or slide suddenly along their flanks, we also find both on the slopes of large mountains and on those of the humblest escarpments, deposits of clay that slides imperceptibly, called *fuller's earth* [Fr. *argile fermentante de Wallérius*]. This clay is ordinarily only one to four meters thick; it is mixed with quartz sand and rests on a smooth layer, rather highly inclined, whose inclination conforms to that of the ground surface. Like all clays, it has the property of swelling when it is wet and contracting as it dries. During heavy rains, it incorporates water and increases considerably in weight and volume. The whole surface of the rock that supports it is wet and at various points and at different heights, large crevices form, sometimes circular, sometimes square; these crevices mark the separation of each mass that has started to move. The masses of the small rock falls that are highest push the next one downstream; they in turn push those that are lower, and so on to the bottom of the slope. In various places, they form hillocks or protuberances of differing elevations.

The progress of this material [Fr. *terrain*] is highly uneven. On some escarpments, it moves downward at a rate of several decimeters every year; on others, some parts move from time to time and then stop for several centuries. But when the mass is undermined for building a road or if a watercourse erodes the base of a moving mass, after the first heavy rains the mass slides as a unit or as separate masses and spreads onto the plain and even stops up the watercourse.

Aqueducts built on this type of material are very often disrupted or broken, and no solid edifice will ever be built there. No matter how well cared for, these structures will crack (1), tilt, and collapse. I have seen numerous villages where, almost every year, some houses collapse. The inhabitants are highly vulnerable to being buried under the ruins and one or another of them are continually occupied with rebuilding.

In this rock type, as in others, there are visible springs and a larger number of hidden springs, but because the ground has no stability springs appear and disappear from time to time, sometimes suddenly, sometimes gradually; they reappear at different places and disappear again. All this ground being upturned and the underground watercourse moving in a disordered way, it is impossible to apply any of the rules that govern the movement of groundwater. A person must thus be content to make use of groundwater that makes itself apparent and to refrain from looking for hidden watercourses because water can be found only by chance and even in the case when it is found, one can be sure that it will disappear sooner or later.

Note

1. Having become familiar with this type of rock in my travels, I have several hundred times announced from afar, sometimes even from very far away, that most walls of a house or a village that I am seeing for the first time are out of plumb and cracked. The villagers who hear these announcements are stupefied and the villagers regard them as superhuman inspirations. However, the discussion above shows that it was easy to observe these conditions.

This is how the *Nouvelliste de Pontarlier* reported on this subject on October 20 and 27 and November 17 of 1844:

"In Oyettes, Mr. Paramelle predicted that if a person planted a row of trees in a straight line today, more than half would have lost their alignment within fifty years and all of them within a hundred years. These remarks are justified by the growth of fir trees, which in this location are present farther down than everywhere else on the hill toward the Lavaux stream; this can be explained only by the imperceptible movement of the ground from high to low. While having lunch in Suans, Mr. Paramelle spoke about the crumbling ground that caused him to renew his prediction about the village of Lods (Doubs), where the moving soil on which it is built threatens to carry it into the Loue one day. On this occasion, he said that while visiting the Department of Var, he made the same judgment regarding a village called Châteaudouble, and by a remarkable coincidence, his judgment coincides with that of Nostradamus three hundred years ago on this same subject, according to the following verses:

Chateaudouble, Doublechateau,

The river will be your tomb.

"When he arrived at the Hôpitaux-Vieux, Mr. Paramelle pointed out four springs. One of them passes under four houses and even under the presbytery. At a distance where it was not possible to see with the naked eye that the priest's house was cracked at the corner of two sides by the action of an underground watercourse, he said: *Go convince yourself of this circumstance, and the spectators hastened to verify it; it was perfectly correct*.

"In the village of La Grand' Combe, a remark impressed and perhaps frightened the inhabitants: '*In the entire Department of Doubs*,' said the learned geologist, '*I have not seen such a large amount of crumbling ground as that on which a large part of the village is located, and I am sure that almost all the houses, as soon as the walls are built, become cracked, not on the front or back facades, but on the sides*.' When it was checked, it was found to be true."

### 2.4.24. Chapter XXIV. Mineral, Thermal, and Periodic Springs

Water from all springs is essentially the same. Its diverse qualities are due only to different heterogeneous bodies (1) that it holds in suspension or dissolution and that modify its weight, taste, color, and odor. There is no perfectly pure spring; those that most closely approach the state of purity are *fast-flowing springs* [Fr. *sources d'eau vive*], also called *rock water* [Fr. *eau de roche*] because it flows from rocks after being filtered through sands or granitic masses where it has encountered no soluble material. This water is ordinarily the lightest, since a cubic foot weighs only about 70 pounds (2); it boils more quickly than any other, cools more quickly, and leaves no sediment in the vessel where it was boiled; it dissolves soap easily, and vegetables cook quickly in it. When it flows on land, it produces watercress and other plants that keep their green color all year long. After springs that flow from granites, the best for drinking and the healthiest are those that flow from porphyries, micaschists, traprock, pure limestones, and sands.

Mineral springs

We commonly give the name of mineral spring to those whose water is cold and contains dissolved saline, earthy, or metallic constituents in a quantity sufficient to cure some malady or produce a noticeable action on livestock production. Commonly we speak of a spring in terms of the dominating constituent in the water; thus we call it a *saline*, *gypsiferous*, *sulfurous*, *vitriolic* [contains sulfate - tr. note], *ferruginous*, *bituminous*, etc. spring because its water has encountered, dissolved, and carried away in abundance some salt, gypsum, sulfur, sulfate, iron, or bitumen in the strata through which it has travelled underground.

Mineral springs follow the same laws as ordinary springs as they travel underground and they are found by the same procedures. This is how I found the big spring of Saint-Galmier (Loire), that of the Pinsaguet chateau (Haute Garonne), etc.

Chemistry provides the most certain methods of determining the composition of water and the nature of mixtures. Analyses of a certain number of known springs are found in all books written on this science. The substances discussed in each of forty-five analyses that I have seen number from four to fifteen and according to Bouillon-Lagrange (page 50) [Edmé Jean Baptiste Bouillon-Lagrange, *Essai sur les eaux minérales naturelles et artificielles* (1811) – tr. note] "one could put at thirty-eight the number of different substances that have been found in mineral water."

If the water is clear, one should not assume that it has no foreign substance because the dissolved saline portions or decomposed minerals are so subtle, so attenuated and divided up that they are suspended in water imperceptibly and do not affect its transparency.

Air bubbles that continually escape from the bottom of some springs and rise to the water surface and produce a sour taste announce that the spring is *gaseous*.

The whitish *color* of the water is an indication of chalky or gypsiferous particles; a yellowish-white color is the effect of coal [Fr. *charbon fossile*]; a black color indicates the presence of asphalt or black chalk. A reddish color present only at the surface of the water denotes some animal substance, and when the redness occurs throughout the whole mass, the water must be carrying iron, *bol* [See Translator's Notes], or ochre; a green color indicates the presence of copper or sulfates; a yellowish-green color that of sulfur or iron mixed with copper; a blue color, that of copper; a blackish yellow color, that of iron.

The *taste* of rust announces the presence of iron or copper in the water; the taste of ink, the presence of sulfates. The taste of salt, sulfur, and peat indicate that the groundwater has traveled through deposits or mineral strata of salt, sulfur, peat, etc.

An *odor* of garlic indicates an arsenic spring; the odor of rotten eggs indicates sulfur. A steel blade plunged into sulfurous water without access to air will turn black.

## Thermal Springs

Hot water springs or *thermal* springs have varying degrees of heat, from boiling water, which is 100 degrees, to temperate. The Cauterêts spring is 36 degrees; that of Barèges, 48; Balaruc (Hérault), 53; Vais, near Aubenas, 55; Bagnères-de-Luchon, 56. At Bourbon-Lancy, the Saint-Léger spring has a temperature of 33 degrees; that of Escure, 43; la Beine, 44; Grand-Puits, 48. These four springs flow out of the ground only a few meters from each other. At Chaudesaigues

(Cantal) the inhabitants use seasoned thermal spring water in their soup, and do not need to heat it more. They cook their meat in it; the eggs harden in several minutes, and they use conduits built under the pavement to heat their houses.

Until the end of the last century people generally attributed the heat of these springs to pyrite, to layers of chalk, lime rock [Fr. *pierre à chaux*], or to volcanoes, but now that geologists have published their observations on this subject, it is recognized that thermal springs located near active volcanoes are the only ones that have an increased temperature and that pyrites, chalk, and lime are evidently too weak or too exhaustible to produce such large and constant effects; in fact, for the many centuries that people have observed this water, they have always found about the same volume, the same composition, the same taste, and the same temperature. Intense cold and heat and heavy rains and long droughts, which ordinarily cause springs to vary, cause no change in the temperature or the discharge of thermal springs. In addition, these springs all arrive at the ground surface through vertical action and they are found in all sorts of rocks types and positions. Most are far away from volcanic rocks.

Thermal water comes thus from depths of the globe where they get their temperature; the various degrees of heat that they have are due to the greater or lesser depths from which they come (3). Today all physicists and geologists accept that the earth has its own heat, which increases about one degree for every 25 meters of depth (4) and that ordinary water that sinks into the earth acquires four degrees of heat per 100 meters of depth. Knowing the degree of heat of a spring, a person can calculate the depth from which it comes; if for example, a thermal spring has 20 degrees of heat, it follows that it comes from a depth of 500 meters, if it has 40, it comes from 1,000 meters, and if the water has a temperature of 100 degrees and it is thus boiling (assuming that there is such a spring somewhere), it comes from a depth of 2,500 meters. These data are subject to exceptions everywhere a thermal spring mixes underground with an ordinary spring that proportionally cools the quantity of water that it provides.

One of the benefits of the central fire is to prevent groundwater from descending to infinite depths. Water that descends to great depths, not reaching 2,500 meters however, are continually pushed out of the earth to form higher temperature thermal springs. The very small quantity of them that reach the incandescent hearth are converted into vapor and are emitted by volcanic mouths or other openings in the ground. This continual discharge of water keeps them all near the surface of the earth where one part circulates at the surface or at shallow depths, another part is preserved in the seas, whose level remains always the same, and the third part is reduced to vapors and drifts in the atmosphere. Without this central fire, all the water would have been precipitated a long time ago into immense cavities from which it would not have left. The surface of the earth would be absolutely arid and no living being, animal or plant, could live there.

The underground pathway of thermal springs being vertical and coming from extraordinary depths, one can find them by applying ordinary procedures in only two cases, which are rather rare; if one of these springs approaches the ground surface and encounters a rock layer that prevents it from rising in a straight line but instead forces it to travel horizontally for a certain distance, or if the spring has ascended toward transported material where it encounters only broken up ground that does not allow it to flow out of the earth, in these two cases it is possible to intercept this spring at one of the points of its horizontal trajectory. Thus, one should not seek to find this type of spring; one should be content with using it when it presents itself or when one finds it by chance.

### Periodic and variable springs [Fr. *Sources intermittentes et intercalaires*]

The flow of intermittent and variable springs has forever piqued the curiosity of both savants and ordinary people.

*Periodic springs* are those that flow during certain intervals and completely stop flowing during others regardless of the season; in other words, they alternatively appear and disappear over set time periods. *Variable springs* are those that at fixed intervals independent of the season alternatively provide different quantities of water. Springs that are really periodic or variable are those whose intermission lasts only several minutes, several hours, or several days. Springs that appear or disappear for months or years or whose variations depend on rainfall or snowmelt are not categorized as intermittent or variable springs; they are called *temporary*.

The reason for these strange variations has always been hidden from our eyes, so physicists [Fr. *physiciens*] have attempted to explain them with various suppositions.

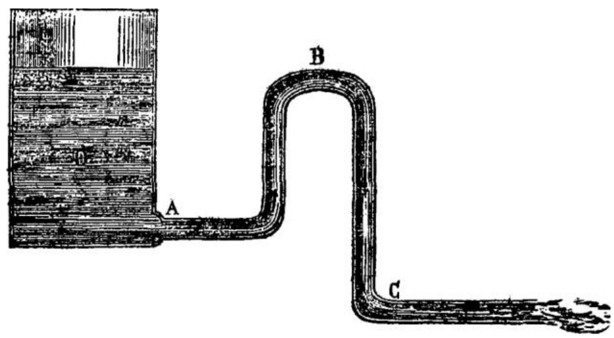
Some have attributed these variations to gusts of underground winds but they do not cite a periodic spring whose flow is regularly accompanied or followed by an air current strong enough to push the water column out of the earth.

Others have advanced the idea that the periodicity of springs is caused by the ocean flux, given that the Mediterranean has no detectible flux. In support of this opinion, they cite several springs located right at the edge of the ocean or several tens of meters distant from it that rise and fall with it. This very simple fact has no relationship to periodic springs that are often located hundreds of leagues distant and hundreds or thousands of meters above sea level. The discrepancy that exists between the ocean flux and the various periodic springs should alone and first of all have caused this hypothesis to be rejected because the duration of the flux is about six hours, and among the numerous known periodic springs perhaps only one has been cited that has exactly the same duration. Furthermore, the intermission of various springs has all sorts of durations, from several minutes to several days, and one can find perhaps only two of them that have exactly the same duration.

To give this phenomenon an explanation based on facts, others have tried to, as one says, catch Nature red-handed. Starting at the outlet of the spring, they have dug a gallery to some length and followed the underground conduit of the spring; but they do not cite a single person who was so fortunate as to see this mechanism function underground. Their curiosity has managed only to destroy forever a phenomenon that was a natural wonder of the region.

In the absence of direct observations, physicists explain the periodicity of springs by the action of a siphon whose mechanism is well known. So that all readers can understand what follows, I illustrate the shape and action of this instrument.

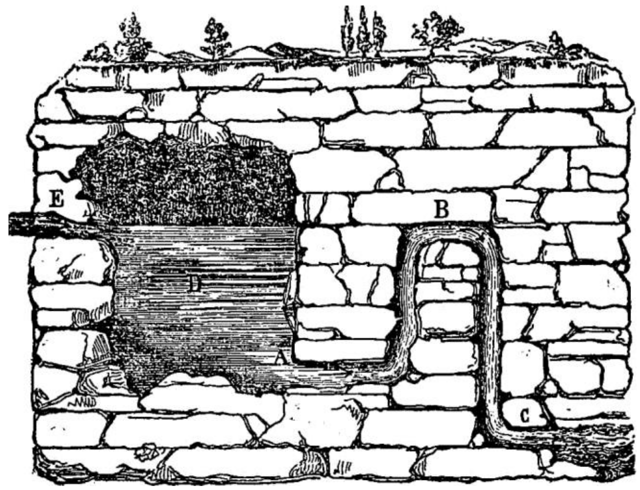
A siphon is a simple curved pipe ABC, whose AB branch is shorter than the other, BC. To use this instrument, end A of the short branch is placed in a vessel D or fitted to a lateral opening A of the vessel. Water or any other liquid is poured into the vessel. As the water rises in the vessel, it also rises in the short branch AB. When the water reaches the height of the curve B, it begins to rise rapidly in the short branch AB and to descend through the long branch, BC. The water continues to escape out the pipe and the vessel empties until the water level is below the opening of the short branch A. At this moment, flow stops. Each time the operation is repeated, the same result is obtained.




Siphon

It makes no difference whether the pipe is composed of glass, metal, or wood, whether it is thick or thin, whether its curvature is arcuate, angular, or bizarrely tortuous. For a siphon to work, its outlet C must be lower than the level of the water contained in the vessel.

Based on these data, which are confirmed by experiments and accepted by everyone, to explain how a spring can alternatively discharge a quantity of water and stop for regular intervals, it would have to be assumed that the water of this spring encounters underground a rather large cavity and then a narrow pipe set up like a siphon. These two types of cavities can be represented as follows:




Cross-section of a rock containing a periodic spring.

D. Spacious cavity serving as a basin.

E. Underground watercourse that flows into the cavity.

A. Opening into the short branch of the underground passageway, which functions as a siphon.

B. Elbow, or curvature of the passageway.

C. Outlet of the long branch of the passageway.

With the cavern and passageway arranged in the shape of a siphon, it is easy to conceive of and explain the operation and non-operation of this underground siphon. When basin D is empty, water from the source E falls into and fills the cavity and the short branch of passageway AB; when the water has risen in the cavity and in the passageway up to the highest height of curve B, it begins to descend into the long branch BC, from which it noisily chases out the air, continues to flow, and the cavity empties until the water level has fallen below the opening of the short branch A. At this time flow stops, and this stoppage lasts until water again rises to height B of the curved pipe.

The duration of flow depends on the size of the cavity, diameter of the passageway, and the quantity that the spring produces; some intermittent springs flow only several minutes, others for several hours and others for several days, and cease to flow during the time the cavity refills with water.

For a spring to be periodic, pipe ABC must carry more water than the supply channel E provides because if this channel discharges into the cavity as much as or more water than the pipe can discharge, the water in the cavern would remain at the height of the curve of the passageway and flow would be continuous.

Flow is equal to the quantity of water found in the cavity at the time the siphon begins to operate and the quantity that flows into it during flow; when the supply channel increases its input after heavy rain, the cavity fills in less time, the intermission is shorter and flow occurs over a longer period. If on the contrary, drought diminishes the amount of water supplied by the supply channel, the intermission will be longer and flow will be shorter.

This method of explaining the periodicity of some springs is the only satisfactory answer found at present and to prove that this cavity, this passageway, and the action that results from it are not gratuitous assumptions, a machine has been built that perfectly reproduces this phenomenon, and for this reason it is called a *periodic fountain*.

As for *variable springs*, that is, springs that provide more water during certain intervals than during others, it is assumed that in the subsurface the long branch of the periodic passageway pours its water into another spring whose flow is continuous; or if there is only one watercourse, that it bifurcates before arriving at the cavity, that one branch follows a conduit whose flow is continuous and the other passes through the cavern and the periodic passageway and that the two branches rejoin before arriving at the ground surface.

Periodic and variable springs are common in all areas. The most remarkable in France is Fontestorbe in the Belesta district (Ariége). Its flow is ordinarily variable from the month of June until the month of October but in winter and even during summer rains it becomes continuous. The flow begins every forty-five minutes and lasts eighteen minutes. During the largest floods, it produces about eight times more water than at its lowest flow.

The flow of the Touillon spring near Pontarlier (Doubs) lasts ten minutes, fills its basin, and disappears completely, leaving the basin dry for three quarters of an hour.

The spring of Colmars (Basses-Alpes) flows eight times every hour and stops as many times, and varies only six to eight minutes at different times of the year.

The Fonsanche Spring between Sauve and Quissac (Gard) flows regularly twice every twenty-four hours and stops twice during the same period. Each flow lasts seven hours twenty-five minutes, and each intermission five hours; the flow and intermissions are about fifty minutes later each day.

The intermittences of the Jaude spring in Clermont are about six minutes.

The Department of Lot has two periodic springs, one at La Mothe-Cassel, where flow increases from ten minutes in the morning to three hours in the evening. The other is Gigouzac, whose flow begins with abundance at about ten o'clock in the evening and stops flowing at about five o'clock in the morning.

The most extraordinary known periodic and thermal springs are the geysers of Iceland, which seem to owe their behavior not to siphon action, but to masses of gases mixed with masses of water contained in vast underground cavities. This island is completely made up of volcanic rock and it is still the site of an active volcano; it emits enormous quantities of gas, which at irregular times, swell the groundwater and push it out with some violence.

The periodicity is likely due to the same cause as the irregularity of some periodic springs, which follow no order in flow duration. These geysers number more than one hundred, are grouped within an area of about a square half-league, and are located a half league from Skalholt. Here is how Mr. de Troïl reports a visit to these springs (5).

"The "*huers*" or sprays, which are very numerous, are more remarkable. I will cite only the three most unusual. One is near Langervatn, a freshwater lake, which is a league in circumference, located two days from Hécla; this is where I saw the first spray, and I must say the sight of it was superb. The sky was clear and the sun began to shine golden on the neighboring mountains. There was no wind and swans were swimming on the lake, which looked like a mirror. All around, I could see eight places where vapors rose from these hot springs and dissipated in the air."

"All of them discharged water; one rose as a column from eighteen to twenty-four feet high, with a diameter of six to eight feet. The water was extremely hot. We used the water to cook our rather large piece of mutton for lunch with some salmon trout and some snipe; their flavor was not at all altered. It was so hot that after six minutes the meat was cooked so well it almost fell apart."

"Any description, such as the one I have tried to give you would never do justice to the subject, but it is certain that in no other place have I felt as full of admiration and veneration for the author of nature."

"There is another spray at Reikum. It is claimed that the geyser there rose to a height of seventy feet a few years ago. A landslide has covered almost the entire hole where the water used to discharge; this is the reason that it does not exceed sixty feet."

"I have not told you sir about what seemed most remarkable to me, and you will have difficulty believing it. I do not hazard a guess about what I have seen and I guarantee the truth of it."

"The largest geyser that exists is that of Geyser, near Skalholt, one of the episcopal residences of Iceland. Those of Marly, Saint-Cloud, Vinterkasten, in the landgraviat of Cassel, of Herrenhansen in the district of Hanover, are nothing in comparison. In the space of a circle less than a half league across there are as many as fifty boiling springs that most likely all have the same source. The water in some of them is clear; in others, it is cloudy like the chalky water they deposit, and in others the water goes through an ochre vein that makes it red as blood while the water of other springs that flow through a lighter clay, is white as milk. All these fountains form geysers, with the difference that in one area water flows continually and in others it flows only at intervals. The large spring in the middle was the one we studied the most. We stayed there from six o'clock in the morning until seven o'clock at night. The diameter of the passageway that carries the rising water is 19 feet. I do not know the depth. The crater located at the end of the passageway has a cauldron shape. Its diameter is 56 feet, and its margin above the passageway is 9 inches. This spring does not discharge water continuously but at different times during the day. The inhabitants of the surrounding area assure us that the water gets much hotter when the weather is cold. When we arrived, we saw water discharge up to a height of 60 feet ten times in five hours. The water, once reaching the edge of the passageway, filled the crater only little by little and it finally overflowed. We expected a jet of great height, which did not occur right away. Mr. Lind, who accompanied us as astronomer, set up his wing compass to take the exact elevation. In the afternoon, a few minutes after four o'clock, the earth trembled and this shaking was also felt in several other places, on the mountaintop at 500 fathoms degree of opening. It was accompanied by an underground noise like several cannon firings in a row. The next instant, the jet began, and the water column that rose to 90 feet according to our observations, spread in different directions but what added to the astonishment were the unusual effects of fire and air; we saw the same rocks that we had just thrown into the opening rise in the jet."

"Following Mr. de Troïl, other travelers have recognized that changes in the number and the power of these shooting springs have occurred. After the 1784 earthquake, some ancient springs disappeared and new ones appeared. Their eruptions have become generally more violent and larger since 1804 when the Danish Lieutenant Ohlsen saw one column rise to about 150 feet and another to 212."

Notes

1. *Tales sunt aquae qualis terra per quam fluunt*. Plin., *Hist. natur*., libro xxxi. [English: Waters are of such a kind as the land they flow through, Pliny, Natural History, Book XXXI] [Edwin Robert, Latin-English translator, personal communication, 2016].

2. The heaviest water weighs 72 pounds per cubic foot and the lightest 70.

3. See Messieurs D'Orbigny, *Géol*., Chap. 1; Boubée, *Abrégé de Géol*. [Short guide to geology], *Chaleur central* [Central heat].

4. Careful and repeated experiments show us that the entire mass of the globe has its own heat that is completely independent of that of the sun. This heat is constant everywhere at a

particular depth and it seems to increase with depth" (Buffon, *Époques de la nature, discours préliminaire* [Epochs of Nature, Preliminary Discourse]).

"Toward the interior of the earth, heat increases progressively and at a rather high ratio. In the mines at Freyberg, the temperature rises as a person descends and at a depth of 300 meters it is more than eight degrees higher than the temperature at the ground surface. This increase is one degree per 37 meters of depth, 35 at least." (D'Aubuisson, *Géognosie* (Geognosy), volume I, pages 480, 453, and 458.)

Mr. Cordier, in his *Essai sur la temperature de la terre* [Essay on the temperature of the Earth], published in 1828, summarizes it this way: "Our experiments fully confirm the existence of internal heat, which is due to the Earth itself, has nothing to do with solar rays, and it increases rapidly with depth. The increase is definitely more rapid than had been supposed; it can be one degree per 15 meters, and even 13 in some regions; for the time being, the average term cannot be set at less than one degree per 25 meters."

For more information on the internal temperature of the earth, see Messieurs Humboldt, Gensanne, Saussure, Rozet, Fourier, and others.

5. *Lettres sur Islande*, [Letters about Iceland] translated from the Swedish, page 304 and following.

### 2.4.25. Chapter XXV. Potable and Non-Potable Springs

Doctors and chemists are the only people qualified to tell us which water is potable and which is not, and I feel obligated to put before the eyes of readers some characteristics that these professionals provide to us to help us distinguish one from the other, in the easiest cases.

Characteristics of potable water

"Good water," says Hippocrates, "should be clear, light, aerated, have neither detectable odor nor taste, should be warm in winter and cold in summer (1)."

According to Tissot: "One should choose pure, cool spring water that makes suds easily with soap, cooks vegetables well, and washes laundry well (2)."

"The signs of good quality water are: a) It is clear, limpid, has no body or substance that clouds its transparency; b) has no odor or color, has a lively, cool, and penetrating taste; c) cooks vegetables well and dissolves soap well (3)."

The article on water in the *Encyclopédie Moderne* [appears to be the *Encyclopédie moderne dictionnaire abrégé des sciences, des lettres, des arts* (1823-32), update of the 18th century French encyclopedia by Diderot and d'Alembert – tr. note] lists the following characteristics: "Potable water should be fresh, clear, without odor, without taste, give no sensation of weight in the stomach, and should dissolve soap easily."

According to Drs. Halle, Nysten, Londe, and Rostan, medical doctors who today who are most concerned with this question: "Water should be considered good and potable when it is cool, limpid, without odor; when the taste is neither unpleasant, insipid, spicy, salty, or sweet, it should contain little foreign matter, should contain dissolved air, should dissolve soap without forming lumps, and should cook dry vegetables well (4)."

"Water from springs and fountains has very great differences in degree of purity and in temperature. Some are almost pure and others are full of gas or saline, earthy, or metallic dissolutions. To the extent that water flows in rocks that lack any saline, alkaline, or metallic principles, they maintain their purity; such are those that flow through bare granite or in pure sand, limestone or clay. They approach the status of rainwater and are very good and healthy (5)."

Characteristics of non-potable water

"Spring water may not be clean enough for domestic purposes when it contains a notable quantity of foreign matter that makes it unhealthy or unpleasant to use (6)."

"Water that comes from gypsiferous rock is full of lime sulfate [calcium sulfate – tr. note]; water that flows from wells where the ground is chalk contains calcium carbonate. Water from wells where the ground is peat, swampy, saturated with water from manure, and water from cesspools, should be considered very unhealthy. Water is of bad quality if it passes near salt mines, swamps, muddy ponds, sewers, or refuse (7).

'When the rock that the water passes through contains soluble earthy, alkaline, or metallic salts, the water takes on these substances and gases that can dissolve them, and they become mineral and medicinal waters. Water often carries with it material it cannot dissolve including petroleum, bitumen or blackish, viscous, or fetid materials. The water of *Trémolai*, near Clermont, is black and precipitates sticky material, and has a strong and unpleasant odor; those of the *Pic de l'Etoile*, an old volcano of Vivarais, also black and revolting, is full of very fetid oily bitumen; the *Font de la Pégue* in Servac near Uzès flows out boiling and precipitates a black sticky very flammable bitumen; the *Fontaine of Gabian* in Languedoc is remarkable for the quantity of bitumen it carries.  In this respect, none is more remarkable than the spring of *Puits de la Poix*, one league from Clermont, from which the water flows with mineral tar of a high degree of purity; it rises from the bottom of the basin and forms a skin at the water surface that covers the entire basin. The springs of *Puy de la Sau* near Montferrand (8) are also like this."

"Water that has any odor whatsoever, an unpleasant, dull, salty, or sweet taste should be considered non-potable. When water has an odor, it is generally due to organic substances, often putrefied, and should not be drunk because these substances are dangerous to health. In summary, any water that has an odor is a mineral water or water altered by organic material and should not be considered good potable water. The taste definitively indicates the presence of organic material, particularly putrefied material in notable quantity. Pure water is perfectly colorless and transparent. Therefore, if water destined for domestic usage has a tinge of coloration, it is a sure sign that it contains in solution some foreign substance, and particularly an organic material. Water of this type is essentially bad and must be rejected. Any water that is turbid, muddy, or lacks perfect clarity, contains foreign suspended matter, particularly earthy material. Most surface water meets this description; water in this condition should not be drunk. Earthy material in suspension not only makes them heavy and indigestible, but this material also contributes to digestive disorders due to the disgust they cause. In winter, no one doubts that spring water is preferable because it seems warm; the temperature of spring water is invariable throughout the seasons; in winter it is about 15 to 20 degrees higher than the atmosphere. But the coolness of potable water during the summer is a much more important condition than its temperature in the winter. It is a fact well known by everyone that cold water or at least water that seems cold in summer, for the reason that its temperature is generally much less elevated than the atmosphere, in addition to pleasing the palate and the stomach, quenches thirst, and immediately provides well-being and rekindles strength. On the contrary, nothing is more unpleasant and more harmful, during the heat, than the use of water whose temperature is close to atmospheric temperature and seems tepid when one drinks it or plunges the hand in it. Regardless of its excellence with respect to the ratio of substances it holds in solution, this water is dull and nauseating; it pleases neither the palate nor the digestive organs; it does not quench thirst even when it is drunk in great quantities but causes insurmountable disgust and leads to vomiting. Very cool water during the summer can be thus considered as one of the principal health necessities for populations in our temperate climates (9)."

### Groundwater is preferable to surface water

Although every now and then a spring is found whose water is not good to drink, it should not be thought that they are numerous; Mr. Héricart de Thury has been able to designate only six in France. This type of spring is very rare, and those that cause harm are even more rare; if in fact we eliminate from the list of bad springs those that are bad by chance, such as, for example, water that has traveled under harmful places, which will be pointed out in the general advice in chapter XXVII and that we know how to avoid; water drawn from wells or springs that have not been cleaned out and those exposed to the heat of the sun, it will be seen see that for every spring whose water is not good, there are in the region several hundred whose water is good or excellent. It is thus a mistake that some people claim that generally speaking river water is preferable to that of springs. This can only be true when comparing the best surface water to the worst springs.

If it is true that tastes should not be disputed and if it is true that each individual is right when he affirms that something is good or bad for him even though everyone has a different opinion, it is also true that rules should not be imposed based on exceptions, and that what most people consider to be good should be called *good*, in spite of the particular taste of a few. Here we must again interrogate authorities and the facts.

In the *Nouveau Dictionnaire d'histoire naturelle* [New Dictionary of Natural History] the article on *Eau* [Water] states the following: "The water of small streams has a muddy taste due to putrid gases that come from the slow decomposition of material it contains and that it continually provides ... A large river receives streams and small rivers that contribute water that has washed mountains, bathed prairies, stagnated in swamps, dissolved saline, earthy, and metallic substances. It travels through large cities where it serves as a sewer for their muddy and filthy streams... The horrid mixture of putrescible material, putrefying material, deleterious gases, saline, earthy, and metallic substances; these filthy streams carry this mixture that revolts all our senses… River water is dangerous to drink when it has been used to ret hemp and linen and when they collect through city sewers all the refuse from renderers, butchers, tanners, laundresses, dyers, etc.; they generally have a taste of sludge, a swampy odor due to the putrid gases resulting from the slow decomposition of organic matter they contain."

The Faculty of Medicine in Paris and a large number of chemists have stated that the Seine, which is far from being the muddiest river in France, contains putrescent substances in solution and that during the hot period it takes on a swampy taste to an unpleasant degree.

Let us now prove by the facts, generally speaking, that everyone prefers spring water to surface water.

Everyone who has traveled throughout France has contemplated with astonishment the immense ruins that the Romans built to bring spring water to all towns near which they were able to find springs high enough to transport. Most of these cities were crossed or bathed by rivers; however, for these masters of the world to obtain spring water they were not afraid to raise arches up to heights of a hundred and fifty feet, to cross these valleys, to make deep cuts in rocks and kilometer-long tunnels to go through tall hills.

These grandiose engineering works, which subsequent centuries have admired but have not known how to maintain, are all in a state of ruin today, and no city has undertaken to rebuild them because most of them could be restored only at a cost of several million or several hundred million francs. Thus the city of Metz, crossed by the Moselle and the Seille, got its water from the magnificent Gorze spring, eighteen kilometers away. A beautiful spring of Arcier, eighteen kilometers away, was brought to Besançon, a city split by the Doubs. The length and height of the ruins of the aqueduct that brought water to Poitiers offers yet another imposing aspect; however, two rivers flow through this city, the Clain and the Boivre. The city of Fréjus, bathed by one of the clearest rivers that exists in France, was given an aqueduct that got its water from the Siagne spring, at a distance of thirty-eight kilometers. The city of Arles, bathed by the Rhône, drew its water from springs located east of Saint-Rémy, twenty-two kilometers away, etc. In our days, we see that all cities, all towns, villages, and landowners who do not have spring water within reach of their houses and who have been able to bring water there, have not failed to do so even though they were abundantly provided by river and stream water. All these authorities, all these facts and many others I could cite, prove thus that generally speaking spring water is the best suited to the taste and needs of man.

Notes

1. *De aere, aquis et locis*. [Air, water, and places] [Hippocrates]

2. *De la Santé des gens de lettres* [On the health of people of letters] [Tissot]

3. *Nouveau Dict. d'histoire naturelle* [New Dictionary of Natural History], article on Water.

4. *Dictionnaire de médecine* [Dictionary of Medicine]

5. Héricart de Thury, §§ 231 and 232.

6. *Encyclopédie moderne*, art. *Eau* [article on Water].

7. *Nouveau Dict. d'histoire naturelle* [New Dictionary of Natural History], article *Eau* [article on Water].

8. Héricart de Thury, §§ 233 and 234.

9. *Des Eaux de source et des eaux de rivière* [On spring water and river water] by M. Dupasquier, doctor of the *l'Hôtel-Dieu* in Lyon, Chap. VI.

## 2.4.26. Chapter XXVI. Methods for Clarifying Turbid Underground Watercourses

Most underground watercourses become turbid after heavy rains or snowmelt. Those at shallow depth are generally more turbid. Rainwater picks up a large amount of earthy and plant materials as it flows across the ground surface; it deposits this material gradually as it sinks into the ground and if the watercourse into which it flows is deep, the water becomes entirely clarified and clear; but if the watercourse is shallow, the water arrives imperfectly filtered or not at all, and then the water moves and spreads laden with all the debris that it is carrying. This happens particularly to underground watercourses that come from regions with swallow holes; even though the conduit is very deep, the rainwater falls in, moves, and discharges without any clarification. The water may also encounter a pool of water where it can deposit a portion of the material it holds in suspension.

Underground watercourses that form and pass under woods, meadows, pastures, and other non-cultivated land, even when they are shallow, are always clear because their conduits are always the same and are washed over a long period of time, so they do not carry impurities; but those that come from cultivated land, such as fields, vineyards, etc. and that travel at shallow depths are turbid every time it rains because agriculture is the principal and usual cause of turbidity in underground watercourses.

The way to prevent this problem is sometimes obvious. If there is a free choice between two underground watercourses and it can be foreseen, based on what has just been said, that one will be muddy and the other clear, the second should be chosen without hesitation; but if a turbid spring has already been discovered and is being used by houses, I know of no other way to clarify it than to leave all the fields in its basin fallow, a method that is almost impracticable, or to clarify the water with filters.

Filtration of muddy water

Water filtration is an operation that consists of passing it through a material that will remove the refuse that it contains.

None of the research and discoveries that have been made to date to filter large quantities of water, such as would be necessary for the needs of a city, for example, offer any method that when put into practice has produced results whose value equals the costs of construction and maintenance; it would thus be useless to describe here the different filtration systems that have been proposed, almost all of which remain theoretical. I will limit myself to talking about two types of filters that are most commonly used and that everyone can set up in his house; these are stone filters and cotton cloth filters.

Stone filters

Most people who lack spring water drink water from a river, stream, cistern or a pond as nature presents them, however muddy and bad they may be. It is true that some people use filters to clarify the water but they are few in number and this method of making water potable is unfortunately not used enough. The cost of a stone filter with a sufficient capacity to provide potable water to the inhabitants of a household of five to ten individuals, ready-made and installed in place is only 10 to 20 francs, according to the region. There is almost no family that cannot obtain one and provide the small cost of its installation. We thus deplore and blame the negligence of all those who, being able to obtain potable water at such a low cost, would sacrifice the well-being and compromise the health of all the people in their households by furnishing only unhealthy and revolting water. All those who do not have potable water near their houses should thus make haste to set up and maintain filters to clarify at least the water they drink.

*Stone filters* are rocks whose structure is porous enough to let water pass through and to hold back the impurities it carries. For us, sandstone is the rock that most commonly combines these two conditions but by no means do all blocks of this rock meet these two conditions; it is only by testing that a person can determine whether a sandstone block is porous enough or too porous to make a good filter. In the same quarry, porosity almost always varies from one stratum to another, and if one or several strata provide blocks suitable as good filters, it should not be concluded that other strata form equally good ones. The composition of a stratum is generally the same along its entire length, so that if it can be determined at its outcrops that it is suitable for making filters, it can be assumed to be the same throughout its entire extent. If in the same quarry, several continuous or separated strata are recognized as being good at outcrop, it can be assumed that they will be so for as far as they extend.

In France, sandstone deposits number in the thousands, and there is probably not a department that does not have one. There must be many that would be quite suitable for making good filters but no one knows about them because no one has ever tried! Every owner of a sandstone layer would do well to dig several blocks as tests; if he succeeds and he wants to exploit the sandstone, he would make a good profit for himself and provide a great benefit for his region.

A stone filter is cut into the shape of a half-globe on the outside and inside it is hollowed out in the same shape; its thickness ranges from 4 to 10 centimeters, depending on the degree of porosity of the stone, and its diameter is about 60 centimeters. This basin is suspended at a height of 60 to 80 centimeters by placing it on a tripod of iron or wood made simply of a circle supported by three feet. This device is placed in the coolest spot in the house, for example, in the basement or in the sink, the water to be filtered is poured into the basin and a pewter, glass, pottery, or terra cotta vessel is placed underneath to catch the filtered water as it falls. Because the water falls only as drops, the operation is always slow and the longer it takes, the better filtered it is. As soon as one sees that water no longer flows through the filter, it is necessary to wash and even brush the interior of the basin. Some water ends up obstructing all the pores of the basin over time and makes it impermeable; at that point, one is obliged to replace it with another.

If the filter no longer purifies the water sufficiently, charcoal can be washed and pulverized and a layer of this powder can be placed in the basin of the filter. This discovery is due to M. Lwis who in 1790, recognized that water filtered through coal dust of charcoal not only clarifies completely but even the most polluted water almost immediately loses its bad odor and bad taste.

### Cotton cloth filters

Cotton cloth filters, although less commonly used, are the simplest and most expeditious. In a cool place in the house a large capacity vessel is placed on a base about 60 centimeters tall and filled with muddy water. A remnant or a band of cotton cloth several meters long is wetted in the water and wrung tightly to squeeze out the water. One of the two ends is placed in the bottom of the water, the cloth is passed through a small wooden crosspiece placed above the vessel, and under the other end is allowed to hang outside the vessel to one or two decimeters below its base, and another vessel is placed under this end to receive the purified water. This water rises and flows back downward through the fibers in the cloth according to the same law that makes it rise in capillary pipes. Several bands of cloth can be placed in the same vessel, if desired, and their product will increase according to their number. This process has even been used to filter large amounts of water at the same time. Here is what the Journal of Mayors reports in its 21 November 1826 issue:

"In Bordeaux, the river water contains a large amount of pure clay in suspension and of such a state of fineness that the best purification process had never been able to clarify it completely; the filters most commonly used in the capital had always failed. In 1814, a former cantor of the cathedral of this city who had become a copper foundry owner decided to solve the problem: in a shed that he built for this purpose, he hung several cotton cloths whose lower ends were immersed into water. Wood crosspieces supported the other end at a height of 20 feet, whose very end, rolled up on its supports, poured the liquid that the cloth had absorbed; the resulting water had a state of clarity superior to what had been obtained previously.

"Such is the simplicity of this ingenious method, whose results we can attest to because we were asked by a higher authority to be present for the first experiments. This success is especially irrefutable when the water contains only refuse or washing of calcareous ground instead of pure clay. We cannot recommend the use of this device too highly; it is easy to set up on all farms, and on the edges of stream, with four poles and several poles and with several ells [Fr. *aunes*] [See Translator’s Notes] of cloth so common today.

"In all purification processes, the water always loses some of the elements that make it so suitable for vital functions (oxygen). In this condition, it is dull and difficult to digest. It can be regenerated by shaking it in the open air; it is thus a mistake to close too tightly the vessels where filtered water is stored."

### 2.4.27. Chapter XXVII. How to Exploit Underground Watercourses

Landowners who have to dig for underground watercourses and build structures to preserve them are often confused during the execution of this work. The architects usually hired to direct this work rarely have experience of this type; they may be inexperienced in this area of their art. Meanwhile, without good direction some efforts are abandoned, others fail or succeed only imperfectly, and others produce results that last only a short time. Having observed these operations on many occasions, although I am not an architect, I think it necessary to discuss them with the hope that many landowners and perhaps some architects will find here precepts that will aid them in finding the greatest amount of water possible by digging and building structures with economy and solidity, preventing accidents, and correcting problems when they occur.

After seawater retreated from the continents and watercourses had established their underground conduits, all watercourses located at shallow depths and under a layer of friable soil immediately removed the small amount of material that covered them, revealed themselves, and began to flow and still flow at the ground surface. But those located at considerable depth, under hard rocks, or that were later covered again with deposits carried by landslides, flowing water, or agriculture, were never able to get rid of the obstacles that prevented their emergence from the ground; they have remained hidden and will remain so forever if the hand of man and perturbation of the soil do not expose them. Hidden watercourses are found at all depths, from two to several hundred meters and it is rare that they are found at depths less than two or three meters.

Underground watercourses are brought to light by conveying them out of the ground through conduits, by constructing fountains, ordinary wells, or artesian wells along their pathways. Each of these four processes has particular rules, the principal of which are the following:

How to get underground watercourses out of the ground

Any underground watercourse that a person wants to extract from the ground must be shallow, must be found at a depth shallow enough for a person to be able to dig to the desired point, and the water must be abundant enough for the needs of the houses it is destined to supply.

Underground watercourses at depths of less than six or seven meters are generally the only type that can be exploited because deeper watercourses involve costs that are too high.

When the passage of an underground watercourse is indicated at the bases of two escarpments that join at the ground surface or if the water flows in a rock crevice from which it cannot be removed, all that is necessary is to make a round cavity in the shape of a well about three meters in diameter on the thalweg line; but when the location chosen for digging is on a plain and the rock is unconsolidated, this simple hole will not suffice because in this case the principal underground watercourse is almost always accompanied by accessory watercourses that flow along its sides at the same depth as the principal one and parallel to the line the principal watercourse follows. Because collection of the largest possible amount of water is generally the goal, a trench should be dug across the vale, perpendicular to the watercourse, about two meters wide, and long enough to capture the largest number of water trickles. When the plain is narrow enough that a trench can be dug from one foot-of-slope line to the other, for example if the plain is only about ten meters across, the trench should extend across the entire plain, without however cutting into the solid ground or rock on the two escarpments; thus, only the transported material will be removed, at the base of which the underground watercourse is generally found.

If the plain is much wider, it is ordinarily not appropriate to lengthen the trench much because it would become too costly and with more distance from the principal underground watercourse, trickles are less abundant. However, if it is necessary to supply a large population and it is obvious based on the extent of the basin that produces the underground watercourse that there is no watercourse abundant enough on the plain and that the underground watercourse moves in a layer or in separate trickles, a trench proportional in length to the quantity of water needed should be dug.

If it is necessary to dig at a point where the invisible thalweg corresponds to the visible thalweg and the visible thalweg has a watercourse during part of the year, a diversion channel should first be dug to direct the surface water away from the edges of the hole being dug to prevent the watercourse from disturbing workers during the digging and to prevent later mixing of its water with the underground watercourse. The beginning of the diversion channel should be several meters above the excavation, have enough capacity to receive the entire watercourse during the largest floods, pass at least two or three meters from the excavation, and extend far enough downstream so that the temporary watercourse can never flow into the excavation. If the temporary watercourse has a channel, a very solid barrier should be built at the beginning of the diversion channel and the old channel filled with the excavated material.

The trench [for capturing the underground watercourse] must be perpendicular to the direction of the watercourse. Digging must be almost vertical. If the walls threaten to cave in, they should be propped up with planks leaned against the rock and maintained in place by beams leaning against the opposite side, and care must be taken to place the excavated soil more than two meters from the edges of the trench so that its weight does not contribute to landslides. Digging should not stop at the depth where water appears because even if the underground watercourse can be seen flowing into the bottom of the trench from bottom to top or even horizontally, it is highly probable that some of the water continues to follow its normal conduits underground. Digging should thus continue until the principal underground watercourse and the water veins that accompany it make a little waterfall of two or three centimeters in the trench; this shows that no more of the underground watercourse remains below.

When the underground watercourse is strong and the abundance of water prevents deeper digging, rather than removing water with vessels or pumps, a trench should be dug downstream to cause the water to flow during construction and then conduit pipes should be installed.

Once the depth of the trench is determined and the principal underground watercourse and the adjacent water trickles are obvious, the bottom of the trench is sloped to capture and collect the water and to cause all the water to go to one end; or two opposite slopes are made to force the water go to whatever other point at the bottom of the trench is desired.

On the bottom of the trench and along the entire length, a dry-rock aqueduct should be built of slightly cut rock, 30 to 40 centimeters wide, 40 to 50 centimeters tall, and this aqueduct covered with solid slabs. The aqueduct should be built with dry rock to allow underground watercourses to enter freely.

Once the aqueduct is built, it is necessary to fill the entire bottom of the trench starting from the top of the slabs with loose stones until they reach a third to a half of the depth and to fill the rest with the material that was removed. This lining with stones serves: 1st) to collect the trickles of water that may be located higher than the principal watercourse and to facilitate their entry into the aqueduct; 2nd) if later a slab is broken or several parts of the aqueduct walls are demolished, the stones will continue to transmit water to the trench outlet; whereas if one filled the trench only with soil, it would compact later and would prevent the upper water trickles from falling into the aqueduct; and if the aqueduct collapses, the dirt would fall into this void, would stop the water, would prevent it from arriving at the trench outlet, and would force it to follow its old conduits.

When adding the loose stones and replacing the soil into the trench, a small well or manhole should be made at the point where all the water arrives and where it is supposed to enter the aqueduct; this well is built on top of the ground and covered with a slab. This well or manhole provides a means for the water to incorporate air, which is needed for water to move within pipes; without this precaution, the water would arrive at the fountain only in sporadic gusts and sometimes it would not arrive at all. This little well also serves to reject water that cannot enter the pipes during heavy rains.

Those who are not limited by strict economy in this work can build two dry cut-stone walls from one end of the trench to the other, 80 centimeters apart, two meters high, instead of the narrow and low aqueduct we just talked about. Solid slabs or a roof can be placed on the two, dry cut-stone walls. This gallery makes it easy to repair the walls and to remove any earth or sand that the underground watercourse might transport there.

A dam cannot be built at the bottom of the trench or even in front of the outlet of an underground watercourse to force it to rise without the risk of losing it because every time a person dams the outlet of a spring, the water is driven back into its rising conduit and if by misfortune it finds a small lateral outlet or crevice it will slowly enlarge it and end up flowing through it; one can remove the dam, but the spring will not come back. In my travels, I have seen many places where very beautiful springs have been lost through this imprudence. Thus, it is best to take springs at the level of their outlet and convey them to a point they can reach.

As soon as it is determined that the underground watercourse is sufficient and of good quality, a trench is dug downstream to lay the pipe. The trench and the pipe must begin at the same depth as the little well and decrease in depth as they move away from it with a slope of at least 30 centimeters per 100 meters. The first pipe placed at the bottom of the pit must be a flask of lead or copper, perforated by a large number of small holes to let the water pass and to prevent any foreign matter from entering the pipes. When the pipe approaches the ground surface, it should be placed underground at a depth of about 60 centimeters for the rest of its path because when conduits are placed too near the ground surface the water heats up in summer and makes it undrinkable and in winter it freezes, ceases to flow, and often causes the pipes to crack. On the other hand, when pipes are placed too deep, they are costly to maintain. For water to spurt it must have a forced pathway in the part of the aqueduct near the fountain or water spray and it is necessary to use more solid pipes in this location. Thus, when the slope of the land permits, the slope of the aqueduct should be arranged so that the part into which the water is forced is as short as possible so that the water is subject to pressure over the least length possible; this also minimizes later expenses for maintaining the aqueduct. As much as possible, sudden turns should be avoided or at least they should be lengthened to diminish the tightness; when the aqueduct follows a road, it is necessary to avoid placing it under ruts formed by the wheels, so that it is not crushed.

The pipes used for conduits are normally lead, cast iron, terra cotta, or wood.

Whatever material the pipes are made of, they must have a diameter and thickness proportional to the quantity of water to be conveyed. In addition to what will be said on the various ways of adding them, all joints must be caulked with mastic composed as follows: half Pouilly cement, one fourth hydraulic lime, and the other fourth well-pulverized tile or brick fragments. This mastic goes bad like plaster and must be used as soon as it is prepared.

*Lead pipes* are the most convenient, most solid, and most durable. They are molded or soldered and they can be given the desired length and thickness. They can go up and down and bend without being damaged. The lifespan of a lead pipe of average thickness is about 300 years. They cost the most to purchase, it is true; but they are also the least costly to maintain, and after their oxidation, they are still worth about half of their purchase price.

The ordinary length of *cast iron pipes* is about two meters and they are often much longer. Some have a wider diameter at one end and a narrower diameter at the other; one pipe fits inside the other about a decimeter. Others have the same diameter throughout, are placed end to end, and their joint is covered with a sleeve; others have rims and are added end to end with a screw and nut, and between the rims are placed washers of leather or felt. Their average lifespan is about one hundred years.

*Terra cotta pipes* cause the least degradation of water purity. They are two to four feet long and their lifespan is highly variable. Some are made in the shape of a truncated cone and the thin end of one is placed inside the large end of the other; others have one wide end and a thinner end and they fit inside each other about a decimeter.

*Wooden pipes* are tubes about two meters long that are perforated along their axis from one end to the other. Long iron augers of different shapes and thicknesses are used to bore them. The pipes are assembled by order of size. They are joined either by increasing the opening of one and thinning the end of the other enough so that they fit together or they are placed end to end and are joined by an iron socket about a decimeter long and about three or four millimeters thick; this socket has sharp edges, a diameter a bit larger than the interior diameter of the two pipes that it is to connect, and it is driven into each one by force. Wooden pipes are the least costly to build but the costliest to maintain. They crack or rot in a few years, especially when they are empty; they also cause the most deterioration of good water.

Some people have tried to use zinc pipes but their oxidation is so rapid that after just a few years they can no longer be used.

To clean a conduit that has continuous slope, the lowest pipe is removed, which is also the pipe closest to the spray fountain [Fr. *jet d'eau*]; the upstream pipe that remains in place is plugged with a wooden plug with tow or oakum stuffing attached; the conduit is allowed to fill with water along its entire length and until it fills up to a certain point the well that the water comes from; then the plug is removed and the water rages downward, carrying away everything that might be found in the pipes. If the conduit crosses a vale with a slope and counterslope, first all faucets and fountains that the conduit serves are closed; the whole conduit is allowed to fill with water, and the plug that stops up the opening on the side of the pipe located at the lowest point of the valley is removed; or lacking an overflow pipe, the one at the thalweg of the vale is removed, and the water, flowing down both sides to this opening will push all the mud found there out of the conduit. Conduits must be cleaned at least once a year.

Any construction that pours out water carried by a conduit is called an *artificial fountain*. This type of fountain has no definite shape or dimensions. Each person can construct and embellish his as he wishes. However, I believe I should add for people who have no other water nearby than that of a spring that is brought to their houses, that it is important to build a trough for animals around or at the side of the fountain; immediately below the trough, a wash basin, and below the wash basin a vast pond to use in case of fire; and finally, the water that leaves the pond can be used to irrigate gardens or pastures. The watering trough and washbasins are paved with slabs that lie flat and are enclosed with other slabs placed on end and clamped together. All joints should be well cemented.

### Fountains

Ordinarily only cities, communes, or wealthy individuals can afford an aqueduct to convey water to their houses. Almost all rural populations supply themselves with an underground watercourse through fountains dug and built in place or from wells. When for some reason or another, a spring cannot be brought from afar and near the house there is one that issues naturally from the ground or an underground watercourse discovered at a shallow depth, a fountain is built on the watercourse itself. This fountain consists of a basin covered with masonry that holds in reserve a certain amount of water produced by the watercourse. This basin should be dug deeper than the level of the watercourse for two reasons: because some of the water might be left below the bottom or because it is always advantageous to have a considerable amount of water in reserve. Because fountains are not very deep, they are almost always built square in shape without fear that the walls will crumble and their dimensions are made proportional to the desired quantity of water. The walls must be built with dry rocks to just above the ground because mortar would prevent the water from reaching the basin; these walls must be continued to 5 or 6 feet out of the ground and the latter part should be built with mortar. The fountain is covered with a roof or with slabs and a door is built on the front. When building fountains, the door should not be placed on the south side because I have seen many fountains that contain tepid and disgusting water although the springs are excellent, for the sole reason that on hot days the water is exposed to the heat of the sun.

If the fountain does not provide enough water several years after it is completed, and it is observed that water trickles flow alongside, they can be collected by digging a pit from the fountain to these trickles; the pit should be sufficiently deep, inclined toward the fountain, and perpendicular to the watercourse. The bottom of this pit is filled with loose stones up to a height of two or three feet and finished by filling it with the material that was removed. If this first pit is insufficient, and there are still other water trickles visible on the opposite side, another pit can be dug there and filled like the first.

## Wells

A *well* is a deep manmade cavity covered with masonry and used to provide water. Most of the inhabitants of France drink water that comes from wells.

Whenever a spring cannot be brought to the vicinity of houses because it is not high enough, not deep enough, too insufficient, or too far away, located on a land surface [Fr. *terrain*] that is too flat, or the landowners do not have the means to pay for a water conduit, a well can be dug on an underground watercourse that is recognized as the closest, the most abundant, and the shallowest. An underground watercourse that would be too meager to maintain a spraying fountain can provide all the needs of a large number of houses if it is collected in a well as in a reservoir because the water collects there continually and withdrawal is far from continuous.

The center of a well that a person undertakes to dig must be on the line that the watercourse follows underground.

Wells are ordinarily dug with a diameter of three to three and a half meters. As soon as the excavation reaches a depth of several meters, a floor is built just above the ground on which a wheel with a solid cable and pail is set up.

When the digging has reached the bottom of the friable ground and encounters rock, it is first necessary to clear away debris, and if the rock is the type I have spoken of, that is, that lets the water sink to extraordinary depths, it is necessary to abandon the enterprise without hesitation. If the rock is of the type that is indicative of water, based on its nature and disposition, it is necessary to examine what type it is and determine whether the strata are inclined or horizontal. If the rock strata are inclined and if the line of intersection of the two stratifications passes through the middle of the cavity, one continues to dig to the depth of the spring. If this line is found not to pass through the middle of the cavity, it is necessary to enlarge the hole until the intersection line is located in the middle, because this line is the true thalweg of the valley and the underground watercourse always passes under the thalweg.

After reaching the rock, if it is obvious that digging has landed on one of two inclined planes that form the base of one of two escarpments, a small gallery should be made in the downstream direction of this plane to determine the distance to the base of the opposite hillslope. If the base of the opposite hillslope is only a meter or two from the cavity already made, it is necessary to enlarge the cavity sufficiently so that the line of intersection is located at the middle and to continue going deeper while keeping the excavation as much on the base of one rock as on the base of the other. If the base of the opposite side is located more than two meters from the cavity, it is necessary to dig another hole and to locate it in such a way that it leans as much on the base of one hillslope as on that of the other; thus, when the excavation reaches the rock, it is more obvious whether the indication that was made on the transported material is the real thalweg or not; and if not, it can now be seen how to rectify it so as to not miss the underground watercourse.

When the cavity being dug encounters rock with a horizontal surface and strata, digging should continue there at that location because there is no reason to believe that the underground watercourse may pass alongside.

If a vertical crevice is found whose direction is the same as that of the vale, digging should continue following the crevice and keeping it in the middle of the excavation, even if it is necessary to enlarge the excavation or make a new one.

When digging in primitive rocks where the rocks have no regular stratification, if the thalweg is well characterized, it is enough to place the middle of the excavation on its trace without any regard for the various directions that fissures in the rock may have, because if fissures that lead the water out of the excavation are observed, at greater depth very likely cracks will be found that will collect water.

In any excavation whatsoever, if the rocks cannot be lifted with tools, they can be blasted with powder without any fear of compromising the groundwater.

Once the underground watercourse has been reached, digging should not stop, but continue one to two meters below it and even more if the water needs are great and the underground watercourse is small so that if the water reverts to its old conduit there will always remain in reserve a certain amount at the bottom of the well. I have seen wells that were traversed at the bottom by beautiful underground watercourses that could not be accessed at all because they arrived from one side and left by the other through the ancient conduit without ever rising a decimeter.

Another problem with a well that has not been dug below the underground watercourse is that some of the water may pass below the base of the well. So many wells are insufficient because digging was stopped at the appearance of the first underground watercourse; these wells would be wildly abundant had they been dug one meter deeper!

If the rock is unconsolidated and threatens to cave in, the walls of the well are shored up with wattle during digging. This wattle consists of placing sticks in a vertical position and at a distance of about a third of a meter from each other around the well and against the walls. The well digger then intertwines long, strong, and flexible canes and places them one by one downward and then weaves them alternatively behind and in front of each stick (1).

Wells should be round in shape because that is the most solid shape, at least a meter in diameter inside the well and more if possible, the rock should be cut in wedge shapes, and walls should be built of dry rock. The walls of square wells are supported only at the corners and can yield easily to the pressure of the ground and cave in. Mortar or cement placed between the rocks or bricks used in the construction of wells will prevent water from flowing in and the water that enters will have a bad taste after a while.

However, it is good to begin to put mortar in the masonry when the masonry is no farther than a meter above the surface of the soil and to put it also on the edge or external masonry, which should be about a meter high.

Machines for drawing water from wells

The machines most commonly used to draw water from wells are: pumps, seesaws [Fr. *bascule*], wheels, and pulleys.

Of these four machines, the *pump* is the best because it is the easiest to maneuver and it raises more water in a given time; its disadvantages include the fact that it is the costliest to set up and often breaks down as a result of simple usage, howsoever solid its construction.

After the pump, the machine that can be built at lowest cost and that can withdraw the most water from the well in the least amount of time and with the least amount of effort is the *seesaw*. It consists of a forked post placed near the well and a beam [Fr. *balancier*] made of a simple tree branch whose length is proportional to the depth of the well. This beam is balanced in the fork of the post and held there by an iron bolt that can be used to move it up or down as desired. A cord equal in length to the depth of the well is attached to one end of the branch and the other end of the cord is attached to a pail.  To lower the pail into the well to fill it, a person pulls the cord to lower the end of the branch, and as soon as the bucket is filled, the beam, suitably loaded on its fat end, raises the bucket to the height of the edge. In place of the cord, some people have used an iron chain, which is much more durable; others have used a simple pole that has a socket with an iron ring at each end. Unfortunately, the seesaw can be used only in wells less than seven or eight meters deep.

Anyone who wants to set up a *wheel* [Fr. *tour*] to draw water from his well must build a structure six feet above the ground with a window-shaped opening on the front and a cover on top. The wheel or winch [Fr. *treuil*] is a large wooden cylinder shaped like a roller, whose length is equal to the diameter of the well; on each end, it has an iron bearing that is pushed into the wall and, near one of its ends, four long dowels or levers used to turn it. This cylinder is placed horizontally at the height of the shoulders of the person who is drawing water.

Rather than building a well-house two meters tall, some people finish the well with an ordinary edge and they place two wooden supports on each side, consolidating each of them with two buttresses; these supports are perforated near the top to place the bearing and they are held in place by a crosspiece placed above the wheel and solidly attached to the supports. Others make the supports out of iron; their foot is forked and embedded in the edge. In place of dowels for turning the cylinder, an iron handle is often used; its shaft passes through the center of the cylinder to serve as a bearing and its elbow turns outside the wall or support. In some systems, the end of a cord is attached to a dowel; the cord length is equal to the depth of the well and its other end is attached to a bucket. When a person brings up the bucket from the bottom of the well, the cord rolls around the cylinder and it unrolls when the bucket is lowered. In place of a rope, an iron chain is often used, which lasts much longer.

A *pulley* is a round and flat object that turns on an axis called the bolt; it has a groove carved into its external circumference to accommodate a rope. The pulley turns inside a part called the shell. The pulley and shell are made of iron or wood. The pulley must be attached to the middle of the well and at the height of the head of the person who will draw the water. A person has to use force equal to the weight of the container to raise the bucket, but this force is applied so advantageously that the weight of his body aids the movement of his arms.

Sometimes two buckets are put on a wheel or on a pulley with a turning shell; one bucket is pulled up full while the other goes down empty. This method has the advantage of saving half the time and a portion of the tensile load.

The wheel and pulley have the advantage of being applicable to all types of wells whatever their depth.

It is still possible to find many villages with common wells that lack any type of mechanism for drawing water and whose inhabitants have never known or wanted to get together to set one up. Each person goes to the well carrying his bucket, his rope, or his pole armed with a hook and once he has obtained his water he carries it all back home. Some people draw water by rubbing the cord against the edge of the well, which causes fatigue for the person and rapid wearing of the bucket, the rope, and even the well edge; others stand up on the edge at the risk of sliding into the well or being pulled there by the weight of the bucket. This condition of things is fit for barbarians or the first people who inhabited the earth.

A solidly built well can last for many centuries. Near Aix in Provence I have seen wells built by the Romans that are still in a perfect state of preservation. Wells should remain continually open. The more water that is drawn, the better the water is because drawing water keeps the flow going. Those who top off the well with a dome and a door on the front should leave an opening above so that unhealthy vapors can rise freely. Wells should be cleaned at least once a year; when this operation is neglected, the well water often acquires an unpleasant taste and is sometimes harmful.

A well that is dug for setting up a noria, or bucket water wheel [Fr. *roue à godets*], should be dug and built like an ordinary well but it should be oval in shape rather than round; the inside measurements after it is built should be a large diameter of at least two meters and small diameter of one meter and a half. Noria wells are known only in the Languedoc and Provence where they are used to water large gardens and even prairies; they should be used in all regions that need irrigation that cannot be accomplished with surface water [Fr. *eaux courantes*].

### General advice on fountains and wells

In selecting the location for a trench, fountain, or well to supply houses, it is necessary to pay close attention to ensure that the underground watercourse chosen as the supply does not pass under a cemetery, dunghill, pigsty, cowshed, cesspool, sewer, pond, swamp, or gypsiferous, peaty, or silty ground. Care should also be taken to not place the trench or the well too near these harmful places because some ground is so permeable that the bad water found there will infect springs that pass at distances of more than ten meters from their margins. How many cities and villages I have seen that had a very abundant water supply at the bottom but whose water was not potable because it passed under houses! If the trench or the well are exposed to receiving unhealthy surface water that flows only temporarily or for a short while, a small diversion canal can be dug and maintained that starts at the upstream thalweg, passes two or three meters from the trench or well, and comes back to the thalweg downstream; or two small pits can be dug that begin at the thalweg upstream, pass at the same distance, and rejoin the thalweg downstream. A well can also be protected from bad water that travels on the ground surface by digging a circular pit two or three feet wide around it and to the same depth, and filling this pit with a thick impermeable lining that surrounds the edge up to a suitable height. This impermeable lining is made of clay deposited in thick layers two or three decimeters thick; it is necessary to wet it, mold it, and tread upon it.

Those who have to dig in rock can do their work in any season but those who have to dig in unconsolidated ground should work only between the months of April and October because anyone who digs in winter exposes himself to landslides that are usually very dangerous for workers and very costly to correct. He may also find false watercourses that flow only in winter and produce nothing in summer.

As soon as the trench is dug and it is determined that the watercourse is sufficient, all the work necessary to bring the water to the ground surface should be completed quickly; a person who has just dug a well should, in the same case, build it without delay, because leaving an excavation open and not shored up exposes it to landslides.

## Artesian Wells

For many years, *artesian wells* were known only in several districts of Artois from which they derive their name. But since 1816 they have been successfully tried in some of our departments, in several European countries, and even in other parts of the world.

This type of well, their depth, and the manner they provide water have nothing in common with ordinary wells.

An artesian well is a simple round hole made in the earth with a drill; it is ordinarily from one decimeter to one and a half decimeters in diameter, and from thirty to three or four hundred meters in depth and sometimes more. When the drill has reached the depth of the underground watercourse, it is pulled out and water rises up the hole and flows, sometimes above the ground, sometimes to the surface, and sometimes the water remains below the ground surface. Those who have not seen this drill and would like to know about its parts and the method of using it should consult the manual entitled: *De l'Art du Fontainier-Sondeur* [The Art of the Well Driller] by Mr. Garnier, Chief Engineer of the Royal Corps of Mines, 1 vol. in-4°; and the *Guide du Sondeur* [Driller's Guide] by Mr. Degousée, engineer and well driller, 2 vol. in-8°.

For an underground watercourse to flow out of a drill-hole, the following are necessary: 1st), the land surface that absorbs the rainfall and provides the watercourse are higher than the point where the drilling is done; 2nd), the strata in which the water moves has the ordinary inclination of watercourses and is eminently permeable, such as layers of sand, gravel, pebbles, rocks with loose texture and those that are fissured in all directions; 3rd), this permeable layer is enveloped along its entire length by impermeable layers located on top, on the bottom, and on the sides; 4th), the water has no outlet toward the bottom of this stratum or only very insufficient outlets where the water can exit only with difficulty.

Rainwater that falls on outcrops of the permeable layer moves downward as in a vast inclined conduit and fills all its interstices and follows it in all directions. The artesian drill pierces the impermeable layers and when it reaches water in the permeable layer, it opens an outlet through which water rises wherever the surface of the water column, which extends downward into permeable rocks, is at a higher level than the orifice of the borehole; water flows out of the ground and rises to the height of this surface. This water rises in the borehole by virtue of the tendency of liquids to seek equilibrium in vessels that are in communication; and it behaves like water passing through a conduit that rises toward its outlet after a continuous and very prolonged descent.

An artesian well produces a large quantity of flowing and good quality water; it is the best one can hope for in springs. When it provides water to a large city, its value is inestimable.

While recognizing the innumerable advantages and the pleasures of all kinds that these wells offer, I will not imitate some authors who encourage everyone to undertake them by citing in detail all that have been successful, but they do not publicize those that have not succeeded or the great expense that some have occasioned.

Not wanting to encourage or discourage anyone, I think I should state that the disadvantages of these wells are the following: 1st) they succeed only rarely; 2nd) they are too costly; there are very few villages or private persons who can risk 100 to 200 thousand francs for such a well; 3rd) they succeed only at certain sites that are generally rare and very restricted; 4th) the ignorance of the depth to which it is necessary to go to obtain flowing water (2), and as a result the expense to which one commits; the poorest person, just like the richest person, can find himself incurring an expense of several hundred thousand francs.

No one should thus be astonished that in spite of all the encouragement offered by the government, about two thirds of departments have not tried a single artesian well or that the number of these attempts has been continually decreasing to the point that, for some years, neither wealthy individuals nor large cities dig them anymore. I restrict myself here to reporting facts that I have seen, leaving to each the duty of drawing the consequences he judges appropriate.

In the forty departments that I have studied in the greatest detail, I have encountered nineteen towns where an artesian well has been dug to a depth of forty to one hundred fifty meters. At Elbeuf I saw one that had just been finished and that had succeeded perfectly; another at the Grenelle slaughterhouse in Paris that was five hundred forty-eight meters deep and cost 403 thousand francs. On the Saint-Sever Square in Rouen, on the Saint-Ferréol Square in Marseille, and at Béchevelle in Médoc, I saw three other artesian wells that had each cost 15,000 to 40,000 francs, each producing a small trickle of water that flowed to a height of two or three feet above the ground through a faucet thinner than the little finger. In the other fourteen locations, which I abstain from designating so as to not tarnish the reputation of those who have advised and undertaken these wells, the wells failed completely after expenses of 20,000 to 130,000 francs.

In examining the fourteen artesian wells that did not succeed, I noted that the locations of all of them were selected by chance, and that in choosing their locations, the only guide was convenience, because all of them were located at the high point of the place and in the most convenient position possible.

If geologists examined the nature of the surrounding ground prior to starting the drilling, none of them considered either the configuration of the ground or the inclination of the interior strata, which are the two principal and the most certain indications that one can have in any search for underground watercourses. I have been called to cities five times to decide if at a given point, which was always the highest point of the city, an artesian well would likely succeed or not, and every time, after studying the rocks, I have been obliged to answer in the negative. I keenly regret not having had the occasion to indicate a certain number of artesian wells based on my theory and give here an account of their results. I sincerely believe that these wells thus indicated would have succeeded in more or less the same proportion as the thousands of excavations that I have done.

One has only to read Chapter XVI for a discussion of all the criteria for choosing a location for ordinary excavations and to use the same criteria for choosing the location of a borehole. There is, however, a difference to keep in mind; to provide enough water to a well or an ordinary fountain, a small underground watercourse will suffice and this small underground watercourse can form in a basin with an area of several hectares, whereas an artesian well, which should be considered only for a large underground watercourse, requires a basin that is two or three leagues long, at least, and a league wide. I summarize by saying that *the borehole must always be placed in a valley or a large vale and on the line of the underground thalweg*. Off this line, a person will find only the deviated watercourses that we have discussed, which flow under hills and give no outward sign of their presence. To expect to find watercourses outside of thalwegs is to count on the exception and not on the rule.

The rock types that I have designated as unfavorable for the discovery of ordinary underground watercourses are also unfavorable for artesian wells; for example, in cavernous limestones, it would be hard to find an underground stream that flows in a cave and then put the drill into this water; the water will not forsake the free course it finds in the cavern to throw itself toward the roof, enter the borehole, and flow out of the earth.

Notes

1. Failure to take this precaution has caused the death of numerous well diggers throughout history and in all countries; others have been buried alive for several days. Even if these serious accidents do not happen every time that a well fills with landslides during digging, the hole has to be dug again and its diameter enlarged, which triples or quadruples the original digging costs. Many landowners become discouraged by the expenses they incur to fix this mistake and give up on the incalculable advantages they would have if they had an underground watercourse!

2. Every time an artesian well has been started, prognosticators have arrived in the hundreds to predict the depth of the water layer, and there have been one hundred different predictions: among them one has been found to be almost exact, which is normal. As soon as the author begins to proclaim loudly the correctness of his forecast, the other ninety-nine fall silent. But can anyone be cited who has guessed successfully and consecutively three or four times? Consequently, the most instructed and the most prudent have openly recognized their powerlessness and have abstained from any decision in this regard.

### 2.4.28. Chapter XXVIII. Underground Watercourses that Appear Late or Not at All

Most indications made on the basis of my theory have left no doubt about their complete success after the excavations were finished; however, from time to time some wells or trenches have not shown satisfactory results immediately after their excavation but showed the desired success several months later. It is often observed that when an underground watercourse appears in a new excavation, only a small amount appears at first; whoever digs during drought ordinarily finds very little water and sometimes none at all. Only the long and heavy winter rains can open and enlarge underground water channels or water veins that pass near new cavities; and when these passages are opened, water continues to flow and its volume continues to increase for four or five years. Because the true result of a new excavation can be determined only after a winter has passed, he who is not satisfied at first must leave it in the current state until the following summer, taking care to prop up the walls if there is danger of landslide. If some permanent water trickles appear the next summer, success is assured and the construction should be done as prescribed in the previous chapter. If there is no water, it is appropriate to dig a bit more deeply because the depth estimate can sometimes be wrong, as we shall see below. If with increased depth and the rain of another winter, water does not flow at all in the excavation, it becomes evident that an error that is impossible to avoid in every single case has occurred.

To determine whether the first water to arrive in a new hole is rainwater or an underground watercourse, the following experiment is done; on a summer day when it has not rained for several weeks, all water should be removed from the hole. If at the same time the next day no water is found, it is proof that the water removed the previous day was only water that had accumulated during rainstorms. If the next day at the same time, a small quantity of water is found, it should be removed completely. The following day, the same procedure is followed; and if in the following few days, a small quantity of water is found in the well, this water is evidently the daily product of an underground watercourse that arrives through one or more openings or dispersed in the ground. It arrives through countless small veins. At the beginning, this product is often meager;

sometimes it even stops at the height of the first drought; however, once it has persisted for several weeks, in a few years it will ordinarily become permanent and increase considerably.

## Failures

I just said that it is impossible to avoid committing errors in indicating underground watercourses; in fact, geologic data, true in general and in the great majority of cases, is always in the category of high probability; it cannot be considered as demonstrated truth and exempt from all exceptions. After the most attentive examination of the ground surface, the most skilled geologist does not always and everywhere know exactly the constitution and arrangement of the interior; this is because under a ground surface that is very regular, there may be disorders and undulations that display no indication on the outside. The disorder of the rock types necessarily causes disorder in the flow of the underground watercourse that it contains and any disorder in the water flow, which cannot be anticipated, ordinarily results in failure. Here are the principal causes of errors that can be committed in the indication of underground watercourses, which are not indicated by any external sign:

1st) An impermeable layer of rock or soil sometimes spans the underground thalweg; it forces the watercourse to deviate and move around this obstacle or the watercourse divides into two branches and leaves an island between them. If a person digs a little beneath this deviation before the place where the watercourse rejoins the thalweg, he will not find water.

2nd) When there is a crevice in the thalweg of the impermeable rock that supports the underground watercourse and the crevice lets the water descend to an extraordinary depth and if a person digs atop this crevice, the watercourse can no longer be found at the presumed depth.

3rd) The underground watercourse is sometimes intercepted above the point where the excavation is made and brought by aqueduct to a house or into a meadow to irrigate it; this deviation of the watercourse, being done by the hand of man, cannot be known except by information that a person should carefully gather from the inhabitants of the area.

4th) The difficulty of recognizing the underground thalweg in some low plains, even though the plains are inclined downstream, because the plains are perfectly smooth from one foot-of-slope line to the other and show no vestige of the thalweg.

5th) Perturbation in the lower strata by explosions of underground gases although the surface strata have remained intact. These abnormalities are more numerous than one commonly believes (1).

6th) Although the land surface where the excavation is done may be very regular, if upstream and nearby there is an old uplift or subsidence that has disturbed the stratification of the layers, the groundwater will follow a disordered pathway and will not ordinarily return to the thalweg for some distance after the perturbation.

7th) If the excavation is located slightly beneath a tufa deposit. The spring that formed it and that continues to enlarge it, is constantly obstructing its passage and does not follow the thalweg at all.

8th) When soil or stones fall into the conduit of an underground watercourse in large enough quantity to obstruct it, the water is retained upstream and flows into the first lateral crevice or crack that it finds. The same thing happens when the underground watercourse carries mud that accumulates at a point in its natural conduit and that ends up obstructing it. Consequently, in most indications that have not succeeded for me, we have found highly regular groundwater conduits with very smooth walls half full of washed sand; this is obvious proof that an underground watercourse has flowed through these conduits in the past and that they have been deviated by one of the causes already discussed.

It is thus certain that an underground watercourse can change conduits but it is also certain that the watercourse cannot be destroyed; and that even when it is lacking, its presence near the hole that has been dug on the basis of the information in this book is always ensured. Coming back to excavations that did not succeed, many times I have had total success by enlarging the excavation only two or three feet on one side. After an excavation has been completed it can be seen clearly whether the underground watercourse is on one side or if it is still deeper than the hole one has dug.

But one might ask, since there are chances of failure in the search for underground watercourses, is it prudent to risk the expense of excavation?

If prudence consisted of undertaking only that which we know will infallibly succeed, we would undertake nothing because almost all of what we do is accompanied by some chance of failure. Thus, the farmer laboriously prepares his land and entrusts precious seeds to it without being sure of harvesting; the father of a family spends great sums, sometimes even beyond his means, to educate his children, without knowing whether the children will draw any advantage from the instruction. The person who undertakes a lawsuit or the lawyer who defends him are never well ensured of winning; a purchaser may be mistaken about the quality and the price of the merchandise; all business people risk capital, etc.

Thus it is not because of the possibility of failure in an enterprise that we should abstain from it. Prudence counsels that before we commit, we carefully examine the advantages and disadvantages, that we weigh the probabilities of success and failure and determine that the laws of the advantage to be gained is of a value incomparably greater than the expenses they expose us to, and that the chances of success are much better than the chances of failure. Prudence advises that we act as if we are ensured of success.

Thus any landowner who has no water nearby, who sees that groundwater near his door would be worth ten, twenty, or thirty times the sum that it might cost to build a well, and who knows for example that out of ten, twenty, or thirty attempts there is only one failure, he must without hesitation conduct the work necessary to have a water supply, if he has the means to do so.

Before beginning, he has only to count the hours and the quarter hours that his servants and beasts lose every day going to get water and multiply these hours by three hundred and nine workdays of the year; he will be astonished at the number of workdays they lose annually and the sum of the number of days, even estimated at the lowest possible price. For example, a person who goes to draw water at a distance of five minutes, who consumes six buckets per day for the needs of his household, and who uses a servant who costs one franc a day for this purpose, spends at least 30 francs per year to transport this water because each round trip takes ten minutes, the six trips take an hour; this hour is one-tenth of his daily work and costs 10 centimes, these 10 centimes spent each of the three hundred nine workdays of the year, add up to 30 francs 90 centimes. If the same landowner has ten work animals whose daily work is worth 10 francs and he is obligated to drive them to water twice per day with each trip taking about a quarter of an hour, these ten animals lose a half hour, which is worth 50 centimes, every day; these 50 centimes lost every day of the three hundred and nine workdays of the year adds up to 154 francs 50 centimes; added to the other 30 francs 90 centimes this equals a total of 185 francs 40 centimes. This annual expense represents a capital of 3,708 francs [Paramelle multiplies 185.4 francs x 20 = 3708 francs. Perhaps for 20 years? – tr. note], which is the real value of groundwater that a landowner could have near his door or of any underground watercourse that he could find five minutes closer than the water source he has. We do not count the moments that are lost at the fountain because they are the same regardless of whether it is near or far.

Such are the expenses of an ordinary rural landowner who seeks water at a distance of only five minutes. This annual expense increases in proportion to the distance of the water and of the number of domestic animals; for a very large number of landowners the cost may be double, triple, tenfold, etc. because their water sources are located at distances of ten, fifteen, and fifty minutes. But if a village or a city is going to supply itself with water at a distance of five minutes, the expense increases proportionally by the number of houses and domestic animals that are maintained, which it will seem incredible to those who have not made these calculations. How much greater this cost will be if the place for drawing water is located much farther away!

By making similar calculations the advantages provided by a good nearby water source can be compared with the modest sum it costs to develop it. This sum, which is ordinarily 10 to 200 francs, is the only one that is potentially risky because the expenses of construction or of piping are made only after the quantity and quality of the underground watercourse are assured, so these costs do not pose a risk. Seeing that the costs engendered by a distant spring show the true value of groundwater available near houses, a value which is tenfold and often hundredfold of what it costs, all wise men should dig with confidence and perseverance; and it should be kept in mind that numerous excavations have failed only because of unwillingness to dig one or two feet deeper. If a first attempt does not succeed, a second can be tried at a different place; when water that is absolutely necessary is being sought, it is necessary, as Héricart de Thury said, speaking of artesian wells, *to be driven by the firm will to do it and accomplish it*.

Note

1. "Violent earthquakes shake up an entire region, break up the strata, and produce cracks. There is no mountain chain that has not experienced shaking caused by earthquakes." La Métherie, §§ 1218 and 1423.

### 2.4.29. Chapter XXIX. Ways to Compensate for Lack of Groundwater

Old fortified cities are usually located on hilltops with steep sides [Fr. *cimes escarpées*]. Towns, villages, hamlets, and country homes are generally built on hillocks or on the crests of hills [Fr. *arêtes de collines*] and other high places to have nice views and pure air, but these two advantages are usually accompanied by the difficulty of providing underground watercourses, which as we have seen are found primarily in depressions [Fr. *bas-fonds*]. It could be said these locations were chosen expressly not to have water nearby. The closest water that can be found is often located at a distance of several hundred meters and at the base of long and steep escarpments. Consequently, when a person plans to build a new house in open country, I strongly advise to begin by looking for and finding an underground watercourse to use and to site the house near it because everywhere that a man can have an underground watercourse at his disposal, he will prefer it because it is the most pleasant and the healthiest to drink.

Although for every house it is possible to find an underground watercourse by going several hundred meters and digging to some depth, these two disadvantages are sometimes so great that water that is inferior in quality but convenient is used. Even if it is acceptable to go find the small quantity of spring water that people need at some distance, it is always beneficial to have water nearby for animals and other domestic needs. The only ways that I know to compensate for lack of an underground watercourse are:

1st) Infiltration wells, 2nd) wells along watercourses, 3rd) cisterns, 4th) ponds, 5th) filtration of muddy water. This latter method was explained in Chapter XXVI, so here I will express some opinions on the other four methods, which are the result of observations I have made on my journeys. These opinions will no doubt be considered superfluous by those who are knowledgeable about this subject but they may be useful to the numerous landowners who do not have an underground watercourse and who plan to take charge themselves of the work required to compensate for this shortcoming.

## Infiltration wells

On some plateaus and some hilltops that have more than a hectare of flat surface there are rock types where all a person has to do is dig a well and it will fill with water in a short period of time. This water does not flow there via a regular pathway, starting at one side only and escaping from the opposite side as underground watercourses do; rather it flows into the well from all heights, from all sides, and shows up there only by seepage or dripping. These wells are commonly dug to the bottom without evidence of a single drop of water; all that is seen is wet earth or some sweating at most, but *as all fluids move toward the least resistance*, the void made by the well presents no resistance and all rainwater that falls nearby is absorbed into the ground, is carried little by little toward the well, and continues to go there until all the wetness of the ground is used up. This flow is usually not permanent and lasts only one, two, or three weeks after each rainfall so it is prudent to make these wells wide and deep so that during flows, they can collect a large quantity of water and store it until the next rain. In my travels, I have seen many of these wells, which although lacking all underground watercourses, nevertheless receive enough water by dripping or seepage to provide all the needs of one or two houses for the whole year. The water is often clear, cool, and of good quality.

The rock types most suited to this type of well are: sandy rocks, granites, porphyries, gneiss, sandstone, conglomerates, lamellar limestones that have horizontal strata and generally all rock types that produce only small springs.

Because there are almost no plateaus or hilltops without a small depression with a thalweg, if attention is paid to digging these wells in thalwegs instead of locating them randomly as done until the present, it will be seen that filtration will be much more abundant; often even if the depression extends only a hundred meters upstream, a small underground watercourse will be found. Attention should be paid to siting these wells at least thirty meters apart because they interfere with each other if they are too close. They should be monitored to ensure that unclean water cannot enter. They should be round and built with dry rock like ordinary wells.

## Wells along a watercourse

River and stream water is the cleanest for animals and it is the water they like the best but it is always tainted or at least suspected to be unclean; it becomes turbid during every rain or snowmelt, it is tepid in summer, and it freezes in winter; even when it contains nothing harmful, people always find that it has a certain tepidness and dullness that makes it unpleasant to drink.

Those who have their houses near a permanent watercourse and do not have groundwater nearby because it is too deep or too far, have only to dig a well along the watercourse to a depth of one or two meters below the level of the lowest water and clarified and cool water sometimes equal to groundwater will enter the well. These wells should never be dug in impermeable rock types; instead they should always be placed in sands and gravels deposited by the watercourse and at an appropriate distance from running water because if they are located too close, water will enter them only partially filtered and cooled, and if on the contrary they are too far away, water will arrive in too feeble a quantity or will not enter at all. The permeability of transported material varies infinitely, thus no rule can be established on the distance for the best location of these wells. Each person has to determine by experience the distance appropriate for his locality. If at the end of a period of time after digging a well, a person finds that he has located the well too close or too far, he can dig another in a better location.

As much as possible, these wells should be placed on a bank high enough to protect them from floods and to be able to use the well during flooding. If required to dig into a gravel layer that is only slightly elevated above the watercourse, if there is a point that is protected from the current by a rock or any other object and where the overflow water forms an eddy, this location should be chosen so that the current will neither wash away the edge nor fill the well with gravel during floods. These wells should be built with dry rocks and in the ordinary shape.

## Cisterns

A *cistern* is an underground reservoir into which rainwater is conveyed and stored for use for various purposes. Rock types in many communities and districts in France are unfavorable for the discovery of underground watercourses and the inhabitants can find water only at great depth and at great distance. There are also many moors [Fr. *landes*], low plains, maritime beaches, and swampy areas where only unhealthy and non-potable water can be found. Those who have the misfortune of having their houses located in such unfortunate places can supply themselves only by means of cisterns. But in addition to their desolation, in many large areas no landowner or mason knows how to build a solid cistern. Most cisterns are enclosed by a simple poorly cemented wall so they lose a lot of water and cause landowners great difficulty.

Of the most common instructions for cistern construction that I have observed, the one that seems the most solid and durable to me, and which at the same time is within the grasp of all intelligences and the smallest of fortunes, is the one that consists of encircling a cistern with a cemented wall and enveloping it with a watertight wall that is six to seven decimeters thick. This is how to proceed:

Choose a vacant and convenient location around your house, make a round hole of a diameter two and a half meters larger than the diameter you have chosen for the cistern. If for example, you wish your cistern to be four meters in interior diameter, make a hole six and a half meters in diameter, excavate it four to six meters depending on the quantity of water you want it to hold.

After the digging is done, a circular wall six to seven decimeters thick is built around the excavation and six or seven decimeters away from the walls [of the well]. The rocks that face the interior are cut into wedge shapes and the outside face is rubble stone. This wall should be entirely built of cement (1). All the joints and interstices should be carefully filled.

To build a good impermeable lining around your cistern, use the best clay you can find in your area, and if pure clay cannot be found, use the most argillaceous earth that you can get. After placing each layer of stones, add a layer of clay about three decimeters thick, completely filling the interval of six to seven decimeters that is left between the rock wall and the sides of the hole. To mold this clay, the worker wets it suitably, takes a round post pointed at one end like a stake, drives it vertically through the entire thickness of the clay, inclines it toward himself and pulls it out; he replants it about a decimeter from the hole already made, inclines it again toward himself and pulls it out; he repeats this maneuver hundreds of times and thus stabs little by little the entire layer of clay. As soon as the first shaping is finished, he does it a second time, taking care to plant the post in the intervals between the first holes. When the clay layer has been shaped and reshaped, it is pressed strongly with a paver's pile-driver; a new layer of stones is then placed, surrounded with another layer of clay formed like the preceding one; this process is continued in this way layer upon layer until the beginning of the roof, which he makes in the shape of a hemispheric dome and on top of which he leaves a round hole surrounded by an edge.

With the construction of the cistern finished, throw a layer of clay about three decimeters thick at the bottom, and level it out well and shape, reshape, and trample on it as just explained. On this first layer of clay you put a second and you manipulate it like the first; you cover this clay with a pavement of slabs or pebbles, you set it in a good layer of cement, and you plug up all the joints and interstices. The bottom of the cistern can even be shaped completely in cement mixed with small stones or coarse gravel. This concrete should be three to four decimeters thick; it is more solid than clay and diminishes the cistern capacity less, but it is a bit costlier.

When the hole excavated to construct a cistern is located in rock or a compact and absolutely impermeable clay layer, there is no need for cement or lining; it suffices to build a dry rock wall around the cistern and a roof with mortar.

All cisterns must be covered with at least a half-meter of earth so that the water remains cool. Cisterns should be round because the walls of a square cistern will not resist the expansive force of the water pressing against the lining. When the cistern water is for people to use, it is good to draw it with buckets so that in filling the bucket one agitates the mass and puts all portions in contact with air and prevents it from going bad; pumps leave the water too immobile.

If cisterns do not collect an underground watercourse or infiltration, water has to be collected from roofs or grassy land surfaces.

To collect water from roofs, lead, tin [Fr. *fer blanc*], or zinc channels are built around buildings and below roofs and painted with oil. These channels collect water from the entire roof and carry it through a pipe that conveys it to the cistern. Roofs where pigeons roost or roofs not cleaned from time to time produce only dirty water. Water from roofs also has the disadvantage of being insufficient for all the needs of a household.

To collect rainwater in a cistern in the desired amount, several ares [1/100 of a hectare; See Translator's Notes] of land near the house are devoted to this purpose. This land surface should have a moderate slope, be compact enough so that rainwater is not absorbed there, be enclosed by a wall or a living hedge or with a fence so that neither animals nor poultry can enter, and it should be covered with grass so that the rainwater will not be too turbid. The grass in this enclosure can be mowed and fruit trees planted but the land should not be worked. At the bottom and across this orchard, a channel is dug to collect all the rainwater that falls on the surface of the orchard and to conduct it to a cemented aqueduct that carries it to the cistern.

Snowmelt water or the first water that falls during a storm should not be allowed to enter the cistern because this water is more turbid and less healthy. For this reason, a small gate is set up at the entrance to the aqueduct that can be opened or closed at will. It is important to put water in new cisterns only after the cement is well dried and solidified; they should be cleaned out at least once a year.

## Ponds

A *pond* is a cavity in the ground that is at least several meters wide and several decimeters deep; it is used to store a quantity of rainwater. This type of basin has no definite shape or capacity. It can have a diameter and depth proportional to the quantity of water needed or the amount that can be poured into it. Some are very flared and accessible on all sides with gentle slopes from the edges toward the middle; this type of pond presents no danger; others are quite deep, surrounded by steep banks that can be rather high, with a single low-slope approach; the latter must always be surrounded by a wall, living hedge, or a fence. As for those to be dug in the future with the latter shape, it would be very prudent to make them no deeper than a meter and a half to prevent the many accidents they cause every year because strangers passing in the night and children and domestic animals drown in them.

Ponds should be dug only in impermeable rocks and soil; if they are not located in such a place, the bottom and the walls should be lined with clay that is wetted, shaped, and pressed as described for a cistern. A pond should always be located in the thalweg of a depression or at the bottom and at the side of a sunken lane [Fr. *chemin creux*] or at the end of a long pit so that it will collect the largest possible amount of rainwater. Trees with high and closely spaced branches should be planted around ponds, assuming they can grow there, to keep the water cool and to prevent evaporation, which ordinarily removes a lot more water from non-shaded ponds than the trees consume.

Pond water, although not suitable for domestic purposes, is very useful for watering livestock and gardens, and in the event of fire, etc. In large ponds, tench, roach fish, goldfish, cobites, etc., that is, fish that multiply rapidly and that like stagnant water can be raised. The only maintenance for ponds consists of cleaning them out from time to time; the mud removed from them is an excellent fertilizer when it is dried. In areas that lack underground and visible watercourses, there could not be too many cisterns and ponds.

Note

1. Cement for cisterns is made of hydraulic lime or the best lime that can be obtained and lime that was recently removed from the limekiln. Well-dried and well-cooked fragments of tile or brick are pulverized in an oil press millstone. Tile and brick that are overcooked or burnt are the best. One quarter or up to one-third very fine sand should be added to this powder and in place of pure sand, this mixture is put into the lime and mixed like ordinary mortar. This cement is prepared only as needed; it must be used as soon as it is made.

When neither hydraulic lime nor first quality lime is available, Mr. Loriot's recipe can be used. With ordinary lime, it produces cement that is even better but it is a bit more difficult to work with. Here is the recipe:

Take some tiles or bricks milled or crushed very finely and passed through a sieve, two parts of fine river sand passed through a sieve, more of the old slaked lime in a quantity sufficient to form an amalgam or ordinary mortar when water is added and wet enough to neutralize the quicklime and throw in powder up to a quarter over and above the quantity of sand and crushed bricks taken together.

With the materials well broken up and incorporated, use them immediately because any delay may cause their use to be unsuccessful or impossible.

A coating of this material placed on the bottom and the walls of a basin, channel, or any type of construction made to hold and cover water has the most surprisingly beneficial effect, even when it is used in small quantities.

### 2.4.30. Chapter XXX. Origin and Development of this Theory

The reader is no doubt curious about the origin of this theory and how it developed; I will attempt to satisfy this curiosity by providing a short report on my hydroscopic work.

The grand line that separates primitive rocks [Fr. *terrain primitif*] from limestone rocks in France starts near the Mediterranean coast and crosses the country by following countless contours through the departments of Var, Drôme, Ardèche, Gard, Lozère, Aveyron, Lot, Corrèze, Dordogne, Haute-Vienne, Creuse, etc.

This line goes through the small parish of Saint-Jean-Lespinasse (Lot) where I was called to serve in 1818. Shortly after arriving there I was surprised by the contrast in springs between the eastern and western parts of the Department of Lot.

The eastern part, completely composed of primitive rocks, has elongate and very regular hills. The valleys and vales, rivers and tributary streams all flow into each other with an order that could be called perfect; springs flow out of everywhere; almost all the houses have a spring, at least one near their door and almost all meadows are irrigated by rivers, streams, or spring water.

The twenty-four cantons that make up the western and southern part of the department are all situated on limestone; they generally have no rivers, fountains, or even wells with underground watercourses. A person can travel in a straight line from east to west from Lissac to Mareuil, a distance of 54 kilometers, without seeing a single watercourse, and from north to south from Mézels to Sauliac, a distance of 46 kilometers, without crossing a watercourse other than the Gramat stream, whose entire lower part is dry three quarters of the year. The portion of the department that has no watercourse covers an area of 50 square leagues.

Stories of the many evils resulting from this dearth of water were the most common subject of conversation in the region; this caused me great sadness. People in most communes would tell me daily that all inhabitants had to use their most precious time, one, two three, four, or five hours per day, to collect water in barrels from the river for themselves and their animals. Those who have neither a team of horses nor a mount, which is the majority of the population, walk one or two leagues to find water and carry buckets on their heads; others have only muddy and fetid pond water to drink. In some places people sell river water for twenty to thirty centimes per bucket, and each draught animal or beast of burden animal consumes about twelve *sous* [a *sou* is equivalent to 5 *centimes* or 1/20 of a *franc* – tr. note] per day. From time to time sheep that have had nothing to drink for several days can be seen along riverbanks; some fall into the water and drown and others gorge themselves with water and die suddenly. When they return from the river, the animals are almost as thirsty as they were prior to their departure. When a fire occurs, there is no means to extinguish it. Landowners who have cisterns are rare and they resign themselves to water shortages themselves if they open the cisterns to the public. Villages with wells that provide water resemble permanent fairgrounds. People and flocks go there night and day, often from far away and they have to wait several hours until people who came first have watered their flocks and filled their barrels.

Hearing these grievances and many others based on the lack of water, I often thought: *Is it possible that God has forever abandoned so many unfortunate people to the anguish of thirst! Is it not possible to find groundwater in these unfortunate areas even if the groundwater is very deep!* Equipped with a few notions about geology and knowing that as much rainwater falls on limestone ground as on other rock types, I began to walk around in all directions on these vast and arid plateaus to try to figure out what happens to this rainwater and to see if I could find some indication of underground watercourses either by a geologic study of the rock units or by indications provided by fountain builders, which we will see in the final chapter. Those who did not understand my goal of examining these properties claimed I was searching for immense and numerous treasures that the man in the street thought the English left behind back when they evacuated "La Guienne" [See Translator’s Notes]; others said that I was working on departmental statistics, etc. Learned men to whom I have had the opportunity to explain the goal of my explorations were quite convinced that no one would ever discover underground watercourses here, given that numerous and deep excavation conducted since the beginning of the world had produced no results, and that if this discovery were possible, it would have been made a long time ago by a learned person from Paris.

I spent almost two years in useless work without seeing the least indication of the presence of underground watercourses.

Having found nothing on the plateau, I began to walk and examine in succession the banks of our three principal rivers, the Lot, the Cellé [Célé], and the Dordogne. I saw many springs there, located at short intervals, some of which were powerful enough to form rivers; many others formed large streams and an even larger number were less voluminous; all of them came out of the earth and flowed immediately into rivers. I then said to myself: *These springs are not formed in the same rock that spits them out, nor in a space of several hectares of ground; they must thus be the product of rainwater that falls on plateaus and that is absorbed as soon as the rain touches the ground.* Having thus begun to understand the fate of rainwater that falls on our limestone plateaus, I walked from the mouth of these springs, I walked across the plateaus that dominate them to try to discover some indications of their passage; but in these first explorations, I had unfortunately stumbled on regions with scattered swallow holes that I was not able to line up at that time and I was not successful. But I remained convinced that underground streams must form under limestone plateaus, must grow and flow like visible watercourses in other regions. But where were they?

Thinking then that I had perhaps misunderstood underground hydrography and that prior to studying it in subsided and upturned rocks, I should begin this study in regular and primitive rocks where springs are numerous, I took two more years to walk about and examine the primitive rocks of the Department of Lot. I examined with particular care springs that flow out of the ground naturally, the nature of the rocks that produced them, why they appear in some places and not in others, why they are unequal in volume, the role that visible streams play in their formation and their flow, etc. It was by observation of these rocks that I developed the true theory of underground watercourses and their outpouring.

I then needed to expand this theory to the limestone plateaus and apply it to the watercourses they harbor. I thus began to re-examine watercourses that flow out of the ground along riverbanks by following the course toward their presumed upstream ends. Quite fortuitously I began this examination at the source de L'Ouysse, which by itself forms a large river. Starting out at its outlet and heading upstream, I first found a very pronounced vale but its depression, although easy to determine, diminished on the way to Thémines where a large stream sinks into the ground; I immediately recognized this stream as the principal tributary that would form the enormous L'Ouysse spring at a distance of 25 kilometers and which, according to all probability, must flow under the valley that I had just walked. After this first study, which I found very satisfying, I repeated this exercise on a number of other watercourses that flowed on top of the ground for a while and then were lost and reappeared along riverbanks. This is how I came to recognize that the streams of Théminettes and Hôpital-Issendolus flow underground into the conduit of the L'Ouysse; that the Rinhac and Salgues streams, after disappearing underground, join the Alzou; that the Miers stream, after disappearing at Roque-de-Corn, reappears at Montvalent along the Dordogne; that the stream that disappears at Sounac reappears at Sainte-Eulalie; that of Assier in Corn and that of Reyrevignes at Boussac; these three latter streams, after flowing underground three or four leagues pour out along the banks of the Cellé [Célé].

All these streams are much wider when they come out of the ground than when they go in and I understood that they had joined up with a large number of other streams.

In going from the outlet to the beginning of each of these underground watercourses and always following the bottom of the vale that marks the passage, I recognized either a natural well at the bottom where the watercourse appeared or a crevice at the bottom of which one could hear noise; this was the orifice of an underground passageway through which the locals ensured me an otter emerged (1) from time to time; following heavy rains, a column of water had been seen shooting upward from the ground there and rising to a height of two or three meters. All these indications, and others, as I continued to find them, repeatedly confirmed me that I was on the right track.

In the Department of Lot we also have numerous springs, which are no less important than the ones just named, springs that flow unseen to riverbanks without a single tributary flowing at the surface in the basins that produce them. The principal ones located along the Lot are: the Touzac fountain near Puy-l'Êvêque; those of Chartreux and Saint-Georges near Cahors; those of

Saint-Géry, Crégols, Cajarc, and Cadrieu. Along the banks of the Cellé are the springs of Saint-Sulpice, the Marchepé well, and the Resserq well in the town of Marcillac and the Bourlandan and the Pescalerie in the town of Cabrerets. On the banks of the Dordogne are the fountains of Mayraguet and Gourg near Souillac, those of Briance and Murel near Maitel, etc.

Seeing most of these springs issue near rivers at the outlets of long valleys where numerous vales and depressions end, I felt confident in concluding that they form, move underground, and follow the thalwegs of valleys or vales like visible streams do. In the southern part of the department in particular are valleys, vales, gorges, and depressions as well excavated and as regularly arranged as in primitive terrain. Although these depressions lack streams and springs, what I had observed elsewhere made me believe that each of them harbored an underground watercourse.

I then had to determine the pathways of underground watercourses that do not issue at the outlets of vales, but issue along riverbanks at the foot of steep rocks and with no presence of a vale on the plateaus that dominate them. After lots of field examination, I figured out that all these springs came from rocks sprinkled with swallow holes that I had long believed were randomly located, with no order. However, after having examined them for a long time, I came to notice that they were arranged in series and that each series occupied the thalweg of a type of very slightly depressed vale; that there was always one of these vales that was a little deeper than the others and that was directed toward the outlet of the spring; although it was interrupted by a type of barrier that formed a cliff at the foot of which the spring flowed forth. It was then I learned to align these numerous swallow holes that are disseminated over most of our limestone plateaus and to see distinctly the different series they form, some principal and others accessory, indicating the line that the principal watercourse follows and that each accessory watercourse follows.

The certainty of the passage of a watercourse under each series of swallow holes being thus acquired, the remaining difficulty was to determine the depth. Starting at the outlet of each spring and assuming it follows about the same slope as visible rivers do, I measured the elevation of a number of these series of swallow holes and I found that almost everywhere they were 200, 300, and 400 feet above the level of the outlet and that as a result, excavation was impractical in this rock type because of the excessive depth to which one would have to dig to reach the water. This is why in Chapter XX I ranked limestone with swallow holes to be an unsuitable rock type for the discovery of underground watercourses. Near the heads of these vales, I commonly observed a depression with no swallow hole and a small underground watercourse, just as at is found everywhere in primitive rocks.

I then went back to the springs that pour forth at the outlets of vales and, assuming them to have the same slope as that of surface streams, I found by measuring that they were ordinarily 10, 20, 30, or 50 feet deep and that as a result, it is always in the valleys, vales, and depressions that it is necessary to excavate, as we saw in Chapter XVI, because the thalweg is the most certain guide for determining the line that a watercourse follows underground and because the depression makes it possible to reach the watercourse with an excavation that is less deep.

The two inclined planes of the two escarpments that make up most vales and the transported material that occupies the bottom made me think that the watercourse must be located at the line of intersection of the two planes, and that the procedure indicated in Chapter XVII could be used as a second way of determining the depth of the watercourse, except for irregularities that can be encountered in the field. This second method, which is very simple once one knows it, came to me six years after I had begun to study underground hydrography.

It was also only after studying underground watercourses and their basins for several years that I came to make another observation, which is no less simple, to wit: *That the volume of each underground watercourse is generally proportional to the extent of its basin, and that by determining the perimeter of each basin and measuring the surface, it is possible to determine an approximate volume of the spring it produces.*

Thus after nine years of study, exploration, patience, and fatigue, I succeeded in theoretically determining the line that each underground watercourse follows, its depth, and its volume. Since then I have been busy organizing the voluminous material that I have collected from books and in the field and writing up this work.

To reduce this theory to practice and to show the value of it with facts that are easy for both the illiterate and the educated to obtain, in 1827 I presented a summary to the Conseil General of the Department of Lot, along with a letter in which I offered to travel, without charge, to towns and private individuals who wanted to test my ideas, and I asked the Conseil to approve funds to cover half the costs of these first experiments on the condition that the towns or the private individuals would provide the other half. I added that this theory was not infallible and that I would no doubt commit errors but my confidence was strong enough to be able to promise that the method would succeed in at least two thirds of the attempts. The Conseil General received these proposals favorably and M. the Prefect placed at my disposition the sum of 600 francs to pay for half of the expenses of the first trials: here is his deliberation:

Prefecture of the Department of Lot

Extract from the Register of Deliberations of the Conseil General

SESSION OF 1827

Meeting of 21 August

"After listening to the report by the Commission appointed to examine the memoir presented by Mr. Paramelle regarding methods for finding underground watercourses in the limestone soil of the department, the Conseil General applauded the zeal of this worthy ecclesiastic to remedy one of the most disastrous scourges of this vast region and recognized that his views are based on observations as correct as they are wise. Hoping that this theory will be justified by facts, and that once experience has demonstrated its correctness, landowners in the department whose houses are located near places where underground watercourses travel will hasten to do the necessary work to make use of them; decrees 1) that a sum of 600 francs shall be placed at the disposition of the Prefect to be used, under Mr. Paramelle's direction, to find watercourses in locations where he thinks he can apply his theory; 2) that the Prefect be asked to inform Mr. Paramelle of the decision of the Conseil General and to thank him for his report.

For the collated exemplified copy, the secretary general of the prefecture, (The seal of the Prefecture is here) Reygasse »

As a result of this deliberation, Mr. Baumes, then the Prefect of Lot, addressed the following circular to the mayors of numerous towns that had no water:

Prefecture of the Department du Lot

"The prefect of the Department of Lot, Chevalier of the Légion of Honor, hastens to make known to the mayors of the Department that the honorable Father Paramelle, author of a system that seeks to provide ever-cool, healthy, and abundant water in all towns that lack it, a system that has received the support of the Conseil General and the approval of the government, will travel successively through all the communes of the department that lack water, for the purpose of applying his theory.

As a result, and having the honor of recommending Father Paramelle, particularly to the mayors of the communes where he will have the occasion to conduct his tests, he [the prefect] invites them to assist him to the best of their ability and to provide him all means in their power to facilitate the success of these worthwhile projects.

In the event of success, the prefect will be pleased to point out for public recognition the communes, administrators, and even private parties who, based on reports by Father Paramelle, have freely provided the largest number of man-days and have provided the most help to assist him.

Issued in Cahors, at the Hôtel of the Préfecture, 23 June 1828.

Le prefect of Lot:

Baumes. "

The idea that it was impossible to find underground watercourses on limestone plateaus was so generally accepted that only eight communes wanted to risk money for these efforts. After

I traveled to these communes to do the requested indications, the mayors prepared a statement regarding each indication, stating the location where the underground watercourse had been indicated, its depth, and volume. This report was prepared in triplicate and signed by several witnesses; one was sent immediately to the Prefect, the other remained with the mayor of the town, and the third came to me.

Out of eight towns, three did not dig at all and five conducted the work that I had outlined. All five had complete success. One of these discoveries was the enormous spring at Rocamadour, which, according to the inhabitants, *would provide enough water for the whole department*. According to the Prefect's recommendation, the mayors sent very detailed reports on these unexpected discoveries; the reports were filled with the joy of the inhabitants of the nearby region.

At the end of August 1829 after a desire expressed by the Conseil General, the Prefect wrote to invite me to the Conseil to explain my theory in person, to propose the methods I considered the best for propagation and publicity in all the communes of the department that lacked water. On September 1, 1829, I was present at the Conseil, which devoted the entire meeting to hearing the explanations that I gave both on the theory and on methods to publicize it. I ended my explanations by repeating that these first five results should not be taken to show that all attempts would succeed but that I continued to believe that I would succeed at least in two thirds of attempts. — *Even if you succeed only half the time*, said several members of the assembly, *you will render immense service to the Department.* After I left, the Conseil made the following deliberation:

Prefecture of the Department du Lot

Extract from the Register of deliberations of the Conseil General

SESSION of 1829

Meeting of 1 September

The Conseil General, composed of the members who had deliberated at the meeting the previous day, and Mr. Théron, took up the subject at eight o'clock in the morning.

"After reading the report of the minutes of the previous day's meeting where it had adopted the draft, the Conseil heard the report of the Prefect on results already obtained from the application of Father Paramelle's theory on the search for underground watercourses. This administrator reported that only five communes had reached the depth indicated by Father Paramelle and that in all five, water had been found. This success gave to the Conseil the hope that the theory of this knowledgeable priest would lead to the discovery of flowing water in many locations, which until now have only insufficient cisterns and ponds to quench the thirst of animals only a small portion of the year.

One member announced that Father Paramelle wanted to submit to the Conseil the basics of his theory, and he was invited to present them. He recounted the series of observations that led him to believe he could detect the direction of underground watercourses and the facts in support of the consequences he draws from his observations. The Conseil listened to the developments presented by Father Paramelle with the liveliest interest and he acknowledged that his theory agrees with the principles of physics; he is no less admired by his generous lack of financial interest as the indefatigable zeal that he has for directing excavations undertaken in the search for groundwater.

Interpreting the sentiments of the Conseil, the President paid him a just tribute of elegies and thanked him for the important services he proposed to render to the Department, for which he deserves recognition.

At the proposal of the Prefect, the Conseil, persuaded that it could not encourage the search for groundwater too strongly, voted to pay Father Paramelle two thousand francs for his sacrifice or to assist towns that wanted to try out his theory. Ci. . . . 2,000 fr.

Certified copy,

Secretary General of the Prefecture,

(The seal of the Prefecture is here) Reygasse. "

The 1830 revolution prevented the Conseil General from working on the question of groundwater; in 1831 it made the following deliberation:

Prefecture of the Department du Lot

Extract from the Register of deliberations of the Conseil General of the

Department of Lot

SESSION of 1831

Meeting of 14 May

The Conseil General, etc.

"The report on the application of Father Paramelle's theory of the discovery of underground watercourses states that in seventeen locations an underground watercourse was reached at the depth indicated and that in sixteen the existence of an underground watercourse was verified in the designated space. The Conseil wants to support the enthusiasm of this honorable priest, to provide the most indispensable element for life and health and agricultural needs in these regions and deliberates that he shall be allotted ten francs for each underground watercourse that he discovers and that the municipal council of the town where the discovery is made will be required to search for the water at the depth indicated within one year of the designation.

Certified true copy:

For the absent Secretary General of the Prefecture,

Councilor of the Prefecture

(The seal of the Prefecture is here) J. J. CAVIOLE. "

Based on this deliberation and new circulars that the Prefect sent to the mayors, I continued to travel to all the localities that contacted me. The string of successes continued until the fourteenth attempt in the town of Carennac, which failed, and the acclaim of these first successes travelled fast from near to far and was soon heard throughout the department. Confidence grew from day to day; people even credited me with an infallibility that I continually denied with all my strength by pointing out the failures that occurred from time to time; never mind, these failures were nothing in comparison to the immense advantages that these discoveries provided, whose number and importance were exaggerated everywhere.

My goal was to provide water for my department only but before I had finished exploring it, I was called to the departments of Corrèze and Aveyron where the successes became as famous as those that occurred in the Department of Lot. The failures were as if they had never happened. *We would be very happy*, I was often told, *even if we succeed only half the time because underground watercourses that are found are worth twenty times and often one hundred times what they cost.*

Seeing that the number of demands was constantly increasing, I submitted my resignation to the bishop, who was of the opinion that I would do much more good in providing water for unfortunate populations that had none than I would by remaining in my post.

After visiting the first three departments, I was called to the Dordogne, where the need for water was so widespread that almost all communes made requests. After my indications resulted in similar successes, the newspapers of the department, for lack of other news, began to publish on a daily basis and with all major details the results that came to the knowledge of their writers. Their articles were reproduced by newspapers in neighboring departments and even by several newspapers in Paris. These articles drew requests from everywhere.

For the first three or four years of my explorations, the man on the street who knows no other physics than magic was amazed at the predictions he saw accomplished every day. "This man," said one "finds underground watercourses because he was born at the time necessary for that; anyone born at that hour would be able to do that. --It is a gift from God that only he received," said another. -- No, said the other, he is truly a sorcerer; don't you see that he guesses perfectly the position, depth, and thickness of each underground watercourse and all the rocks that a person has to dig through to reach it? --He is neither inspired, nor a sorcerer, says the third, it is because he has more piercing vision than any other man and that he sees through the land and can see everything that is below. --He has better vision than us, said still another, he alone sees a column of vapor coming out of the ground over each spring" and one hundred other similar nonsensical statements.

Some of these quasi-scientists are convinced that no one can know what they themselves do not know, although they have not seen any of the results obtained; they decided from on high that the discoveries that they had heard about were *impossible* (2). Those who had had the opportunity to see some of them said that the underground watercourse had been found by chance. Others said: *This spring, it is true, flows well for the moment but it will soon dry up*. Others said: *It is certain water that flows out of the ground and flows into this hole, but it is not a spring* (3).

In many places, trouble-makers set traps for me; some led me to a place where there was water that they had brought there from a distance via an aqueduct and on which there was not the slightest trace of excavation at the ground surface; or they very cleverly hid basins of their fountains and said: *There is a spring near here, where is it*? In response to all, I went to the underground watercourse. Sometimes they led me to wells that had no underground watercourse, where they had thrown water a few moments before my arrival, and they said to me very seriously: *Our well has good water, but it is too deep*. — *Your well has no underground watercourse*, I replied, and they laughed as they acknowledged it. Others led me into enclosures where numerous and very deep wells had been dug, without success, to see if I would make an indication on one of these entirely filled-in wells. When I arrived, the most learned man of the village often said to me: *Sir, can you tell us where our underground watercourse is*? — *Yes, sir* I replied, and at the same time I walked directly to it as any inhabitant of the village could do.

Through God's grace, all these stratagems and other similar tricks were everywhere in vain. It amused me each time they thought it appropriate to test me; I always took them in good spirit. Little by little, the troublemakers recognized the uselessness of all these traps and finally stopped doing them; and for the last twenty years of my tours, only once or twice has anyone tried to trap me.

After several hundred attempts proved that the number of successes greatly exceeded the failures, prefects and agricultural societies published circulars and numerous newspaper articles to encourage subscriptions in their departments and send them to me. To satisfy these numerous demands, I explored progressively and in the following order the Departments of Charente, Lot-et-Garonne, Cantal, Vienne, Gironde, Savoie (which at the time of the Empire formed the Department of Léman and that of Montblanc), Seine-Inférieure, Cher, Loir-et-Cher, Charente-Inférieure, Basses-Alpes, Gers, Bouches-du-Rhône, Var, Hautes-Alpes, Hérault, Gard, Vaucluse, Drôme, Loire, Ardèche, Doubs, Jura, Haute-Saône, Saône-et-Loire, Vosges, Meurthe, Côte-d'Or, Haute-Marne, Moselle, Meuse, Haut-Rhin, Aude, Haute-Garonne, and Ariège; forty departments in all. I also explored some parts of five other departments and made several excursions into nations adjacent to France.

Here is an extract of my prospectus that explains how I operated:

"When he arrives at the location to be examined, Mr. Paramelle first conducts a geological examination and designates a plot of ground where the underground watercourse is located, and states its depth and volume. If the landowner says that the underground watercourse is too far, too deep, or too meager or that he does not have the money, Mr. Paramelle does not indicate the location and the landowner does not pay him. If the landowner thinks that the underground watercourse meets his needs and requests the exact location, Mr. Paramelle marks the precise point [for the excavation] and accepts his fee, which is based on the following:

"In the Department of Lot, he charges 10 fr. for every underground watercourse that he indicates; in the six neighboring departments, 15 francs; in departments contiguous to the latter, 20 francs, etc. The fees increase 5 francs per department with increasing distance from Lot, in the Department of *** they are set at *** francs per underground watercourse [*** as in Paramelle’s text].

"Mr. Paramelle promises in writing to return the fee to each person if at the determined place and depth he does not find groundwater in an amount more than sufficient to meet the needs of the house or houses to be supplied; however, those who do not dig within a year of the date of the indication lose the right to request a refund. These fees are reimbursed, when the case arises, by a correspondent established in each district where Father Paramelle makes indications. The poor are served for free everywhere. "

In all departments, the number of requests exceeded 300; in some it was as high as 1,000, 1,500, and even above 2,000. In departments where the rocks were most favorable, I was able to indicate underground watercourses for one third to one fourth of the subscribers; in others, I was able to indicate groundwater for only one seventh or one eighth of those who had contacted me.

The number of indications compared to demands would have had a higher proportion if I had had the ground available, that is, if the subscribers had been landowners of several more hectares of land around their houses; but the majority had only a courtyard, garden, and sometimes an orchard with an area of several ares [one *are* = 100 $m^2$ = 1/100 of a hectare - tr. note]. Underground watercourses are not present in every hectare of ground, so the majority of them who asked my assistance did not have groundwater on their property; very often it is very abundant, shallow, and near their houses but it is on their neighbor's property.

Landowners on whose property I recognized that groundwater was not present at least had the advantage of knowing that they should not spend money to look for it, and that to get water they should try one of the methods indicated in the preceding chapter. I always took care to advise them on what was most suitable for their position, and this advice was free everywhere.

Between 1832 and 1853, my tours regularly lasted from March 1 until July 1, and from September 1 until December 1 of each year. Every day, except Sundays and holidays, I worked from sunrise until sunset, going from one place to the next by horse, and stopping only one hour per day between ten o'clock and noon: I recorded all the underground watercourses I indicated. Each certificate of indication states the location of the underground watercourse, its depth, and volume and is signed by the landowner of the underground watercourse and by several witnesses. An extract of my register was delivered to the landowner, in which I committed to reimburse him the fee if at the location and at the depth indicated, he did not find groundwater as I had described it, on the condition that the hole was dug within the year.

In 1854, at the age of sixty-four I suffered from infirmities that no longer permitted me to travel and I was obliged to notify thirty-seven departments that had sent requests. I have since been occupied with revising the report I composed in 1827 as *The Art of Finding Springs*. I find that my first report contained several principles that were too absolute, just as with all theories that have not been applied and I learned to modify them with practice. My first report also lacked a numerous facts and observations, which my travels led me to add.

I cannot end this chapter without giving in to the need I feel to express my appreciation to the archbishops and bishops, the peers, deputies, prefects, sub-prefects, members of royal courts, tribunal judges, and men famous for their science whom I have met during my travels, for the goodwill and honesty that they have deigned to shower upon me; to subscribers and priests for the cordial hospitality they granted me; they treated me not like a stranger but like a dear friend or relative that they were seeing again after a long absence; to the members of the municipalities and populations of almost all the towns that greeted my arrival with such kind demonstrations and followed my explorations with interest and attention.

The innumerable acts of kindness that have been lavished on me everywhere and that I am pleased to recount in my book and to tell friends during my retirement, excite in me the sentiments of the most vivid gratitude and I am sure that they will be extinguished only when my life ends.

The enthusiasm of the populations of the communes that I visited that has caused others to follow and observe someone they thought to be a person worth seeing, leads me to believe that some people who did not see him will perhaps be curious to read the portraits that have been published in newspapers, from which however, they will have to diminish several obviously flattering traits.

*L'Université catholique, volume ix*, February 1840:

"The learned and modest priest arrives escorted by town notables who have gone out to the edge of town to greet him; they press him, surround him, examine him; they are surprised to see him traveling alone on his horse, a tall man of robust size, dressed in black, a frank and open face, a broad forehead, penetrating look, who smiles with benevolence and hastens to declare to the inhabitants who show him a flattering impatience that he does not have the gift of miracles but only a bit of experience in discovering the ways nature uses to transport and circulate water hidden within the earth.

"Nothing simpler and more modest than the exterior and manners of this simple good priest, who however is interesting on other subjects than that of his special science."

*L'Écho des Cevennes*, 29 May 1841:

"The modesty of Mr. Paramelle is equal to the simplicity of his clothing. Of a tall and robust size, an interesting and kind face, his physiognomy announces intelligence and sincerity. His conversation is neither brilliant nor affected, but always solid and useful. Gifted with a great intellect, he has the art of sizing up men. Quite laconic in his responses, he does not like people to ask him repeated, inopportune, or idle questions.

"This hydroscope, more useful to society than a great conqueror, lives his life without noise, without sparkle, without ostentation; all around him, he discovers precious treasures."

*Le Courrier de la Drôme*, 27 November 1842:

"Father Paramelle is about fifty-two years old. He is tall and straight and his health is so robust that he has all the vitality and muscular strength of a much younger man. His clothing is extremely simple, even proverbial. He ordinarily wears black clothing that reminds us of his priesthood, which certainly should not bother him except because of its fullness. His face is calm, interesting, and gentle, his look is investigative and piercing; his manners simple, but always at ease. His physiognomy announces intelligence and sincerity. There is a bit of the ruggedness of the mountain person in his overall personality but it displeases all the less because under this rustic appearance, one can make out right away a gentle soul, a fine and penetrating mind. His conversation is neither brilliant nor affected; instead he is brief, lucid, always useful and solid.

Father Paramelle dislikes words and people of many words… He cuts short all the trivial questions that the crowd overwhelms him with.

"Often, in areas that are particularly lacking in water, the announcement of Mr. Paramelle's arrival is an event. They think he's a man from on high like another Moses and the population goes out to meet him. They push, surround, examine, and interrogate him. But he remains impassive; he looks at the land, the ground, its depressions, and the vegetation rather than the people who press around him. Once this first moment has passed, he smiles with benevolence and declares first of all almost invariably everywhere that he is neither a saint nor a sorcerer."

*Le Journal de l'Ain*, 14 April 1845:

"Father Paramelle is about fifty-five years old. With his tall height and almost athletic constitution, the difficult life he leads does not seem to affect his health. His face shows a combination of open affability and finesse. His forehead is broad, his eyes expressive and his complexion full of color. He tops off his black clothing with a round wide-brimmed hat."

*L'Espérance de Nancy*, 18 November 1847:

"At first glance the face of Mr. Paramelle, like his bearing, is quite ordinary; but when examined closely, especially during his explorations, a ray of intelligence can be seen to glisten in his blue and meditative eyes.

When Mr. Paramelle happens to talk, his features take on a cheerful air that smoothes the thinker's brow . . . His investigative look passes over the land surface; he studies, it probes it, and seems to understand it in the wink of an eye... You see him traversing the territory and indicating to you from afar springs that already exist, the volume of their water, etc., and that with a precision, an exactitude that surprises you, that makes you look at him as some sort of soothsayer."

*La Tribune de Beaune*, 4 April 1849:

"Father Paramelle is a simply dressed man who wears on his ruddy face the sign of a good man. He leads a very frugal and active life. He leaves his lodgings early in the morning without eating and rides on horseback reading his prayer book toward the place where he is expected. He eats lunch around eleven o'clock and chooses the simplest foods. He has a spirit that enjoys jokes and he often makes people laugh."

*Le Spectateur de Dijon*, 12 May 1849:

"Under the simple and easy exterior of Father Paramelle, a strong and deep intelligence can be seen, although he compares himself modestly with *bâtons flottants* [floating sticks] [See Translator's Notes]. His conversation reveals a cultivated mind, not only by the study of geology but also that of several other sciences. He has read widely and retained much... His frugality goes so far that eating and drinking count for practically nothing in his life... Truth is at the core of his character. He may make mistakes, but at least he does not make them knowingly."

Notes

1. The presence of an otter in the middle of these arid lands suggested to me not only the presence of an underground river in this location but also a river full of fish because this animal eats primarily fish.

2. In October 1834, I went to Lavalette, county seat of the canton (Charente), a city where every summer the citizens had to seek water at a distance of more than a kilometer and where only two landowners had summoned me. When I arrived, one of them took me aside and said to me: "*Be careful, sir, in everything you do and say, you are in a country of philosophers who refuse to believe in your art because of who you are*." — "*Rest assured, sir*," I responded, "*you will soon see all your philosophers at a loss for a reply*."

At the first underground watercourse I had the occasion to indicate, about one hundred meters from town about thirty town folk and a large number of other people followed me. To the landowner who had asked me to indicate groundwater, I said: "*The underground watercourse is* *under that point there, please mark it; it is at a depth of 16 feet and is as big as my finger*." Then taking a high position and a louder tone of voice, I said; "*Gentlemen, I do not claim to be infallible; however, if someone wants to bet 300 francs that what I announce is not so, I will bet 600 francs that the three declarations I just made will prove to be true. We can record the two sums right here and now and in three days we will know who has won.*" A long silence followed these words, and almost all the faces became long and pale. After four or five minutes of silence, a voice was heard from the middle of the crowd, saying: "*Hey, speak, you now, speak; you said that you wanted to confuse him when he arrived; speak up, and win the 600 francs*!" After these words, the silence continued; at the end of several minutes of waiting, I began again and said with a smile: "*There are men who swear to something but who will not bet; to the contrary, knowing that I am fallible, I will bet on what I say will be, but I will never swear to it*."

In several days, the groundwater was in fact discovered at the announced depth and volume. Before leaving the small city, there were more than one hundred requests and I indicated thirty-seven underground watercourses.

What I did in Lavalette, I did in all my travels. Almost everywhere that I indicated underground watercourses, I offered to bet two to one that the three declarations that I made were true and I never found anyone who would accept my bet.

3. The following was reported in the Courrier de la Drôme, 27 November 1842: "In a large town in the Department of *** [tr. note: as in French original], Father Paramelle was called one day to indicate an underground watercourse sufficient to supply the flowing public fountain. The geologist hurried to the place and indicated the underground watercourse the same day. This result, so delightful for the city, was however not equally appreciated. The working people celebrated with three days of endless dancing and rigadoons. But it was otherwise among some big shots. They began to question if was really possible that there was an underground watercourse there where Father Paramelle had indicated one even though no one had questioned it in front of him.

However, the mayor began to dig and found the underground watercourse exactly as the learned hydroscope had predicted it. But the opponents would not accept defeat; on the contrary, they were the majority within the municipal council, who declared "*the underground watercourse invented by Father Paramelle was not an underground watercourse, so there is no reason to build the planned fountain.*"

The mayor, put in a very awkward position, wrote to Saint-Céré asking Father Paramelle to help him, with a summary demonstration, to refute once and for all the objections of the majority but the geologist did nothing. He recalled the margaritas ... of the Scripture [See Translator's Notes], and judging that water, springs, fountains, and science were foreign to the deliberation made, he responded to the mayor, simply: "*Mr. Mayor, your opinion is the same as mine. Yes, the water that in the space of four hours filled the hole that was five meters deep that had just been finished within the wall of your city and for sixteen months has not stopped flowing to the ground surface is truly an underground watercourse. Those who believe this water is an underground watercourse can draw water there; the others can go to the watering trough. Sincerely, yours. .* "

The letter was read in the city council and no one, they say, wanted to go to the watering trough."

### 2.4.31. Chapter XXXI. Underground Watercourses Found on the Basis of this Theory

The reader would no doubt like to know the exact number of successes and failures that I have experienced since the beginning of my explorations and my most ardent desire would be to satisfy this curiosity, but to accomplish this, it would have been necessary for everyone who excavated according to my indications to have informed me of the results and the mayors to have confirmed them; but neither of them did this. I committed in writing to reimburse my fee to every private party in the event of failure, all failures were regularly confirmed by reports [Fr. *procès-verbaux*] sent to representatives I had established in all departments to reimburse fees; but when it came to informing me about confirming success, it was totally different. In spite of the most express recommendations I made at the time of each indication, of advising me regarding the result of the excavation whatever it was, I can affirm that out of 10,275 indications that I made during my twenty-five years of exploration, not even fifty private persons took the pains to write to me to tell me about success. Some did not do it for fear that the underground watercourse might fail later, and that this written declaration would take away their right to request a reimbursement of fees, others for lack of time, and others out of pure apathy.

During the first fourteen years, I sent printed report forms to the mayors of the towns where underground watercourse discoveries were made, form letters in which there were only a few words to insert along with a printed letter asking them to fill them out and send them to me. At most three or four out of a hundred answered; none of the others responded. The majority of these magistrates received these forms five or six times, with repeated requests to fill them out; altogether they received, at different times, a total of *four thousand forms*, and almost all of them to no purpose. In December 1842, I did one last mailing of two hundred-thirty-seven forms to request these reports; only *five* forms were filled out and returned to me; there was no response to the others. Then, tired and weary at having printed, sent, and stamped these forms and letters at a total loss and seeing in addition that the value of my theory was abundantly verified by deliberations of the Conseil General as we have seen and by six certificates that will be cited, I stopped sending requests and I have let the facts speak for themselves in the seventeen departments that I have explored since then. Proof that the facts have spoken favorably is that the number of requests increased continuously from the beginning until the end of my hydroscopic work. When I had to give up exploring departments, I had more requests to honor than I had ever had and it would have taken at least eight years even if I had not done any additional ones.

Here are, according to what I have been told, the reasons why mayors did not deliver these certificates:

They regarded with indifference the verification of a success, which according to them could add nothing to the already large number that was already known. Some did not provide certificates because they wanted to be sure for a certain number of years that the underground watercourse would not dry up; others because in the act of indication, I had announced only *one* underground watercourse and in the excavation they had found *two* and sometimes *three*; others because the underground watercourse that was found was shallower than what I had declared; many others because when water was discovered the underground watercourse had filled the excavation with water, which prevented them from verifying that it had precisely the volume that I had declared, etc.

As a result of the universal negligence of landowners who had found springs toward reporting them and the mayors toward confirming them, I probably do not know one eighth, perhaps not even one tenth, of the underground watercourses that were found. But based on the ordinary progress of the projects I observed, I have reason to believe that *at least eight to nine thousand excavations* were made in response to the 10,275 indications I made.

Here are certificates that the prefects of Lot gradually delivered to me, as reports of successes were sent to them from the Department of Lot or other departments and the number of failures were recorded.

*Prefecture of the Department du Lot*

"The prefect of the Department of Lot certifies to whom it may concern that reports prepared by mayors and submitted to the prefecture show that out of fifty-three wells or fountains that have been dug as of today based on the theory of Father Paramelle, hydroscope of the

Department of Lot residing in Saint-Céré, forty-nine have succeeded in finding healthy and abundant groundwater and all have been found at depths less than he had stated.

Issued at the Hotel de la Prefecture, Cahors, 5 February 1834.

"For the Prefect and by delegation, the dean of the prefecture council, secretary general,

(The seal of the Prefecture is here) “Perier"

*Prefecture of the Department du Lot*

"The prefect of the Department of Lot certifies to whom it may concern that reports prepared by mayors and submitted to the prefecture show that out of seventy-five wells or fountains that have been dug as of today based on the theory of Father Paramelle, hydroscope of the Department of Lot residing in Saint-Céré, sixty-nine have succeeded in finding healthy and abundant groundwater and all have been found at depths less than he had stated.

Issued in Cahors, at the Hôtel of the Préfecture, 2 August 1834.

“The prefect of Lot:

(The seal of the Prefecture is here)

DECOURT "

*Prefecture of the Department du Lot*

“The prefect of the Department of Lot certifies to whom it may concern that reports submitted to the prefecture show that out of one-hundred-and-thirteen wells or fountains dug based on the theory of Father Paramelle, hydroscope of the Department of Lot residing in Saint-Céré, one hundred and four have succeeded in providing healthy and abundant groundwater and all have been found at depths less than he had stated.

Issued in Cahors, at the Hôtel of the Préfecture, 29 January 1836.

The prefect of Lot:

(The seal of the Prefecture is here.) “De Ségur d'Aguesseau "

*Prefecture of the Department du Lot*

"The counsel to the prefect of the Department of Lot certifies to whom it may concern that reports prepared by mayors and submitted to the prefecture show that out of one hundred seventy-four wells or fountains dug based on the theory of Father Paramelle, hydroscope of the Department of Lot, one hundred sixty-one have succeeded in finding healthy and abundant groundwater, and all have been found at the depth indicated or at shallower depths.

Issued in Cahors, at the Hôtel of the Préfecture, 21 November 1837.

(The seal of the Prefecture is here.) "BOBY DE LACHAPELLE"

*Prefecture of the Department of Lot*

"The counsel to the prefect of the Department of Lot certifies to whom it may concern that reports prepared by mayors and submitted to the prefecture show that out of two hundred fifty-two wells or fountains that have been dug based on the theory of Father Paramelle, hydroscope of the Department of Lot, two hundred thirty-four have succeeded in finding healthy and abundant underground watercourses, and that all have been found at the depth indicated or at shallower depths.

Issued in Cahors, at the Hôtel of the Préfecture, 27 August 1839.

(The seal of the Prefecture is here.) BOBY DE LACHAPELLE. "

*Prefecture of the Department of Lot*

"The counsel to the prefect of the Department of Lot certifies to whom it may concern that reports prepared by the mayors and submitted to the prefecture show that out of three hundred thirty-eight wells or fountains dug based on the theory of Father Paramelle, hydroscope of the Department of Lot, three hundred and five have succeeded in finding healthy and abundant underground watercourses, and all have been found at the depth indicated or at shallower depths.

Issued at the Hotel de la Prefecture, Cahors, 1 February 1843.

The seal of the Prefecture is here. BOBY DE LACHAPELLE"

As of the date of the last certificate, in addition to the 305 underground watercourse discoveries announced, I had in my possession a list of 237 other successes that had been reported to me and that I was able to confirm. Since that time 446 others have been reported to me; which comes to 683 announced but not confirmed successes. Almost all these successes have been made known to me by departmental newspapers that have come into my possession or by inhabitants of regions visited that I have met by chance in my travels, whom I believe to be well informed and of good faith. The proportion of successes to failures has, as we have seen, remained almost the same during the first fourteen years of my exploration, and it would not be hard to believe that this proportion would have remained the same over the last eleven years.

To substitute for the lack of regular certificates, which were impossible for me to obtain, and to establish the value of this theory for the public, to the extent that it is in my power, I had to take recourse to testimonials recorded in certain newspapers, which report many of the results, and the opinion that has been shaped by them. It is true that full confidence should not be placed in a single newspaper that reports one or two successes that I obtained in a location or that publishes an individual opinion on this subject; however, when a large number of them report facts that have occurred in their vicinity and that have not been contradicted by persons who were in a position to verify them, these opinions and numerous facts cited in support end up establishing a moral certainty to which a sensible man would not deny his assent. It is with these reservations that I set forth for the readers' eyes the opinions and discoveries of underground watercourses reported in newspapers.

*L'Abeille du Lot*, 11 November 1829: "Father Paramelle undertook research and experiments on a large area of our causses [dry karstic limestone plateaus - tr. note] based on the simplest theories of physics; they have been a complete success almost everywhere; they show the zeal and intelligence of their author."

*La Gazette du Périgord*, 6 November 1833, after reporting seven discoveries, adds: "All these declarations and successes have been verified by reports from the mayors. His theory is not infallible, as he himself says with naivety but it astonishes the most learned people and destroys the incredulity that generally precedes him and never follows him."

Same newspaper, 16 November 1833: "Today now that multiple and incontestable facts have destroyed beyond a shadow of doubt in all minds, the enthusiasm and confidence of the most blind have given way to the so natural sentiment of suspicion regarding the solution of a problem that has occupied all people on earth since the time of the Egyptians and learned men of all ages."

Same newspaper, 26 March 1844 [typo in original, year is probably 1834 - tr. note]: "Father Paramelle has returned to our department. On all sides, the requests multiply as he travels; his reputation has spread since his last tour. There are none more incredulous than those who have not seen and do not understand. It is not us who take it upon ourselves to make understood that which we have difficulty explaining, but it would be easy to make it visible to anyone who does not want to close his eyes."

"The facts are stubborn by nature; the facts are thus the best response to present to those who still doubt."

On 28 March 1834, the same newspaper reported seventeen discoveries and on 30 March 1834 eighteen more discoveries.

*L'Écho de Vésone,* 9 November 1833: "Father Paramelle, famous for his hydroscopic work, has arrived in Périgueux, and at this time he is walking around this city ... He has progressively worked his way through the cantons of ... and everywhere has left the most convincing proof of the infallibility of his method; he has everywhere indicated and exposed springs, fountains, and watercourses whose existence had not been suspected."

Same newspaper, 18 May 1834: "The success that Father Paramelle has in the discovery of underground watercourses becomes increasingly incontestable. How can we not bow before the evidence of the numbers? The reports show that among underground watercourses indicated and dug, the ratio of water found to water not found is thirteen to one. Father Paramelle's process has, if not complete certainty, at least a high probability of success."

*La Gazette du Berry*, 27 September 1834: "His knowledge is really something of a miracle. How can we understand that during his first inspection of the landscape, he can say with certainty: *There is groundwater here; it is at such depth, such volume; the water is good or bad quality; it goes in this direction*. This is how he spends his days."

*Le Journal de Savoie*, 4 June 1836: "Father Paramelle has just completed a tour in the province of Savoie proper, during which the following were discovered: (A list of underground watercourses follows.) They appeared precisely at the depth and volume predicted. "

*La Quotidienne*, 7 December 1836, reports on a memoir read by Mr. Geoffroy-Saint-Hilaire to the Académie des Sciences, of which the newspaper cites the following passage:

"Among priests whose work has some lasting effect, we cite Father Paramelle. His skill in the art of finding underground watercourses has nothing to do with the instinctive movements of the divining rod; it is based on science and observation. Through practice he has acquired an accuracy of first glance so that all he needs is the simplest inspection of the lay of the land to indicate the place and depth to which one must resort to find underground watercourses. His successful results have earned enough celebrity to convince the most incredulous."

*Le Rhutenois*, 15 February 1837: "*There is groundwater here*, he says, upon simple inspection; *it is at such depth, has such volume, the water is good or bad quality; it flows in such and such direction*. Let us cite one fact among thousands. A landowner whose spring used to irrigate his prairies saw his spring disappear. The basin where it once flowed had filled in with stones. Our hydroscope was asked to find this fugitive spring. Refusing all documents, he soon designated the original basin of the spring, its new direction, the point where the waters separated, the point or points where the water reunited again. These indications were found to be exact. Mr. Paramelle's gaze seems to penetrate the entrails of the earth and to probe layer by layer. "

*Le Garde national de Marseille*, 17 April 1838: "Father Paramelle continues his exploration in our territory. So far, research conducted based on the indications of the famous hydroscope have produced excellent results." And he cites three successes.

*Le Mémorial d'Aix,* 19 May 1838: "Something that arrogant studies had never been able to find, a poor country priest, somewhat of a geologist, no doubt, but an especially good observer has finally discovered. Here no hesitation, no long calculations. After a quick glance at the location, Father Paramelle indicates not only the place where an underground watercourse should be excavated, but also the depth at which it will be found. He predicts the volume, and more surprisingly, the quality. All this is said with such terseness, such precision, and at the same time, such simplicity that the most skeptical are led to believe.

"Moreover, Father Paramelle has already traversed several departments and the newspapers have spoken only with the praise that his precious discovery merits. We think that our arid Provence and the city of Aix in particular should not neglect this help that is in some way providential... Thus, as soon as the benevolent indicator appeared, the crowd hastened to follow him."

*La Gazette du Midi*, 24 October 1839: "Father Paramelle arrived in the Department of Var on the 10th of last April and explored the districts of Toulon and Brignoles. He indicated a considerable number of underground watercourses and there are already about fifty known and officially verified successes. (Here follows a list of nineteen discoveries.) All these underground watercourses have been found at the exact depth indicated by Mr. Paramelle or at a lesser depth. They all have a volume greater than he had predicted.

"The other results are not yet known, but the first successes have given such impetus to the districts of Draguignan and Grasse that the number of subscriptions has doubled since the end of June; they have increased to 1,400 at this time and each day new ones arrive at our prefecture.

"At the Marseille prefecture and the sub-prefecture in Aix, they have officially verified seventy successes obtained in the Department of Bouches-du-Rhône. There are still only four non-successes, and two officially confirmed.

"These numbers and names say more than a thousand words. What science has had more success and has received fewer denials than this able hydroscope?

*L'Université catholique*, Paris, February 1840: "Father Paramelle indicates the number of meters and decimeters at which one should discover an underground watercourse, designates the nature and thickness of the layers to dig through, and finally the quantity of water that one will find. The exactitude of all these indications proven a thousand times and the speed with which they are given are truly surprising and admirable.

"In these southern regions, the work of Father Paramelle is appreciated as it should be and the announcement of this arrival is an event. Populations get stirred up when he arrives."

*La Haute-Auvergne*, 21 December 1844: "We read in the *Presse*: Thanks to geologic science, we can today follow with the mind's eye the subterranean pathways that water digs in the depths of the earth. What could be more astonishing, for example, than the hydroscopic investigations of Father Paramelle? Take him to an area that is entirely unknown to him, let him walk for several hours around the territory of the town, and when he comes home he will prepare a map of all the watercourses hidden under the earth. He will describe their movement and thickness and he will tell you where they start and where they go, and he will calculate with certainty the expenses one would incur to take advantage of them. The smallest trickles of water cannot escape his piercing view."

*Le Courrier de la Montagne*, newspaper of Pontarlier, 1st May 1845: "The towns of the Department of Doubs already enjoy thirty-eight discoveries based on his indications."

*Le Spectateur of Dijon*, 12 May 1849: "Can one doubt or contest the merit or the science of Mr. Paramelle when each day countless facts speak in his favor? Do we not have as of today twenty-nine departments in France that have heaped praise on the fortuitous discoveries of this learned geologist? At this moment do we not see our neighbors (Doubs and Jura) make these marvelous discoveries reverberate in newspapers, discoveries designated with a surprising perspicacity in the course of his exploration that he is actively pursuing today?

"The cantons of Lons-le-Saulnier, Beaufort, Saint-Amour, Saint-Julien, Orgelet, Conliége, and others just explored today have the satisfaction of possessing numerous underground watercourses that were unknown to them and that seem to have been born under the feet of this knowledgeable man. The inhabitants of cities and countryside are amazed."

*La Sentinelle of Jura*, 16 September 1845: "They notify us from Saint-Amour that everywhere that Father Paramelle indicated underground watercourses in the vicinity of this city, his geologic science has never once been wrong. (A list of four discoveries follows.)

*Le Journal of Reims*, 8 May 1846, reporting on yesterday's meeting of the Académie of this city, says:

"Mr. Pinon shows copies of various letters from the prefects, who all attest the excellence of Father Paramelle's procedures for discovering springs and underground watercourses; of a report made to the Société of Agriculture and Commerce of Rouen by Mr. Girardin, distinguished professor of chemistry; of another report to the Société of Agriculture of Seine-et-Oise presented by Mr. Huot, the successor of Malte-Brun; and an extract of a speech by the Prefect of Seine-et-Oise, which says:

"Now that experience has confirmed the reality of Father Paramelle's power, we could not popularize too much his science in our regions, and we must give the greatest publicity to the success he has obtained. The facts are so numerous and have accumulated to the extent that doubt is no longer allowed. We estimate the number of springs discovered by this learned hydroscope at about 6,000 in more than thirty departments."

*La Gazette of Metz*, 12 January 1848, lists six discoveries in the area near Rambervillers (Vosges), and adds: "About two months ago, the official documents announced that the number of springs found in the Vosges was twenty-five. This number has been vastly exceeded today because for one thing, we are aware of numerous discoveries that occurred after this period of time; and in addition, it is certain that through lack of concern or other motives, many mayors or landowners neglected to inform the higher administration of the success of their research. "

In addition to the newspapers just mentioned, I also have in my office *two hundred sixty-four issues* of various newspapers from Paris and the departments that writers had the extreme kindness to send me or that subscribers have kindly sent me; they also spoke to me of more than one hundred other articles from newspapers I have not seen. All report facts analogous to those that have just been discussed or express the same opinions. I limit these citations here to avoid making this chapter excessively long and boring.

However, it is not enough to establish the value of this theory for the public by reporting testimonials that are favorable to it; I must also discuss three newspaper articles in which this theory is attacked. These are the only ones that are known to me.

1. *L'Écho de Vésone*, newspaper of Périgueux, in the month of November 1833, published a letter that a lawyer had sent to point out to the public an unsuccessful excavation conducted at the home of his brother-in-law and to warn all landowners that they should not resort to my indications.

2. *Le Sémaphore de Marseille*, in issues of the 3rd and 4th of July 1838, contains an essay on my exploration in which a learned man, without citing a single failure, undertakes to prove that I have never found any underground watercourses. Here in his own words are the assertions that form the basis of this article: "*We are convinced that he* (M. Paramelle) *does not discover underground watercourses...he is in no way a discoverer of underground watercourses...we establish that Mr. Paramelle does not discover underground watercourses that he does not proceed from the basis of the nature of the ground or the direction and inclination of layers...and these conclusions are pushed as the evidence of a demonstration*.

3. *L'Éclaireur du Midi*, newspaper of Avignon, July 1842, published an article on magicians, soothsayers, and sorcerers, at the end of which one reads the following:

"What do you think of Father Paramelle? I think he has geologic knowledge because he finds water on a regular basis. It would be truer to say: *He has impressions, convulsions, sensations, diabolical visions*. Mr. Paramelle is no more skillful nor more of a sorcerer than ordinary sorcerers. He just takes more care to hide *the diabolical signs that he receives from the evil spirit*. He covers these *magical procedures* with appearances and scientific jargon."

Various people responded immediately through newspapers to these attacks by citing my daily successes. For my part, I have never written a word trying to refute them and I think it would be useless to do so today.

Such are the documents for and against what I have been able to provide as the results of this theory. I feel very deep regret at not being able to give an exact number of all the successes and failures resulting from my work; this would have spared me the displeasure of citing newspapers that considered it appropriate to mix into their reports elegies that I am far from meriting. What is certain is that, although no one would take into consideration what is reported in the public pages or what had been announced to me, and that a person would want to hold strictly to successes and failures verified by the prefecture of Lot, by taking the average of the two, we find that *failures account for about one twelfth the number of successes*, which greatly exceeds the promises I made to the Conseil General and surpasses even my earliest hopes.

Such is in all simplicity the theory of *the Art of Finding Springs* that I applied for a quarter of a century in forty departments and that I have just explained to the best of my ability. Anyone who wants to apply it and succeed on a grand scale will prove that he has perfected it, and he who succeeds to a lesser degree will find that I was not able to explain it or that he was not able to understand it.

## 2.4.32. Chapter XXXII. Ancient and Modern Methods of Finding Underground Watercourses

After this presentation of new methods that have been developed for finding underground watercourses, I think the reader will enjoy learning about some methods that ancient and modern fountain builders have given us, to compare them so that the reader can use methods he prefers.

Vitruvius worked for the glory of Augustus and in his ten books on architecture he shows us the perfection that the arts and sciences reached during the reign of this emperor. He also discusses the various ways used at that time to find water; here is what he says in book VIII, Chapter 1, according to Perrault's translation:

"To find places where water is present, it is necessary to lie on one's stomach with the chin leaning on the ground a bit before sunrise at the place where he is seeking water and to look across the countryside; because with the chin thus supported, the viewpoint will be no higher than necessary; but it will certainly extend at level and if at some place a humid vapor is seen to rise in an undulating way, it is necessary to dig there, because that does not happen in places that lack water.

"In addition, in the search for water, the quality of the ground should be examined because in some places water is found in abundance; because water found in chalk is never abundant and does not have a good taste. In shifting sand [Fr. *sable mouvant*], water is present in small quantity, even muddy and unpleasant if it is found after deep digging. In *terre noire* [chernozem – tr. note], water is better if it is collected from rain that falls in the winter and after flowing across land located in solid and not spongy places; water that springs from sandy ground such as water found on riverbanks is also good, but the quantity is mediocre and veins are not guaranteed. Water is most certain and good in fine sand [Fr. *sablon mâle*], gravel, and *carboncle* [did not find an English equivalent – tr. note]. In red rocks [Fr. *pierre rouge*], water is also good and abundant provided it does not escape through joints in the rock. At the foot of mountains, among rocks and pebbles, water is abundant, cooler, and healthier. In valleys water is salty, heavy, tepid, and unpleasant; if the water comes from mountains and only if it is conveyed underground to these places or shaded by trees will it have the pleasant freshness that people notice in water that comes out at the foot of mountains.

"In addition to what has been said, other signs point to places where water can find be found. These are places where small rushes or willows have grown by themselves, alders, vitex [genus of flowering plants in the *Lamiaceae* family – tr. note], reeds, ivy and all other plants that spring up and grow only in places where water is present. However, it is important not to rely on these plants if they are seen in swamps because these places are lower than the rest of the countryside and receive and collect rainwater that falls on surrounding fields and during the winter preserves water for a long time; but if these plants grow naturally in places that are not swamps and without having been planted there, water may be found there.

"If these signs are lacking, this test can be done. After digging a hole in the soil three feet wide and at least five feet deep, a container made of bronze or lead, or a basin, is placed at the bottom of the hole at sunset. The container is rubbed with oil on the inside and turned over and the pit is covered with cane and leaves and finally with soil. If water drops are found inside the container on the next day, this shows that the location has water.

"Or a terra cotta pot can be placed in this pit and covered as described previously; if water is present in this place, the pot will be damp and waterlogged with humidity. If wool is also left in this pit, and if on the next day, water flows from the wool, this is a sign that the place has a lot of water.

"If a lighted lamp full of oil is enclosed and if on the next day, it is not completely used up, and the oil and the wick are not totally used up, or even if the lamp is wet, this signifies that water is present under this place because the gentle heat attracts humidity.

"Another test can be done by lighting a fire in this place because if a thick vapor arises after the ground is heated, it is a sign that there is water.

"Once all these tests have been done and the signs we have just discussed show up in a place, it is necessary to dig as for a well: if an underground watercourse is found there, it will then be necessary to dig other wells all around and join them together by underground conduits; but it is necessary to know that it is principally along the northern slope of mountains that water should be sought, and that it is there that the best and healthiest and most abundant water is found because these places are not exposed to the sun, they are covered by thick trees, and the downward slope of the mountain makes shade, ensuring that rays of sunlight that the slope receives obliquely cannot desiccate the ground.

"Rainwater also collects in hollow places on top of mountains and trees grow there in large numbers and store snow a long time, which melts little by little, and flows imperceptibly through veins in the ground; and it is this water that comes down to the foot of mountains and makes springs there. But underground watercourses that flow from the bottom of valleys cannot have much water and even if it were abundant, it would not be good because the sun heats plains that have no shade to prevent it and consumes and exhausts all secretions or at least pulls out the lightest, purest, and most healthy, which are dissipated into the vast extent of the air, leaving only the heaviest portions, the most flooded, and the most unpleasant in country fountains . . ."

Pliny understood the importance of good water to a comfortable life too well to have neglected to give methods for finding it in arid places. Thus, he did not fail to talk about it in his *Histoire Naturelle* [Natural History], Book XXXI, Chapters XXI, XXII, and XXVIII. He summarizes what Vitruvius, who had preceded him, had written at greater length. This is what he says, based on the translation of Mr. Ajasson de Grandsagne, Paris, published by Panckoucke, 1833.

“It is appropriate to indicate here how the search for water is done. Water is found primarily in valleys, either at the intersection of diverse slopes or at the foot of mountains. Many authors want to believe that all slopes exposed to the north provide water.

"Natural indications of water are rushes, reeds, or the plants named below, and especially frogs found lying on their stomachs. The erratic willow, alder, vitex, bushgrass, or ivy, either grow spontaneously or are watered by rains that fall from high places onto depressions. Thus, they often give false indications. One less problematic indication is the nebulous exhalation [Fr. *exhalaison* *nébuleuse*] which is seen from afar before sunrise and that some people observe from an elevated location, lying on their stomachs, with the chin lying on the ground. Only experts are aware of another way of seeing it, which consists of noting, in the middle of summer and at the hottest time of the day, the place where sun rays are reflected most strongly. If, in spite of drought, a similar place is found to be humid, the presence of water can be concluded; but the view must be so strongly held that the eyes suffer. To avoid this problem a person has recourse to other tests: the earth is excavated to a depth of five feet, the hole is covered with an unfired earthen pot or a copper basin basted with oil; a lighted lamp surrounded in a nest of leaves is placed on top. If the clay pot is found to be wet or cracked, the copper container wet or the lamp extinguished without the oil being used up or the wick soaked, these are signs of water. Some people light a large fire at the place, which makes the experiment more decisive.

"The land indicates the presence of water when it has stains, either white or green. Steady flowing water rarely flows on chernozem; potter's clay [Fr. *terre à potier*] removes all hopes of finding it. Those who dig wells stop digging when they observe several layers that are like layers of soil and the ground changes from black earth to green. In sand, water is in small quantity and it is murky. Gravel provides only uncertain veins; however, they have an excellent taste; sand, fine sand, and hard tufa always contain permanent and healthy water. Rocks at the foot of mountains and flint indicate extremely cool water. But when digging in the ground, one must encounter wetter and wetter layers and places where iron sinks more easily."

Cassiodorus, who was minister to Théodoric, king of the Ostrogoths, was devoted to providing prompt and exact justice to people and giving them relief by decreasing taxes. He applied himself with particular care to encouraging the search for springs. He had a man come to Italy from Africa who had knowledge of finding water and in addressing the governor of a province who had asked for him, he wrote him a letter of recommendation in which he said: "If you see during the experiments that will be done that this man has as much ability as they say, take care to provide for him and pay his travel from public funds; it will also be money well spent if he teaches the secrets of his art to someone. Please treat this fountain-builder with the respect that is due to all who perform useful arts for the public, so that no one can say, in our administration, that there was any neglect whatsoever in what Rome could have wished for in terms of its comfort and embellishment."

This minister, whom posterity has called the *Great* and Le Beau called a *model for ministers*, was not content with encouraging by kindness those who worked in search of springs; he himself also worked to collect indications that in his day were used to find it; here they are:

"It can be speculated with good cause that where grass is green and trees are remarkably tall that water is not far. Favorable indications include land that remains humid near the surface and that vigorously supports certain types of vegetation such as rushes, reeds, aquatic shrubs, willows, and poplars, and even any tree that reaches a greater than usual height. If one places dry wool on the ground at nightfall and covers it with an upside-down cauldron covered with soil, the wool will be wet the next morning if there is water nearby. If, in the morning after sunrise, fountain builders see clouds of small flies flying face down, always in one location, they can conclude that water is certainly present below. They also say that wherever a very slight column of vapor can be seen coming out of the ground, there is a hidden spring [an underground watercourse] that is as deep as the column is tall; and what is even more surprising is that after this sign and several others, they predict the depth of the underground watercourse they are looking for; they also predict the taste of the hidden water. In this way, costly construction to reach groundwater that is bad can be avoided, and they can take care not to neglect that which is good; they claim that water that comes out of the ground from the east and south are sweet, transparent, light, and healthy; that water that rises from the north and west are too cold and cause discomfort because of their heaviness." (*Cassiodorus*, Book III, Letter LIII).

Palladius, Dupleix, Kircher, Bélidor, Paulian, etc., also go into some detail about the signs that can be used in the search for underground watercourses but they just repeat the instructions already discussed.

In the *Encyclopédie* [*Supplement to the Encyclopedia, Nouveau Dictionnaire pour servir de Supplément aux Dictionnaires des Sciences, des Arts et des Métiers*, 1776-80 – tr. note] the article on *Abreuver* [Watering] summarizes everything that these authors had written on the art of finding springs and presents everything that the science of the day could add; here are the procedures the author indicated:

"1. If when lying on the ground slightly before sunrise, on the stomach and with the chin leaning and looking at the surface of the landscape, vapors are seen rising and undulating in some place, digging should be done there boldly. The best season for this test is the month of August.

"2. When, after sunrise, clouds of small flies are seen hovering near the ground, especially if they fly continuously at the same place, it should be concluded that there is water below.

“3. When there is reason to suspect water in a place, a pit should be dug, five to six feet deep, three feet wide, and at the end of the day an upside-down cauldron whose interior is rubbed with oil should be placed at the bottom; close the entrance to this pit with planks covered with sod. If on the next day, you find water drops attached to the inside of the cauldron, it is a sure sign that water is present below. Some wool can be placed under the basin, and by squeezing the wool, it can be determined if the underground watercourse is abundant.

"4. A wooden needle can also be placed in equilibrium in this pit, with success; a sponge should be attached to one of its ends. If there is water, the needle will soon lose its equilibrium.

"5. Places where frogs are frequently seen lurking and pressing the earth will infallibly indicate the tributaries of an underground watercourse; just like places where rushes, wild balm, silverweed, ground ivy, marsh parsley, and other aquatic plants are seen.

"6. Chalk provides a meager amount of bad water. In shifting sand, one finds only a small quantity. In chernozem that is solid, not spongy, water is most abundant. Sandy soil provides good but not abundant water. Water is more abundant in fine sand [Fr. *sablon mâle*] and bare gravel; it is excellent and abundant in red rocks. To determine the internal composition of the land, augers are used. If beneath layers of soil, sand, or gravel, a bed of clay, marl, or good soil [Fr. *terre franche*] and compact is seen, without doubt an underground watercourse or trickles of water will soon be found.

"7. At the foot of mountains, among rocks and pebbles, springs are most abundant, cooler, more healthful, and more common than elsewhere, principally at the foot of slopes that face the north or are exposed to a humid wind. Mountains with gentle slopes covered with plants generally have lots of ridges; the same is true of mountains split up by small valleys located on top of each other, the east or northeast sides, or even the west are commonly the most humid. Only dupes can be tricked by the divining rod and superstitious fountain-makers or charlatans who dare to use them."

In the same book [*Nouveau Dictionnaire pour servir de Supplément aux Dictionnaires des Sciences, des Arts et des Métiers*] is an article on *Source* [Springs] that contains the following indications: "1. Late at night or in the early morning when all is tranquil, if a hole is made in the earth and if an ear or the large end of a paper funnel is placed there, with the small end of the funnel in the ear, if there is water flowing under the ground in this place or nearby and if it is not too deep, a murmur will be easily heard; but if the water is not moving, this method will not be useful. 2. Another indication is that of odor because in the morning or evening someone who has a fine sense of smell can, when it is dry, distinguish between humid air and air that is not, especially by opening the ground in various places and comparing the different airs.

"But the most certain way of finding *underground watercourses* is to use a probe. It seems that right away other methods could be avoided because this method is the best. However, recalling what was previously said, although the nature of the ground is such that it can contain water, a lot of work may have to be done before being able to find it by opening the ground. Thus, the probe should not be used purely and simply; because if the ground does not contain moving water or trickles of water that flow within a small space, how would it be possible to find them right off without some element of risk using an instrument that makes a hole that has a diameter of two inches? Thus, before probing, it is necessary to use the preceding indications to determine places through which underground watercourses or water trickles flow; then by using the probe in these places, it can be assured that water will be found after this investigation, especially if it is a small trickle of water that occupies a small space because if there is some small reservoir in that place, one would not fail to find it on the first attempt.

Finally, here is a summary of everything that the science of today has been able to add to the methods we have just seen; we read in the *Globe*, 14 November 1848:

“HOW TO FIND WATER UNDER THE GROUND. If during the winter when the land is covered with snow, you notice places where snow melts quickly or grass is piercing through the snow, if during a dry and calm time you observe in the same place and at the same time a type of vapor, place a stake at this location to conduct research because it is probable that you will find water there.

"In springtime, note locations where snow melts most rapidly, where the greenery appears first and darkest, and if winter birds gather there, you can believe in the presence of a spring.

"Dew in places that would normally not have it or the presence of frost at the end of the season are also indications.

"During the summer when all the plants fade and turn yellow, look to see if some other more favorable place has a more pleasant appearance, a livelier vegetation; there you will have a good chance of finding water.

"If lots of grasses grow in wheat fields, if they put out suckers without going to seed, if the greener growth is smaller and fragile, and if after cutting, this grass grows back promptly, discovery of water can be hoped for at this place.

"The presence and healthy growth of certain plants and certain trees that love humidity in soil that does not suit them also indicates an underground spring. The presence of alder, willow, rushes, reeds, catmint, silverweed, ground ivy, bogbean, and finally if the plants that habitually grow in swamps live easily in other places, they also serve as indications.

"Places where in the morning before sunrise or after sunset on a calm evening, you observe wet and bluish vapors, if you look at the horizon as you lie on the ground; vapors that rise in certain places or places more particularly wetted by dew, also indicate the presence of underground water.

"Other general indications also lead to the discovery of underground watercourses: for example, if the land that is being dug is more humid in one place than in another; if a small amount of water is seen to be ponded and still there; if blue or plastic clay is seen located at some depth, a water discovery can be hoped for below this clay; in areas where the rock is granitic, after a layer of sand called arenite, clay is found and almost always water below this clay.

"Research done during hot periods is more useful because it can indicate underground watercourses that are less likely to dry up during drought.

"Different authors have advised various ways of trying. Bélidor suggested digging into the earth to a depth of several feet, lowering into the hole a glass or metal bell garnished with a sponge or wool, and depending on how much humidity these materials have, the presence of an underground watercourse can be inferred.

"Others have advised placing a needle about one meter and fifty centimeters long, one centimeter wide and one centimeter thick, made of a piece of well-dried linden tree on a pivot at a depth of about one meter on a summer night and leaving it there until the next day. The side that is most swollen is the one that indicates the presence of water."

END

## 2.5. TRANSLATOR'S NOTES

French words are cited in brackets in the translation if they are not obvious cognates or in cases where translation is complicated.

The following list provides explanations and research on terminology, units, and historical and literary allusions found in Paramelle's text.

1. English spring, underground watercourse; French *source*

As Paramelle explains in Chapter X, he uses the word *source* to mean both the location where water flows out of the ground and the groundwater system that supplies water to the spring. For the reader's convenience, I have translated *source* as "spring" where Paramelle is talking about the location where water flows from the ground. I have used the words "underground watercourse" in cases where Paramelle talks about the underground movement of water and/or groundwater. Paramelle was looking for shallow water that farmers could access by digging, perhaps best described as water in the "epikarst". The concept of a water table did not exist in Paramelle's day, and as near as I can tell, Paramelle thought water moved underground primarily as a single watercourse or multiple trickles.

2. English fountain/spring; French *fontaine*;

The French word *fontaine* means fountain, spring, and also the wellhead where people collect water. I have translated it as fountain when Paramelle is referring to a man-made device to supply water to people. I have translated *fontaine* as spring in cases where it seems to me that Paramelle is describing a place where water flows from rock or soil. When in doubt, I have included the French word in brackets.

3. English geognosy, geognost; French *géognosie, géognoste*

These terms have been used since before 1750. Abraham Gottlob Werner (1749-1817) applied the term geognosy to the science accounting for the origin, distribution, and sequence of minerals and rocks in the Earth's crust (Laudan, 1987).

According to Hans Baumgärtel,

“Werner purposely chose the name “geognosy” because the term “geology,” coined shortly before, seemed to him too heavily burdened with the speculative character of geogonic hypotheses. Geognosy was not to include unproved ideas, only the factual ‘knowledge of the earth’ (Schneer, 1969)

Geognosy was originally the universal study of mineral deposits, of particular interest to miners, for whom theoretical speculations were of no interest. Geognosy was the study of the structure and content of the subsurface at all scales. (Ellenberger, 1999).

Paramelle does not cite Werner, but he cites Aubuisson’s book *Traité de géognosie*, published in 1819. Aubuisson, born in 1769, left France during the 1789 revolution; during his time outside of France, he studied with Abraham Gottlob Werner in Freiberg, Germany. In 1803 Aubuisson translated a book on mining that Werner had written in 1791. Thus, it is likely that many of Werner’s ideas were contained in Aubuisson’s *Traité*.

By 1807 when the Geological Society of London was formed, geology had absorbed geognosy, had added paleontology and petrography, and had rid itself of the “vagueness” that had previously characterized the term “geology” (Ellenberger, 1999).

A geognost is a person who practices geognosy.

4. English escarpment; French *coteau*.

   English slope; French *pente*.

   English hillslope; French *versant*.

   English cliff; French *escarpement*.

Throughout the translation, escarpment means specifically *coteau*, as defined in Chapter VII, the steep part of a hillslope (Fr. *versant*). Because Fr. *pente*, *versant*, and *coteau* can all occur in the same French sentence and all can be translated as slope, there can be confusing repetitions of the word slope in the English sentence. To avoid this confusion, *coteau* is always translated as escarpment, which Paramelle defines as the portion of a hillslope between the plateau at the top and the plain at the bottom; it is the most steeply sloping part of a hillslope (Figure 3.6). Note that

that this use of "escarpment" does not imply a slope as steep as the English word escarpment implies. The French *pente* is translated for the most part as slope in the sense of dip or inclination; Paramelle also uses it to refer to an inclined surface. *Versant* is everywhere translated as hillslope. I have translated the French *escarpement* as "cliff."

5. English diluvium and diluvial; French *diluvium, diluvien*.

As used in Paramelle's time, these terms described sediments deposited by conditions that no longer prevailed in the 19th century. Geological theories related these surficial deposits to various causes including large water and mud flows. Alluvial deposits overlay diluvial deposits and diluvial deposits included erratic blocks transported long distances that sometimes overlay polished surfaces. The alluvium/diluvium distinction was of interest because while 19th century processes produced alluvium, diluvial deposits could not be explained by actual, present-day geologic processes. This perceived break in continuity of earth processes thus challenged the concept of uniformitarianism, the idea that the present was key to the past and generated intense controversy among geologists of the day. Beginning in the 1820s, geologists began accumulating evidence of erratic blocks over large areas of Europe and other continents, discovering polished surfaces and striations. Today we consider diluvium to be glacial deposits (Rudwick, 2008).

6. French *clysmien*

This word is related to the word "cataclysm" Greek in origin and equivalent to a flood; thus a "terrain clysmien" is an alluvial deposit (Bakalowicz, personal communication 2017).

7. English hydroscopy, hydroscope; French *hydroscopie*, *hydroscope*

Numerous newspaper articles refer to Paramelle as a *hydroscope*, a person who practices the science of *hydroscopie*, the search for water. According to the *Dictionnaire de la langue française* (Littré, 1873-74), a hydroscope is a person who looks for springs or groundwater, especially a person thought to have the ability to feel emanations from groundwater. The word *hydroscope* was also used for a dowser (Bakalowicz, personal communication 2017).

The Littré defines *hydroscopie* as the art of finding springs, especially through emanations from groundwater; also, the ability to predict storms, by experience, especially at sea. The etymology of the word is two Greek words, for "water" and "examine." The word has been recycled; *Webster's New Collegiate dictionary* (1981) defines a hydroscope as a mirror device enabling a person to see an object at a considerable distance below the surface of water.

8. English hydrography; French *hydrographie*:

In 20th century usage, hydrography refers to the science that deals with the physical aspects of water on the Earth's surface. A hydrographer: person who practices hydrography. Paramelle uses the term six times in the book, always as *hydrographie souterraine*, underground hydrography.

9. English primitive, primary, transition, and secondary; French *primitif, primaire, transition*, *secondaire.*

These words have a long tradition in the study of the earth. Abraham Gottlob Werner divided the Earth into five formations or series: primitive, transition, secondary, alluvial/tertiary, and volcanic. Although Paramelle does not cite Werner as a source of geologic information, it appears that during Paramelle's time Werner's classification was widely used. Paramelle cites the book of Aubuisson des Voisins (1769-1841), *Géognosie*, which appears to be the *Traité de Géognosie* published in 1819, one of the first geologic books published in France. The word primary appears to be used as a synonym of primitive.

Earlier use of these terms goes back to Italians Marsigli in 1711 and Moro in 1740. The terms were included in a classification by a pre-Wernerian geognost named Giovanni Arduino (1714-1795), a forward-thinking Italian mining engineer and careful observer who divided local rocks into four divisions: primary, secondary, tertiary, and fourth. Primary were high mountains with ores, micas, and quartz veins but no fossils; secondary were high mountains such as marbles and limestones with parallel strata, which overlie, underlie or juxtapose against primary mountains; tertiary were hills consisting of debris from the first two categories; and fourth were alluvial rocks. These terms are used in the modern geologic time scale. (Ellenberger, 1999)

Apparently Werner added the term "transition" to Arduino's classification.

Because of their historical significance, I have left these terms as primitive, primary, transition(al), secondary, and tertiary in the translation.

10. English terrain and others; French *terrain, terrein*

This French word falls into the category of the “false friends,” words that look alike in French and English, but have different meanings. To determine the 19th century meaning of *terrain*, I consulted the on-line Littré dictionary (*Littré*, 1873-1874). The French word “*terrain*,” also spelled “*terrein*” had multiple meanings in the late 19th century; here we will consider the three geographic/geologic definitions. 1) “an expanse of land;” this term would be translated into English as “ground, land, field.” 2) “land” in general; “*un excellent terrain*” = “excellent land.” Definition 3 is a “*terme de géologie*, a name given to rocks considered with respect to the extent they occupy and according to the method and time of their formation. Geology is the science of *terreins*. The *terreins* are distinguished according to the relative time of their formation and divided into, secondary, tertiary or later.” It is clear that definition #3 has the meaning of English rocks, rock units, and formations, a vertical meaning as compared to the horizontal meaning of definition #1.

For the 20th century meaning of this term, the *Dictionnaire des sciences de la terre* [Dictionary of Earth Sciences] (Michel et al., 2004) French-English geologic dictionary lists the following English meanings for *terrain*: ground, land, earth, rocks, strata, formation, terrane (US). The *Dictionnaire des sciences de la terre* [Dictionary of Earth Sciences] (Moureau and Brace, 2000) French-English dictionary lists the following English meanings for *terrain*: ground, land, terrain. This dictionary defines *terrain de transport* as diluvium or glacial drift deposits, as opposed to alluvium.

Paramelle’s book contained a list of 52 different phrases containing the word *terrain* so I used additional sources of information to translate these terms. Two French reviewers (J.P. Nicot and G. Frébourg of the University of Texas Bureau of Economic Geology) provided help with this terminology. My translations of the term *terrain* in Paramelle’s book include the following: rocks, rock units, ground, land surface, field, area, surface geology, formation, material, plot of ground, soil, and terrain. In some cases, there is no word for *terrain* in the translation, as in: *terrain tuffeau = tufa.*

11. Thalweg

Paramelle introduces the German word and concept of thalweg in footnote 2 of Chapter II of *The Art of Finding Springs*, defining it as "*chemin de la vallée*" or valley path, the path that water follows, always the lowest line on the plain, and he encourages the "student hydroscope" to study it because of its importance in the search for water. The *Glossary of Geology* (Neuendorf, et al., 2005) defines "thalweg" as a geomorphological term meaning "a line of continuous maximum descent from any point on a land surface," as a groundwater term "a subsurface groundwater stream percolating beneath and generally in the same direction as the course of a surface stream or valley," and in relation to streams as "a line connecting the lowest or deepest points along a stream bed, also the median line of a stream." Today most geologists would define thalweg as the groundwater flow path of high discharge.

The term thalweg entered French geologic vocabulary in the early 19th century. The first use I found was in Aubuisson's book *Traité de géognosie* published in 1819. The term and concept were readily accepted into French. It appears in Rozet's *Cours élémentaire de géognosie*, published in 1830 and in Huot's *Nouveau cours élémentaire de géologie* in 1837. Paramelle cites Aubuisson's *Traité de géognosie* in both his 1827 and 1856 books, and in the preface to the first edition of *The Art of Finding Springs*, Paramelle recommends Aubuisson, Huot, and Rozet to readers interested in acquiring more geologic knowledge.

The concept of thalweg had been described prior to Aubuisson's 1819 book, but without using the word thalweg. Desmarest had described it in part II of his article on "*Eau*" [Water] in volume 4 of *Géographie Physique*, published in the *Encyclopédie Méthodique* between 1811 and 1816 (Taylor, 2013). Paramelle cited both Desmarest and Aubuisson as references in his 1827 *Mémoire*.

12. Alambic (or alembic) theory

Between the 16th and 19th centuries, there were two major theories on where spring water comes from: rainfall and ocean water. Bernard Palissy promoted the rainfall theory, and another group of "physicists" maintained that sea water was piped through numerous underground tunnels to reservoirs beneath mountains where the water rose to the surface via a variety of mechanisms. To explain the salinity difference between sea water and fresh water, Descartes embellished this reservoir theory with the idea of distillation, creating the "alambic theory" whereby the central fire in the Earth heats the sea water present in the underground reservoir and the resulting vapors move upward to infiltrate surface rocks from below, cooling and condensing as they do so, and resulting in water in surface rocks that can flow to the surface as springs. The alambic theory conveniently removes the salt and makes the spring water fresh.

Demarest describes the history and progress of these ideas in his article *Fontaine* in the *Encyclopédie*. Paramelle's discussion of erroneous ideas on the origin of springs (Chapter XI) appears to be based in large part on Desmarest's article.

13. Encyclopedias and Dictionaries

Paramelle cites the following encyclopedias and dictionaries in abbreviated form. I have provided a full citation here and in Appendix B. Paramelle makes no distinction between the *Supplement to the Encyclopédie* and the *Encyclopédie*; he cites both as "*Encyclopédie*."

*Dictionnaire de l'Acad*. Full citation: *Dictionnaire de l'Académie Française*, (http://dictionnaires.atilf.fr./dictionnaires/ACADEMIE)

*Dict. de Trévoux*. Full citation: *Dictionnaire universel françois et latin contenant la signification et la définition tant des mots de l'une et l'autre langue, avec leurs différents usages, que des termes propres de chaque état et de chaque profession*, Nancy, 1704. Six editions were published between 1704 and 1771.

*Dict. de M. Landais*. Full citation: *Grand Dictionnaire général et grammatical des dictionnaires français,* by Landais, Napoléon. Nouvelle Edition, Volume 2. Paris, Didier, 1854.

*Encyclopédie*. Full citation: *Dictionnaire raisonné des sciences, des arts et des métiers par une société de Gens de Lettres*, 1751-1772. (http://encyclopedie.uchicago.edu)

*Supplement* of the *Encyclopédie*. Full citation: *Nouveau Dictionnaire pour servir de Supplément aux Dictionnaires des Sciences, des Arts et des Métiers*, 1776-80.

*Encyclopédie Moderne*. Full citation: *Encyclopédie moderne dictionnaire abrégé des sciences, des lettres, des arts*. Paris, 1823-32.

*Encyclopédie de Valmont de Bomare*. Full citation: *Dictionnaire raisonné universel d'histoire naturelle*, 1764.

*Nouveau Dict. d'Hist. nat*. Full citation: *Nouveau Dictionnaire d'histoire naturelle appliquée aux arts, à l'agriculture, à l'économie rurale et domestique, à la médecine. Par une société de naturalists et d'agriculteurs*, Nouvelle édition 1816-19.

14. French *bol*

*Bol* is a fine red earthy substance used to apply a red color to faïence, first used in France in Rouen around 1708. The best *bol* was reputed to come from Armenia; it is described as extremely clayey, having no sand, and red in color without any white veins. It should stick to the tongue due to its clay content. (Archeosciences website: https://archeosciences.revues.org/224 Accessed 12 September 2016).

15. *Guienne*

Also spelled *Guyenne*. This is territory in southwestern France surrounding Bordeaux that was owned/occupied by the English for centuries prior to the Revolution. (Taylor, personal communication 2017)

16. *Margaritas* of the Scripture

This is a reference to the Gospel of Matthew, 7.6. Margarita comes from an ancient Greek word meaning *milky*. It means *pearl* in Latin [Gaffiot, 1934]. In the King James Version of the Bible (www.kingjamesbibleonline), this passage reads:

Give not that which is holy unto the dogs, neither cast

ye your pearls before swine, lest they trample them under their feet, and turn again and rend you.

The metaphor advises against giving valuable gifts to those who do not appreciate them. (https://en.wikipedia.org/wiki/Matthew_7:6 Accessed December 2016)

17. *Batons flottants* are floating sticks.

This is a reference to *Le Chameau et les Bâtons flottants [The Camel and the Floating Sticks],* a fable by La Fontaine. The fable goes as follows: the first time a person sees a camel, he runs away from the unknown beast; the second time he sees a camel, he will approach it; and the third time, he will put a halter on the beast. Similarly, a ship that first appears huge on the open sea gets smaller as it approaches and finally looks like just a bunch of sticks floating on the water. Point of the fable: Repetition and familiarity turn the unknown into the ordinary. Paramelle is reflecting that his ability to find water, which amazes the general public, has become routine to him as a result of years looking for water and that anyone with some training could do the same. (*La Fontaine, 1964)* (M.A. Piwowarczyk, personal communication September 2016)

18. Tritonian sandstone

Paramelle describes this sandstone as lacking fossils but the *Littré* dictionary defines it as a rock that contains remains of marine animals (Littré, 1873-74).

19. Oligist, oligist iron is a synonym of hematite (Neuendorf et al., 2005)

20. Leptynite is mica-poor, quartz-feldspar gneiss (Kalmar and Dovacs-Palffy, 2008)

21. Eurite is a compact feldspathic rock, felsite (www.thefreedictionary.com/Eurite) cites Webster's *Revised Unabridged Dictionary*, 1913.

22. Weights and Measurement Units

| Length | | | |
|---|---|---|---|
| French | English | Metric | Source of information |
| Ligne | 1/12 of an inch | 3.175 mm | Grand Robert 2008 |
| Pouce | 1 inch or 12 lignes | | Levallois, 1988 |
| Pied | Foot or 12 pouces | 0.3248 m | Levallois, 1988 |
| Toise | 6 feet = 1 fathom | 1.949 m | Levallois, Wiki-toise, Wiki-fathom |
| Lieue | League | 3.25 to 4.68 km | Wiki-league |
| Aune | Ell | 137.2 cm | Wiki-ell |
| | | | |

| | | | |
|---|---|---|---|
| Volume | | | |
| Muid | 482.54 gallons | 1.824 $m^3$ | Wiki-muid |
| Muid | 72 U.S. gallons (wine) | 1873 liters of wheat | Larousse, 1992 |
| | | | |
| Area | | | |
| Are | | 100 $m^2$ or 1/100 hectare | |
| Weight | | | |
| Livre | Pound | 489 - 500 g | Grand Robert, 2008. |
| Gros | 1/8 ounce | 3.824 grams | Wiki-units |
| | | | |

Key to internet references

Wiki-ell: https://en.wikipedia.org/wiki/Ell Accessed May 2017

Wiki-fathom: https://en.wikipedia.org/wiki/Fathom Accessed May 2017

Wiki-league: https://en.wikipedia.org/wiki/League_(unit) Accessed May 2017

Wiki-muid: https://fr.wikipedia.org/wiki/Muid Accessed May 2017

Wiki-toise: https://en.wikipedia.org/wiki/Toise Accessed May 2017

Wiki-units:

https://en.wikipedia.org/wiki/Units_of_measurement_in_France_before_the_French_Revolution

Accessed May 2017

23. Additional information on units

Prior to the French Revolution, measurements in France were based on the Carolingian system established during Emperor Charlemagne's reign (800-814 CE), which standardized measurements across the empire. Over time, other measurements were introduced to the point that by 1789 as many as eight hundred different names for various units of measure were used.

The term *ligne* or line is used in present-day Canada, where a line equals 3.175 mm.

The *pouce* (inch), *pied* (foot), and *toise* (fathom) were relatively consistent throughout France over time. The *pied du roi* (the king's foot), dating from Charlemagne's time, remained relatively unchanged (Wiki-units), at 0.3248 m (Levallois, 1988).

The *toise*, equivalent to a fathom, originally established in 790 CE, is equivalent to 6 *pieds* (feet); it was replaced in 1668 by the *toise du Châtelet* (Wiki-units). The *toise du Châtelet* was the distance separating 2 lugs or spurs embedded in a wall of the Grand Châtelet, a castle near the Seine in Paris, where cloth and other merchants were required to compare or set their measuring tools (Levallois, 1988). In 1747, the Châtelet *toise* was replaced by the *toise du Pérou*, which was very similar in length (Wiki-units). In 1799 when the metric system was established, the *toise* was defined as equivalent to 1.9490366 m (Levallois, 1988).

The *lieue* or *league* (from vulgar Latin, *leuca*) (Larousse, 1992) was originally the distance a person could walk in an hour (Wiki-league). At different times, it ranged from 3.258 km in Beauce to 5.849 km in Provence (Wiki units). As used in Jules Verne's *Twenty Thousand Leagues Under the Sea*, a league is equivalent to four kilometers (Wiki-league).

An *aune*, etymologically related to Latin *ulna* for arm, related to "el" of "elbow" was a unit used for measuring cloth (Wiki-ell) Accessed December 2016).

The *muid* (from Latin *modius*, measure) is an ancient unit of measurement for liquids, grains, and surface area. Its values varied over time, from region to region, and depending on the merchandise being measured.

In the 18$^{th}$ century, the Paris muid (for dry materials) was 1,824 $m^3$. At the same time, the Paris liquid muid was equivalent to 2884 liters (based on a *muid* being equivalent to 36 *setiers* and a *setier* being equivalent to 8 *pints*) (Wiki-muid)

24. Money

*franc*: National currency of France from 1795 until 1999, 1 franc = 100 centimes. Question: What was the value of a franc in Paramelle's time? In Chapter XXVIII, Paramelle talks about a servant's wage of 1 franc/day and of ten work animals whose daily worth is 10 francs. It is not clear if Paramelle was using these number as illustrations or if they were actual wages of the day.

*sou*: equals 1/20 of a franc. Numista (http://fr.numista.com/forum/topic969.html Accessed December 2016.

25. Metric System

The Law of 10 December 1799 instituted the metric system and set the following equivalencies:

1 meter = 443.296 *lignes* = 3 *pieds* 11.296 *lignes* of the *Toise de Pérou*

https://en.wikipedia.org/wiki/History_of_the_metre#M.C3A8tre_des_Archives

The *pied du roi*, the French royal foot, was set at 0.3248 m https://en.wikipedia.org/wiki/Foot_(unit)

26. Paramelle's use of units

I conducted a quick analysis of the text of *The Art of Finding Springs* to quantify Paramelle's use of metric and older measurement terms.

Paramelle uses the following metric terms:

| Term | Frequency |
|---|---|
| millimeter | 5 |
| centimeter | 27 |
| decimeter | 29 |
| meter | 91 |
| hectometer (100 meters) | 1 |
| kilometer | 27 |
| myriameter (10,000 meters) | 7 |

Overall, there are 339 occurrences of "*mètre*" but many are parts of words such as *perimètre, diamètre, udomètre, atmidomètre*, etc.

Paramelle also uses the following old measurement terms:

| term | frequency | notes |
|---|---|---|
| ligne | 22 | Does not always have the meaning of a fraction of an inch. *Ligne* also means "line." |
| pouce | 33 | |

| | | |
|---|---|---|
| pied | 72 | Paramelle uses "*pied*" a total of 147 times, but often with the meaning of foot as in "at the foot of a hill." |
| toise | 5 | |
| lieue | 46 | |
| muid | 7 | |
| livre | 45 | "*Livre*" means both "pound" and "book;" many of these occurrences may refer to books. "*Livre*" is also a unit of money. |

In general, Paramelle uses the metric system when discussing the work he did later in his career, and uses *feet* in describing events earlier in his career, as during the 1820s when he was developing his ideas. He uses the older system when discussing previous authors and their work, and does not convert pre-Revolutionary units to metric (*muid*, for example).

The metric system did not come into universal use immediately after its introduction in 1799. By the end of Paramelle's career, he was using it consistently except for discussions of historical work. He did not often give equivalent measurements in the old and metric systems. By 1847, he was using the *meters* on receipts he provided to clients (Figure 3.10).

## 2.6. References for Translator's Notes


Ellenberger, F., 1999, History of Geology Volume 2, The Great Awakening and its First Fruits – 1660-1810: Balkema/Rotterdam/Brookfield, 404 p.

Gaffiot, F., 1934, *Dictionnaire latin-français*: Paris, Hachette: www.lexilogos.com/latin/gaffiot.php (Accessed April 2017)

Grand Robert & Collins French-English Dictionary, 2008: Paris, Le Robert, electronic dictionary.

Kalmar, J. and Dovacs-Palffy, P., 2008, Geochemical Study of Leptinites from Stejera (Romania): Carpathian Journal of Earth and Environmental Sciences, Vol. 3, No. 1, pp 49-64.

La Fontaine, Jean de, 1964. *Fables Tome Premier Livres I à VI*: Bordas.

Larousse, 1992. *Dictionnaire de la langue française*, LEXIS 2nd edition. Paris, Larousse, 2109 p.

Laudan, R., 1987, *From Mineralogy to Geology*: Chicago, University of Chicago Press, 278 p.

Levallois, J.J., 1988, *Mesurer La Terre: 300 ans de géodesie francaise*: Paris, Presses de l'Ecole Nationale des Ponts et Chaussées, 389 p.

Littré, Emile, 1873-74, *Dictionnaire de la langue française*: Paris, L. Hachette. http://www.littré.org

Michel, J-P, Carpenter, M.S.N., Fairbridge, R.W., 2004, *Dictionnaire des sciences de la terre* [Dictionary of Earth Sciences], 4th edition: Paris, Dunod, 496 p.

Moureau, M. and Brace, G., 2000, *Dictionnaire des sciences de la terre* [Dictionary of Earth Sciences]: Paris, Editions TECHNIP, 1096 p.

Neuendorf, K., Mehl Jr., J., and Jackson, J.A., 2005, *Glossary of Geology*, 5th Edition: Alexandria, Virginia, American Geological Institute, 779 p.

Rudwick, M.J.S., 2008. Worlds Before Adam, University of Chicago Press, 614 p.

Schneer, C.J., 1969, Toward a History of Geology: Cambridge, Massachusetts, M.I.T Press, 469 p.

Taylor, K.L., 2013, A Peculiarly Personal Encyclopedia: What Desmarest's Geographie-Physique tells us about his life and work: Earth Sciences History, vol. 32, no.1, pp. 39-54.

Webster's Revised Unabridged Dictionary, 1913: Springfield, Massachusetts, G. & C. Merriam Company.

Webster's New Collegiate Dictionary, 1981: Springfield, Massachusetts, G. & C. Merriam Company.

# Chapter 3. Abbé Paramelle and the Observational Method

In 1856 Paramelle published *The Art of Finding Springs*, a book describing the method Paramelle developed and used successfully throughout France between 1827 and 1854. During these years, he found water for municipalities and individuals in more than 10,000 places in 40 of the 86 French departments that existed at that time (Figure 3.1). Paramelle began his hydrogeologic activities in 1818, when the science of geology was in its infancy, when the word "geology" was in the process of being adopted to designate the new science, and before the science of hydrogeology existed. Paramelle was a rural priest who wanted to find small quantities of water for his congregation who lived on the Causses du Quercy in the western part of the Department of Lot, a limestone plateau that lacks surface water over vast expanses. Paramelle had no formal geologic training but he knew that the eastern part of the Department of Lot had springs and that the same amount of precipitation fell on both areas.

Paramelle began his search for geologic knowledge in the library and concluded that no one since the Romans had contributed significantly to water knowledge, so he started walking around on the limestone plateaus looking for traces of water. He remained convinced that information on finding water must exist, and between 1818 and 1827 when Paramelle submitted a report to the local government, he had obtained and read not only the ancients, but 17th through 19th century authors including Mariotte, Buffon, Desmarest, and Garnier. He also had read the 18th century *Encyclopédie* (Paramelle, 1827).

Initially Paramelle resorted to the only tools available to him: observation and fieldwork. He may have learned about observation and the scientific method during his seminary training in Cahors, Lot; either by nature or training he was an astute observer of landforms. His early fieldwork was on foot; later travels across France on horseback at a maximum speed of about two miles per hour gave Paramelle ample opportunity to observe landforms.

Observation is a key step in the scientific method, which is central to modern science. Today's scientific method consists of a sequence of questioning, observing, hypothesizing, predicting, testing by observation, drawing conclusions, publishing, and peer review, and looping back through the sequence as necessary. Modern geologic training is based on observation of earth minerals and processes in the laboratory and in the field. Observation plays an important role in the related disciplines of civil and geotechnical engineering and rock mechanics. In 1945, Karl Terzaghi discussed the importance of the "observational method" in civil engineering by noting "most projects that … failed had done so due to the unanticipated action of water because the behavior of water depends … on minor geological details that are unknown" (Peck, 1969). Terzaghi devised and promoted an "observational method" to help engineers prevent engineering failures by bridging the gap between calculations and observations. Working on a similar topic about a century earlier, as naturalists and scientists were attempting to develop methods appropriate to their purposes, Paramelle established an observational method for finding shallow groundwater based on an examination and identification of minor geological details that were unknown and unrecognized at the time. In addition to observations, Paramelle used questions, hypotheses, predictions, and conclusions to augment his method.

### 3.1. Development of Paramelle's observational method

In *The Art of Finding Springs*, Paramelle recounts how in 1818 he began nine years of research by walking the surface of the Causses du Quercy unsuccessfully looking for water. During this time he examined rivers in the Department of Lot where he observed large springs flowing into the rivers and concluded that the water must come from the plateaus; he re-examined the plateaus for signs of the water's passage; he saw sinkholes but did not understand their significance. He had spent his childhood in the eastern part of the Department of Lot, where the clay-rich Liassic surface hosts numerous springs and streams. (Figure 3.2). In the Department of Lot he spent several years studying springs in similar "primitive" rocks, the nature of surrounding rock, and the role of visible streams in spring formation. He then applied this knowledge to the limestone plateau (Chapter XXX).

In 1827 Paramelle submitted a manuscript entitled "Hydrologic and geologic report on the Department of Lot indicating methods for finding water that is cool, clean, and abundant for all towns that need it" (Paramelle, 1827) to the Conseil General (government) of the Department of Lot. Paramelle posed and answered two questions: 1) where is the water? and 2) how deep is it? The Conseil provided a subsidy to supplement the landowner's cost of Paramelle's water-finding services within the Department of Lot and Paramelle began indicating places to dig for groundwater. When Paramelle's successes became known, neighboring departments requested his services, and by 1832 Paramelle resigned his job as priest and began a career as hydroscope, as the profession was then called (Taisne and Choppy, 1987).

### 3.2. Paramelle's concept of springs

For Paramelle, a spring is not just a place where water pours out of the ground; it is the entire system, including where the water initially gathers and infiltrates, the water as it travels underground, and its outlet at the surface. A spring is "an objectively observable quantity of water that collects and flows for a certain duration underground" (Chapter X). According to Paramelle, "all springs are the product of an infinite number of veinlets and small water trickles that are interspersed and increase in volume to form the spring we see at the land surface" (Chapter XIV). He was describing the discontinuous groundwater common in karst; his definition of "spring" includes groundwater. The "springs" he found were groundwater occurrences; his clients paid him to point out or indicate where to dig for groundwater. "Underground watercourse" is the term I use to express Paramelle's concept of "spring water as it moves underground," which is the shallow groundwater he was seeking.

### 3.3. Observations on surface water, groundwater, springs, and water quality

Paramelle understood the water cycle, which confirmed his observations on surface water, groundwater, and springs, as he states in Chapter XIII. As quantitative supporting data, Paramelle cites Perrault's and Mariotte's late 17$^{th}$ century measurements showing that rainfall far exceeds the amount of water that flows to the ocean, leaving abundant water for spring formation.

According to Paramelle, spring formation starts with precipitation and infiltration; after water has infiltrated, the process continues with evaporation, transpiration, and spring formation. He cites 19th century scientists Dalton, Dickinson, and Charnock regarding the amount of precipitation that infiltrates (35%) (Chapter XIV). He accepts that 2/3 of infiltrated water is consumed by evaporation and transpiration (Chapter XIV).

Based on his observations and supplemented by his study of contemporary scientists and naturalists, Paramelle explains that water penetrates to a minor depth during first hours of rainfall and infiltrates to various depths in different rock types over time. The amount of water that can infiltrate into a rock depends on its porosity. Paramelle divides the rock world into two categories: impermeable and permeable. Impermeable rocks include massive rocks such as granites, metamorphic rocks, sandstones, and clay soils; they usually lack springs unless they are intermixed or covered by permeable layers. Permeable rocks such as fractured non-stratified rock, limestones, and detrital deposits allow water to move downward; springs form when this water encounters an impermeable layer that conveys the water outward potentially to the land surface (Chapter XIV).

Paramelle points out that groundwater does not move randomly in its downward movement along impermeable layers; it follows the topography as it moves toward the thalweg, the high discharge flow path, which collects water from all higher elevations to form larger watercourses (Chapter XV). He observes that springs almost always flow out of the ground into the valley bottom along the thalweg line; when springs are not apparent, they are often hidden under alluvium. He states:

> based on several thousand springs I have observed, and on the large number of excavations done as a result of my indications, I can say that, aside from a few exceptions … in every valley, vale, defile, gorge, and depression, there is an apparent or hidden watercourse. The visible one moves along the ground surface because it is held up by an impermeable layer, the hidden one also moves along an impermeable layer covered by permeable rock that cannot support it at the ground surface. (Chapter XV)

Paramelle bases many of his concepts of underground watercourses on observations of surface rivers and streams (Chapter IX) on the Causses du Quercy. This concept of the superimposed visible and invisible thalwegs can be traced back to antiquity (Chapter XIV, footnote 3). A 21st century model of conduit formation on the Causses du Quercy supports the concept and Paramelle's observations (Chalikakis, 2006) (Figure 3.3).

Paramelle claims that visible and hidden watercourses flow on top of each other, except when this order is disrupted by geologic, human, or geomorphic factors. Paramelle states with certainty that "in any dry vale several hundred meters long, whether the bottom is rocky or covered by shallow or deep sediment, there is a watercourse that follows the underground thalweg" (Chapter XV). The way to find the thalweg, and thus the groundwater, is to observe temporary water flows during heavy rains.

Paramelle points out that his observations on the pathways that underground watercourses follow will be useful for miners and quarry operators who want to avoid water (Chapter XV); these observations would also be useful for the engineers for whom Terzaghi elaborated his observational method.

Paramelle explains that groundwater formation begins as infiltration at surface depressions and continues as flow toward and along an underground thalweg under the influence of gravity, just as surface streams do. The underground watercourses receive tributaries; each vale that joins a valley brings an underground watercourse.

Regarding water quality, Paramelle observed that the best water comes from granite and flows fast; that clear water is not necessarily pure; that color can indicate contaminants (e.g. white indicates the presence of chalk or gypsum); that taste indicates contaminants (e.g. a rusty taste indicates iron), and that odor can indicate contaminants (e.g. a garlic odor indicates arsenic) (Chapter XXIV).

In spite of these natural contaminants and after citing numerous authorities on water quality and pointing out the immense effort Romans made to bring spring water to their cities, Paramelle declares that "generally speaking, spring water is the best suited to the taste and needs of man" (Chapter XXV).

> At the same time, he recommended that the groundwater chosen for a water supply should not pass under a cemetery, dunghill, pigsty, cowshed, cesspool, sewer, pond, swamp, or gypsiferous, peaty, or silty ground. One should even avoid placing the trench or well too near these harmful places because some ground is so permeable that bad water found there will infect springs that pass at distances of more than ten meters on their margins. How many cities and villages I have seen that had a very abundant water supply at the bottom but whose water was not potable because it passed under houses! (Chapter XXVII)

Paramelle notes that many springs and groundwaters become turbid after rainfall because rainfall dislodges earthy and plant particles and runoff carries them across the land surface where they infiltrate. Shallow wells are more susceptible to this problem. He notes that in limestone where dolines are present, water that enters the earth through dolines can emerge unfiltered at depth. Groundwater that circulates under woods, pastures, and other non-cultivated land is less turbid than groundwater from cultivated fields and vineyards. However, all is not lost if the only groundwater available suffers from turbidity; Paramelle describes and recommends the use of stone and fabric water filters (Chapter XXVI).

### 3.4. OBSERVATIONS ON EXPLOITING GROUNDWATER

Where to look for water

Paramelle discusses favorable locations for finding water in several chapters. Chapter XVI, entitled "Where to Dig for Water" contains observations on where to find the shallowest water, the most abundant water, and how to find water on mountains and slopes.

Noting that an underground watercourse is not always at the same depth or abundance along its pathway, Paramelle shares his observations on how to find the shallowest or most abundant water. Groundwater is most shallow in four places: a) the bottom of the depression on an elevated dry section where trickles of water coalesce (that is, at the place where surface water infiltrates) (Figure 3.4); b) the center of a circular area where it forms (again, usually on an elevated dry section of a vale or in a cirque-shaped vale) (Figure 3.4); c) at the bottom of a drop-off of a visible thalweg; and d) near where a spring flows out on the land surface. Although water is shallow where the recharge begins, it is not abundant. According to Paramelle, shallow and abundant water is found near the spring's issuance to the surface because an underground watercourse grows larger along its flow path, and the spring's manifestation at the surface is the end of the path. The optimum location for the combination of abundant water and shallow depth is at the base of a steep slope, according to Paramelle (e.g. below a drop-off of the visible thalweg). Regarding abundance, the most abundant water can found at a place where a plain extends across a vale, provided the vale is full of unconsolidated sediment and an impermeable layer underlies the unconsolidated sediment; in this location, an even larger amount of water can be found if multiple water-bearing layers are present.

Under special conditions, groundwater can be found on mountains, but not on sharp ridges or dome-shaped summits, contrary to claims popular in the 19th century. Paramelle investigated numerous claims of springs present at the summit of mountains; in all cases, the springs were located adjacent to a sizeable plot of land composed of a thickness of rock capable of producing a spring. As an example, Paramelle points out that the Montmartre butte in Paris has a large enough area of suitable rocks to produce a spring (Chapter XVI). A plateau needs to be at least 500-600 meters wide to produce a spring; smaller areas will not produce springs, according to Paramelle.

Large springs can be found on slopes of mountains and hills that cover large areas; in this case, the inclination of the strata is the most important factor. To demonstrate the importance of dipping strata, Paramelle describes three examples of plateaus. The first is a plateau located between two vales that dips slightly and whose strata are parallel to the plateau surface, (a *butte témoin*, for example) (Figure 3.5a). The second is an anticlinal plateau with a watershed divide near the middle of the plateau and strata dipping in different directions on its slopes, with each slope carrying an equal amount of water to its vale (Figure 3.5b). The third is an asymmetrical plateau or cuesta with a watershed divide toward one side, where the slope nearest or underlying the divide is steeper and its bedding planes form stair-steps, which are sometimes visible and sometimes covered with colluvium; all rainwater that falls on this plateau flows along the gentle slope to the vale that is more distant from the divide (Figure 3.5c). Thus, Paramelle says, a person should never look for water on the steep slope because water that falls on strata there will be carried into the hillside and will flow along bedding planes toward the side with the gentle slope (Chapter

XVI). Paramelle cites exceptions to this rule. If the rocks are vertically fractured down to an impermeable layer that has a different dip direction, the water will follow the path of the impermeable layer (Chapter XVI). Small springs may be present on steep slopes, if the rock type is favorable.

On clay hills that are sufficiently large and are topped with a limestone plateau 8 to 15 meters thick, springs will occur at the base of the escarpment that forms the lower edge of the plateau, especially if a layer of marly limestone is present between the limestone and the clay; the springs are often hidden in a recess or depression covered with rock debris and aquatic plants. By observing the top of the plateau, a person can determine if a depression is present; the depression will lead to the recess and the spring.

Paramelle advises against trying to find water near the top of a hillslope.

> I have verified numerous times that underground watercourses have only the ordinary slope of visible watercourses and that cascades are as rare in one as in the other; from this it follows that a person who wants to dig near the top of a slope to intercept a spring that comes out of the ground at its base would choose precisely the most unfavorable point of its entire course and would be obliged to excavate to a depth equal to the height of the slope. (Chapter XVI)

Regarding hillslopes, Paramelle provides detailed observations on those that are smooth; those that have a single vertical depression; those with furrows that extend from top to bottom; furrows that disappear into a slope; and furrows that begin mid-slope and continue to the base. For all these environments, Paramelle advises on where to look for water (based on distance from drainage divide, direction of stratification, etc.) and how to use trenches to intercept water. He also counsels on where not to look, for example, the slope of a small hilltop.

Paramelle observes that hidden springs are most numerous, abundant, and shallow on the foot-of-slope line that marks the base of the slope and the beginning of the plain, as discussed above, but not along a salient or a small hillslope or where the foot-of-slope line is covered with rubble (Figure 3.6a). Paramelle recommends digging along the foot-of-slope line at the most concealed end of a reentrant and in places where water appears during rains and where shrubs or aquatic plants are present, among other places (Chapter XVI). He notes that springs are often present in recesses at the foot of an escarpment on a low plain (Chapter XV).

In Chapter XIX, Paramelle shares his observations on rock types most favorable for hosting groundwater. The most favorable combination is permeable rock at the surface underlain by an impermeable layer. Multiple layers of alternating permeable and impermeable rock may increase the amount of water present. Mountains are more favorable for springs because they usually receive more rain than lowlands.

Multiple small springs may be found in covered or fractured primitive rocks (See endnote) although these rocks are generally not permeable. Again, multiple superimposed layers may produce abundant springs. Bare smooth primitive rocks will not produce springs. Secondary rocks (See endnote) host large springs but the springs are not numerous. The secondary rocks most favorable for groundwater production are certain limestones (oolitic, siliceous, shelly, marly, etc.). Tufa indicates the presence of a spring, because springs produce tufa as the water flows out of the ground. Molasse, green sands, millstone grit, and a few other limestones can host springs, as can alluvial rocks if they are in suitable positions; that is, underlain by an impermeable layer (Chapter XIX).

In Chapter XXX Paramelle discusses the development of his method over the years and his observation of "favorable" rocks, which is based on rock type and feasibility of exploiting the groundwater. Paramelle recommends excavating in vales because the thalweg is the most certain guide to finding groundwater and the depth to groundwater is reduced in a surface depression, particularly in a vale near where the vale joins a stream or river. Paramelle claims that below the vale an underground watercourse joins the stream as a spring. In this location, the elevation difference between the water level of the underground watercourse and the elevation of the land surface in the vale will be minimal, usually 10 to 50 feet, in Paramelle's experience, which made the groundwater exploitable by hand digging.

## Where not to look for water

Water seekers also need to know where not to look; for this purpose, Paramelle wrote four chapters (Chapters XX through XXIII) on rock types not likely to contain groundwater. The list includes limestones and dolomite, volcanic and friable rocks, landslides deposits, and hillsides with strata that dip more than 45 degrees (Chapter XX).

In Chapter XX, Paramelle discusses limestones and dolomite. Limestone with dolines and limestone in which caverns and caves are present contain water but the water is too deep for manual excavation, so Paramelle considered them unsuitable rocks for his clients. Swallow-hole limestone is present on plateaus; it is the source of springs that flow into rivers with no surface indication. Dolines are generally 200 to 400 feet above the water level of the underground watercourse, and thus not feasible water sources given the technology of Paramelle's day.

Cellular limestone, a silica-rich, hard, and commonly stratified limestone that contains numerous tubular and other voids, does not contain water because water drains through it. Dolomite does not contain water because it is impermeable.

Paramelle states his observation that volcanic rocks generally do not contain groundwater because they lack stratification, are disordered, and are extremely porous (Chapter XXI). Water can accumulate in these rocks but the water flows down to an impermeable layer and follows this layer outward to the perimeter where springs, sometimes large, may be found.

Paramelle enumerates his observations on why friable rocks are unlikely to contain groundwater (Chapter XXII). Friable rocks include clay, chalk, marl, and recent water-deposited sediment. Clay does not allow water to pass through it; chalk is too permeable and water flows out the bottom of it; marl may contain water if it is stratified; and recent water-deposited sediment is among the least favorable because of its disaggregation, lack of stratification, disordered deposition, and lack of surface depressions.

Paramelle lists other rocks unlikely to contain water: steeply inclined stratified rocks, non-stratified rocks with vertical cracks from top to bottom, and stratified rocks that contain large blocks. Water infiltrates into these rocks but pours out the bottom. Paramelle also discusses why subsidence, landslide, and slump areas are unlikely to contain water (Chapter XXIII).

Subsidence areas such as where rivers disappear into the subsurface to re-appear elsewhere will not contain water; he cites the Vaucluse (Department of Vaucluse #84 on Figure 3.1), Touvre (Department of Charente #16 on Figure 3.1), and the L'Ouysse springs (Figure 3.2) as resurgences produced by rivers that disappear into plains of unconsolidated material.

Likewise, landslides and slumps are unlikely rock types for the discovery of groundwater because the ground is porous, unconsolidated, and disordered and Paramelle's observational method is thwarted; he says "it is thus as difficult for a geologist to know the interior of these rock units as it is for an anatomist to understand each part of a cadaver that has been chopped up."

Paramelle offers an observation on fuller's earth, a type of clay, which Paramelle considers an unreliable water source; in this rock, springs come and go suddenly or gradually (Chapter XXIII). Finding water here is a lucky accident, but the water is not reliable and will likely disappear.

### 3.5. Depth to Groundwater

Paramelle based his determinations of groundwater depth and volume on observations and he recorded the predicted depth and volume on a receipt he provided to clients. Paramelle describes the four methods he used to determine depth to groundwater (Chapter XVII). He admits they may not always be exact, but they provide a maximum depth that gives the client the maximum expense of drilling and the client will know whether the water source is at an elevation that will allow it to flow by gravity to the desired location.

Method 1. In the thalweg of a vale, Paramelle advises the water seeker to observe water elevations both in the visible watercourse and in any previously dug wells and to note whether the locations of these points are above or below the chosen excavation site and at what distance. Each measurement can give an idea of the height of the excavation site above the outlet of the underground watercourse, which gives an approximate depth to groundwater.

Method 2. If the underground watercourse cannot be found or lies within transported material, Paramelle advised the use of geometry (Figure 3.7) to determine the depth of the excavation necessary to reach water. Paramelle writes, “The bottoms of most vales are filled with transported materials, except in gorges, and many experiences have shown me that the line of intersection of the two slopes is generally the greatest depth at which groundwater will be found. This idea came to Paramelle six years after he had begun searching for water. Paramelle also cites exceptions in highly dipping strata and advice on where to perform the geometric analysis.

Method 3. Depth determination on slopes or plateaus requires different methods, primarily a knowledge of permeable and impermeable layers, which Paramelle says can only be gained by studying geology texts and observing rocks in the field. Paramelle advises the water-seeker to observe the dip and composition of the strata on the slope, whether they dip toward the slope (in which case water is not present) or toward the vale. Paramelle advises the water seeker to find an impermeable layer on the slope outcrop and survey from that point to the point where he wants to dig for water.

Method 4. On low plains, a person who observes water depth in nearby trenches and wells will know that his well will have the same water depth. Paramelle states, “These four methods of determining the depth of an underground watercourse are the only ones that thirty-three years of research and experiment have led me to discover.”

### 3.6. VOLUME OF GROUNDWATER

To provide an estimate of the minimum quantity of water a spring would produce, Paramelle used a calculation he developed through experience.

So as to obtain as exact knowledge as possible on this subject, I have spent a long time observing the amounts of water produced by plateaus located on mountains or isolated hills where it has been easy for me to measure the volume of water of each spring and to measure the surface of the basin that produces it. (Chapter XVIII)

According to Paramelle, during a period of "ordinary dryness," a five-hectare surface area of a plateau with a layer of sediment seven to eight meters thick overlying an impermeable layer will produce a spring "one centimeter in diameter" that discharges about four liters of water per minute. Less favorable rock types may produce no water, even over an area of 100 hectares. Paramelle said,

After nine years of theoretical studies and observation of springs, I spent almost every day of the following twenty-five years indicating underground watercourses of all volumes. I would declare, in a document maintained by the landowner, the quantity of water each underground watercourse would produce and in the great majority of attempts, the estimated quantity was found. (Chapter XVIII)

Paramelle originally surveyed the land to determine the depth of the spring and the surface area of the watershed, but because he found that spring variation was not subject to rigorous calculation and he knew that geologic phenomena are subject to exceptions, he ended up surveying and measuring by sight, and he considered the result to be as exact as surveyed results (Chapter XVIII).

### 3.7. How to Get Water out of the Ground: Wells and Fountains, Conduits, Artesian Wells

Depth to water determines the method of exploiting it. Paramelle states that groundwater is present at depths ranging from two to hundreds of meters, but rarely occurs at less than two to three meters. For successful exploitation during Paramelle's time, water had to be shallow (6-7 m. deep at most) and abundant. Paramelle offered suggestions to his clients on the construction of economical and stable structures for getting water out of the ground. Based on his observation and experience, he discusses three of the principal structures: conduits, fountains, and wells and trenches.

The fourth structure Paramelle discusses is artesian wells, which were in vogue in Paramelle's day. Paramelle points out that although an artesian well is the best a water seeker can hope for, artesian conditions depend on a particular geologic environment: recharge at high elevation, permeable strata, permeable layers enveloped by impermeable layers, and no water loss at the base of the system. Paramelle lists the disadvantages of artesian wells; they are rarely successful, they are expensive, they require a special geologic configuration, and water is at an unknown depth (Chapter XXVII).

Paramelle's observations on artesian wells were pertinent at a time when numerous artesian wells were being drilled throughout France. Paramelle lists the successful Grenelle Well in Paris, drilled between 1833 and 1841 to a depth of 548 meters at a cost of 403,000 francs; wells in Marseille, Rouen and Médoc that cost 15,000 to 40,000 francs that produced only a trickle of water; and artesian wells at 14 other locations where 20,000 to 150,000 francs were spent on wells that failed completely. Paramelle observed that the locations of these 14 wells had been chosen for convenience, not in locations where the special geological configuration was present. Paramelle does not mention the city of Dijon, which dug an artesian well in 1829-1832 to a depth of 155 meters. The water quality was excellent, and water rose to within 2 meters of the surface. In 1835 a rotary pump was used to raise the water to street level. The well cost 31,000 francs (Darcy, 1856).

### 3.8. Wells that are slow to flow or that fail to flow

Often a well does not produce water at first, and Paramelle observes that the true water flow can be determined only after one winter has passed. He describes a test to determine whether the water in a well is rainwater or groundwater to help the client determine if the well is a success or failure. Paramelle says that water finding is based on probability and that hidden features can turn a likely prospect into a failure. Some causes of failure of his method are: impermeable rock blocking the underground thalweg, a crevice in an underlying impermeable layer, perturbations beneath the lower strata under the well, and disturbed layers in the thalweg. Often water is yet accessible, and Paramelle suggests enlarging the well to find it (Chapter XXVIII).

### 3.9. Observations on karst

When Paramelle returned to the limestone plateaus after studying streams and springs in the "primitive" rocks of the Department of Lot (sometime prior to 1827), he applied his observations to the limestone plateau to find water for his congregation. Paramelle began by walking up the valleys from the riverbank where springs discharged. After walking up the valley of the L'Ouysse, Paramelle understood that the large river that sinks into a swallet (*perte*) at Thémines likely flows under the valley that he had walked and that it became the L'Ouysse stream that flows into the Dordogne – after flowing underground a distance of 25 km. Thus he recognized the perte-resurgence connection; he repeated this exercise on a number of other streams that disappear to re-appear in the L'Ouysse, the Alzou, the Dordogne, and the Célé (Chapter XXX), (Figure 3.8). This is one of Paramelle's major contributions to knowledge of karst in the Department of Lot (Taisne and Choppy, 1987). Paramelle also noticed that streams were wider when they came out of the ground than when they went in and concluded that they had joined up with other underground watercourses, a configuration he also observed in the arrangement of chambers in caverns (Chapter XXX).

Other springs flow into the Lot, the Célé, and the Dordogne without any surface presence; these include the Chartreux and Saint-George near Cahors (Figure 3.2). Paramelle inferred that these springs form, move underground, and follow thalwegs, as visible streams do; he finally recognized that these springs came from limestone plateaus via disseminated dolines. Paramelle had originally considered these sinkholes to be randomly ordered but after much study, he noticed that the dolines were arranged in series, each occupying the thalweg of a very subtle surface depression oriented in the direction of a spring. By aligning these dolines, he was able to determine the direction of principal underground watercourses (Chapter XXX).

Paramelle noted that in some places dolines were disseminated on the plateaus whereas in other locations they occupied the valley bottom along the thalweg and that a person could follow them from the end of the vale to the beginning. Walking up the vale a person would see vales coming in from both sides, with dolines aligned along the thalweg (Chapter XX). The regular alignment of the dolines in the thalweg of each vale led Paramelle to conclude that each line of dolines overlies a permanent or temporary underground watercourse and that the downward flowing water erodes the walls of the rock that encloses them, enlarges the voids, removes their support and causes them to collapse. He also noted that during heavy rains, columns of water would shoot out of dolines, and that sometimes during storms, water that could not flow into one doline would continue down the thalweg until it was able to drain into the next doline. These observations, plus the observation that it was sometimes possible to hear running water by putting one's ear to a doline, confirmed Paramelle's observations of underground watercourses (Chapter XX).

Paramelle observed that caverns in limestone are generally an elongate string of chambers with vaulted roofs connected by corridors and with branches off the main stem. The chambers are elongate in the general direction of the cave. Paramelle points out that the presence and direction of caves are indicated by series of dolines and that subsidence and new doline formation indicate the presence and direction of caves. He notes that aqueous vapors that rise from caves and air currents that caves inhale and exhale also point out their presence. Thus, Paramelle clearly made a link between dolines and cave formation (Chapter XX).

### 3.10. Observations of plants

Paramelle discusses plants as indicators of soil moisture and potential springs. He points out that trees increase the amount of infiltration and thus spring water. He notes that the use of plants as indicators of soil moisture has a long tradition dating back to the ancients and he cites a warning by Pliny who claims that plants are sometimes false indicators. Paramelle cautions that willows, poplars, alders, rushes, and reeds grow in all ground that contains moisture; they serve as indicators of groundwater only if they are located on a thalweg or at the bottom of a recess. O.E. Meinzer found Paramelle's observations important enough to translate and reprint in a USGS Water Supply Paper (Meinzer, 1927).

### 3.11. Use of observation to refute unsubstantiated ideas

Paramelle used his observation to refute numerous "erroneous" groundwater notions on spring formation, mountaintop springs, and periodic springs, among others. In his Chapter XI on "Erroneous opinions on the origin of springs" he says that the ancients and most writers prior to the eighteenth century have left "hypotheses and systems so devoid of satisfying proof that one is profoundly amazed that the truth has taken so long to be known." Paramelle then lists twenty authors and a short summary of their ideas on springs (Chapter XI). In the following chapter (XII), Paramelle summarizes the erroneous ideas such as a) water underground being exempt from the laws of gravity, b) air and land changing into water to supply springs, and c) springs coming from the sea. The latter was the most popular and Paramelle refutes it by addressing three questions: Are there underground channels that go from the sea to the land? Can seawater rise to springs, given that there are springs at elevations of one to several thousand meters? How does seawater get rid of its salt and provide fresh-water springs? (Chapter XII). Paramelle points out that no one has ever seen evidence of the channels that were proposed to transport sea water to springs and other processes central to these ideas.

Paramelle argues that his explanation of spring formation is much more natural and better confirmed by excavations than the supposition of underground lakes, reservoirs, basins and water masses that no one has ever seen function and that are described by a large number of authors who do not cite examples. To quote Paramelle, "All these underground lakes, reservoirs, water masses and all these mother springs that they have assumed to be at the center of mountains to supply springs should be relegated to the category of illusions" (Chapter XIV). Paramelle admits exceptions but points out that the exceptions do not account for the majority of observations.

As discussed above, Paramelle refuted the idea that springs could flow from mountaintops and that all springs thought to flow from mountaintops are actually adjacent to an area at higher elevation and thickness of rock capable of creating the spring. In his day, authors including Saintignon, Nollet, and Héricart de Thury (Chapter XVI) claimed that reverse siphons carried water over vast distances and caused it to rise to the tops of mountains where it supplied springs. In addition to pointing out that there was no evidence of these conduits, Paramelle cites Pluche and Mentelle and Malte-Brun. "A spring cannot, says Pluche, flow from the height of a mountain if there are not at least several *toises* of higher land. *Entr*. [Discourse] XXI. There is no spring, say

Mentelle and Malte-Brun (*Géogr*. book vi), that does not have some higher ground above it." (Chapter XVI).

Paramelle adds "It seems that these authorities and many others that I could cite, plus the sheer implausibility of the belief that springs could exist at the summits of certain mountains and that they arrive there by way of reverse siphons, should have encouraged educated men to verify the facts for themselves prior to including them in their writings and to not to lay themselves open to inserting assertions that lack proof" (Chapter XVI).

Regarding periodic springs, a subject that has fascinated people for centuries, Paramelle cites "physicists" who have attributed them to underground wind gusts and ocean fluxes, and proposes an explanation based on a siphon. He provides a diagram that shows how a siphon works and a cross section of a natural siphon within a rock unit (Figure 3.9). Paramelle says, "This method of explaining the periodicity of some springs is the only satisfactory answer found at present" (Chapter XIV). In 1969, Mangin proposed a model that refuted Paramelle's siphon explanation (Bakalowicz, pers. comm., 2017; Mangin, 1969).

### 3.12. Use of Observation for Prediction

In the preface to *The Art of Finding Springs*, Paramelle encouraged students of hydroscopy by saying

> after several years of travel and exploration, it was possible for me to indicate some springs and their volume from a distance, to describe the back side of some mountains and hills where I could see only one side, and to point out springs on the reverse side, and also to indicate springs on Cassini maps [See endnote] and determine from a great distance that certain homes had cracked walls.

Referring to *The Art of Finding Springs*, he continued:

> "I have cited the designations and the observations on which they [these indications] are based, and the reader will see that these were easy to make. For those who have not made these observations, it is a marvel; but for those who have observed or will do so, it is nothing.

Paramelle discusses his ability to stand on a plateau and observe several dolines in a row near the beginning of a vale and use this observation to point out or designate the locations of dolines that he could not see because of topography or vegetation. These predictions amazed onlookers (Chapter XX, note 2).

After a discussion of how to find water on hillslopes, Paramelle states his observations on where water will occur and where it will not (Chapter XVI). Paramelle also discusses his ability to describe topography on the other side of a hill and to predict springs:

> After observing attentively this arrangement of strata for several years and having practiced the other observation stated in Chapter 1: Every peak of a mountain ridge is the departure point for two ridges that go in opposite directions, and each pass is the point of departure of two opposite valleys, everywhere that I have looked at a slope of a mountain, I have been able, based on the side I was looking at, describe almost exactly the opposite slope, which I had never seen, and to announce the following: "From the top of this peak, a ridge or hill takes off in this direction toward slopes that we do not see; a vale departs from that pass, it has more or less this slope and it goes in this direction on the other side of the mountain" and when the rock types were favorable for springs, I said: "Leaving from this pass and following the bottom of the vale that goes from the other side of the mountain, after walking so many meters you should find a spring of about this volume and beginning at this spring the slope changes and becomes less steep." In all the departments where I have worked, thousands of people will attest to these facts. Now that the reader knows the data on which these announcements are based, he should find that they were quite easy; however, the spectators found them extraordinary. (Chapter XVI)

A number of newspaper articles are cited to support these claims.

### 3.13. Peer review of Paramelle's observations

Paramelle was not a member of any elite scientific society, but his work attracted the attention of agricultural and learned societies, among others.

The famous naturalist Geoffroy Saint-Hilaire reported to the *Académie des Sciences* in 1836 that Paramelle's method was based on science and observation and that with a simple inspection of a site Paramelle was able to determine the location and depth of groundwater (Chapter XXXI)

J.J.N. Huot, author of a geology textbook and contributor to the *Encyclopédie moderne,* delivered a report in 1836 to the *Société d'Agriculture de Seine-et-Oise* on Paramelle's application of geologic facts to the search for groundwater (Chapter XXXI). It appears that Huot based his report on Paramelle's 1827 memoir, perhaps also on personal communication. Huot says that Paramelle uses methods never tried before and that applied geology is a science of the future. Paramelle evidently stated up front that his method was applicable only to limestone. Huot summarizes and discusses key ideas of Paramelle's method, such as underground and surface watercourses following the same rules, the common presence of water at the base of a steep slope in a valley, and that abundant and shallow water can be found on plains, not in vales. Huot concludes that Paramelle bases his work on analogies drawn from observation of physical geography and that if Paramelle also contributes geologic observations, his theory merits the attention of savants. Huot adds that if Paramelle can apply his theory to limestones of different ages in other parts of France and if the results are the same as in Lot, where in 1833, 48 out of 51 excavations encountered water, Paramelle will have found one of the most useful applications of geological science (Huot, 1836).

Paramelle's *The Art of Finding Springs* was published in 1856, the same year as Henry Darcy's *The Public Fountains of the City of Dijon*, in which Darcy reviewed Paramelle's book. Darcy introduces Paramelle as "the man who seems to have done the most work on underground hydrography in recent years." Darcy's staff geologist Parandier of the Corps des Ponts et Chaussées accompanied Paramelle in the field to learn his method; this likely happened in the 1840s when Paramelle was in Besancon, Doubs, where Parandier was working. Darcy used the Parandier report as the basis for his review of Paramelle and his method. Darcy states emphatically that Paramelle has a thorough knowledge of geology. The account of the field trip makes it clear that Paramelle discussed many of the observations he set out in his book: the upper and lower thalwegs, Paramelle's calculation of spring flow based on watershed size and rock type. Darcy has difficulty understanding the Seneca's concept of "believing what is below is the same as what you see at the surface" because there is no water at the surface and yet Paramelle believes there is water below. Darcy also thought Paramelle's system could work only if the underground impermeable surface were parallel to the ground surface, and Darcy claimed that the parallelism does not necessarily exist. Darcy's third difficulty was Paramelle's determination of groundwater depth and calculation of spring volume in which Darcy found too much uncertainty and randomness. But Darcy praised Paramelle's motivation and success and his "curious and useful" book (Darcy, 1856).

A few years after Paramelle's death, an industrialist in Reims successfully used the instructions in Paramelle's book to find water; he therefore replicated Paramelle's results. Alfred Lefebvre found karst groundwater near Villers-Marmery in the Champagne region of France and used the water to supply his property. Spelunkers later reported that the water was found in a recess above a dry valley as an underground river flowing in chalk above the level of the valley and 35 meters below the plateau.

In gratitude for the discovery of water, Mr. Lefebvre constructed a monument topped by a 2-meter statue of Paramelle at the site of the spring in 1899. A brand of champagne was also named after Paramelle. The monument and statue stood until 1955 (Taisne, 1986).

Paramelle also had critics. In contemporary newspaper accounts, some accused him of magical procedures and diabolical signs from the evil spirit (Chapter XXX). The most scientific critic was E. A. Martel (1859-1938), a lawyer and pioneering speleologist who established the *Société de Spéléologie* in 1895. In his 1894 book *Les Abîmes*, Martel discusses four theories of doline formation: subsidence, mechanical action of surface water (erosion), chemical action of surface waters, and the geyser theory proposed by Omalius d'Halloy (1783-1875) involving upwelling of mineral water from depth. Martel claimed that dolines are due to multiple causes and criticized anyone who held too tightly to one theory. He reduced Paramelle's observational method to a "theory of *jalonnement*" [marking out], a name Martel gave to Paramelle's observation that underground watercourses erode their conduits and roof supports until the roof caves in and creates a doline at the surface. Although Martel pointed out that many French and Austrian geologists accepted Paramelle's "theory," Martel considered this type of subsidence "an exception to the general rule.” He agreed that subsidence occurs above groundwater conduits but claims that the appearance of sinkholes at the land surface result from “taking the top off” narrow pre-existing fissures where plows and storms remove plugs of soil and pebbles.” According to Martel, “exaggeration of the subsidence theory … led to *jalonnement*” (Martel’s term), which he defines as Paramelle’s statement that “under each line of dolines, there is a permanent or temporary underground watercourse that has created them.” Martel did not dispute that dolines communicate with underground rivers but cited another author (Kraus) who points out exceptions to the statement that “surface manifestations depend absolutely on underground watercourses and have been caused by them.” Martel points out that there are “underground rivers without dolines and dolines that lack underlying rivers.” Martel says that not enough attention had been given to surface fractures and surface runoff; and that complete subsidence can take place only where the rock units are not too thick.

In the 20th century, Robert de Joly (1887-1968), a renowned speleologist who revived the by-then-defunct *Société de Spéléologie*, agreed with Paramelle that surface water circulation in valleys results in aligned swallets and the establishment of underground watercourses (Gèze, 1969).

In addition, Martel did not share Paramelle’s observation that groundwater is the most healthful water for mankind. Martel was instrumental in creating a 1905 law that prohibited the use of karst springs for water supply. The 1905 law was evidently never enforced and modern laws require registered hydrogeologists to use groundwater and springs rather than surface water for water supply systems. Modern groundwater protection regulations reflect Paramelle’s rejection of water that flows under cesspools, salt mines, muddy ponds, cemeteries and other sources of contamination (Bakalowicz, pers. comm., 2017).

### 3.14. Paramelle: the man behind the method, the teacher, the businessman

In 1854 Paramelle retired at the age of 64. At that time, he had requests for his services from 37 additional departments (he had already explored 40 departments). He evidently did not have an apprentice to continue his work. In his retirement Paramelle expanded his original 1827 report into *The Art of Finding Springs* by adding the observations accumulated during his working career. Paramelle read widely, as can be seen by the number of authors he cites in *The Art of Finding Springs*. During his career, he amassed a library of some 3000 volumes of geology textbooks by French and English authors. In his retirement, in addition to writing *The Art of Finding Springs*, Paramelle wrote books on the history of the Saint-Céré and other topics (Taisne, 1986).

Three thousand copies of *The Art of Finding Springs* published in 1856 sold out quickly; there were two printings, one by Bailly and the other by Dalmont. A second edition was printed in 1859, and a third in 1874. Three more editions came out posthumously, the last in 1926. The book was translated into German in 1856 and Spanish in 1863.

Paramelle preferred observation to theory; in his book he does not devote much space to various theories of the Earth and its creation; he uses prevailing geologic theories to introduce his topics but this introductory material does not detract from or invalidate his observations. Some of the prevailing theories and assumptions of the day included the hot water origin of volcanic rocks (Chapter XX); withdrawal of the sea created dolines (Chapter XX), the central fire and geothermal gradient responsible for hot springs (Chapter XXIV).

Paramelle often stated that anyone could have done what he did, given some theoretical background and several weeks of observation in the field. Paramelle's book teaches readers how to observe: how a student geologist should examine hills and slopes (Chapter VI); how a student should find the high places in his department and explore them; what to look for on plains, slopes adjacent to river, variations on plains, how to find the "thalweg" and why the "thalweg" is important (Chapter VII). In Chapter XVI, he points out optical illusions to avoid and how to examine springs in the field. According to Paramelle, "To be able to find underground watercourses, it is not enough to study theory in the office or even to learn it by heart, it is necessary to gain a thorough knowledge of rock types, knowledge that can only be obtained in the field." He continued,

> Only after studying for a long time the occurrence of rock types in which springs occur and the numerous places where they occur, was I able to do something I had never expected, that is, to be able in any place I went to designate immediately and exactly on any land surface within my field of vision, the point where each spring would appear and even to predict the volume every time, once I had seen the area of its watershed. I did not make these designations just a few times; during the twenty years I traveled, at a distance of a half-league and even a league distant from a slope that I was seeing for the first time, at the request of the curious observers who were following me, almost every day I had the opportunity to indicate with precision all the springs that occur there. I would say for example: At so many feet to the east or to the west, to the north or to the south of such and such house, tree, or bush there is a visible spring that has such and such volume. Each inhabitant of the area asked: That's true, sir, it's very true. How did you know? The simple application of the ideas contained in this book was a marvel to them. (Chapter XVI)

From his home base in Saint-Céré in northern Lot, where he spent the winter, Paramelle traveled every year from March 1 to July 1 and from September 1 to December 1, from 1832 until 1853.

Paramelle had started his career by writing a report to the departmental government of Lot. After successes in the Department of Lot, requests for his services came in from other departments, and he continued to work through departmental authorities to advertise his services; these prefects, after receiving reports from the prefect of Lot and reading newspaper accounts of Paramelle's successes, sent notices to mayors and asked them to draw up lists of subscribers, proprietors who wanted Paramelle to find water. Paramelle prioritized his travel; the department with the largest number of subscribers was served first and Paramelle actively encouraged competition among departments. He based his fees on distance from his home base; within the Department of Lot, the fee was 10 francs, neighboring departments 15 francs, and so on. He used form letters and circulars to communicate with his clients (Figure 3.10).

When Paramelle was at a client's site, if water was not present, he informed the client, collected no fee, and moved on to the next site. When water was present that met the client's needs in terms of distance, depth, and quantity, Paramelle indicated a precise point on the ground surface where the client should dig for groundwater. Paramelle provided a written receipt to the client and a promise to refund the client's money if the client dug a well or trench within one year of the indication and did not find water at the location, at the depth, or in the volume Paramelle claimed (Figure 3.10).

Paramelle estimates that he investigated about 30,000 sites, and indicated water at 10,275 sites. He estimates that 8-9,000 excavations were conducted on the basis of his indications. Paramelle charged no fee to the poor and to religious communities.

### 3.15. Conclusion

Clearly, Paramelle's attention to detail in his observations of geologic features led to his success at finding water. His observational method was used well into the 1970s in the Department of Lot (Andre Tarrisse, personal communication). At that time municipalities began looking for larger quantities of water, which required a more regional approach and new methods such as geophysics and cave mapping, among others. We can be sure Paramelle would have welcomed these methods. Results obtained from 20th century methods show that structural features, which Paramelle could not have known about, play a significant role in groundwater movement in the Department of Lot, particularly regarding deeper larger quantities of groundwater.

In comparing the observational methods of Terzaghi and Paramelle, there are different starting points but the use of similar approaches. Terzaghi uses equations and calculations to aid in reaching his goal; his problem is that earth materials are not homogeneous enough to guarantee success. He has to reassess the gap between calculation and the behavior of water in soils continually. Assumptions of homogeneity contrast with a heterogeneous reality. Paramelle starts with nothing and develops an understanding of earth materials and water based on heterogeneity. Both men are using observational methods and the methods have common factors. Both methods seek maximum economy. Terzaghi's method works if practitioners start with no preconceptions, consider all possibilities, even possibilities they can't imagine, and examine all available evidence with an open mind. Both Peck and Paramelle cite instances where practitioners lacked open-mindedness or experience; Paramelle saw sinkholes on the Causse and did not immediately recognize what they were. For Terzaghi's method to work, observations must be reliable, the operator must heed the observations and incorporate them into the project management, and the operator must have a plan of action for unfavorable situations engendered by unexpected observations. The engineer ignores his observations at great peril.

As a result of his observations, Paramelle made major contributions to hydrogeology and the study of karst. He probably did more to popularize and promote groundwater use than any other figure in French geologic history.

Endnotes

*Primitive, secondary*: Paramelle's terminology likely refers to Werner's ideas, which were publicized in France by D'Aubuisson. According to Werner, primitive rocks are the first precipitates from the ocean prior to the emergence of land; they include intrusive igneous rocks and meta-sediments. Secondary rocks result from the emergence of mountains from beneath the sea and are composed of erosional products deposited on the flanks of these mountains; they include stratified fossiliferous rocks.

*Cassini*: Astronomer Jean Dominique Cassina came from Italy in 1671 to serve as director of the newly-built Paris Observatory. His offspring continued to direct the observatory for four generations. Between 1756 and 1815, this family also produced 181 sheets of triangulated maps covering the entire country of France. Cesar-Francois Cassini de Thury (1714-1784) conducted surveys for the maps between 1756 and 1789. His son, Jean-Dominique Cassini (1748-1845) continued the project. They used a new measuring apparatus in mapping, geodetic triangulation. They produced topographic maps that depict unchanging landscape features at a scale of 1:86,400; that is, one centimeter equals 864 meters on the ground. Most of the map sheets were published as a new edition in 1815. Paramelle used these maps and it seems that clients and local administrators enjoyed asking Paramelle to point out springs on them by topography and geographic features before starting exploration of a region. (https://en.wikipedia.org/wiki/French_cartography

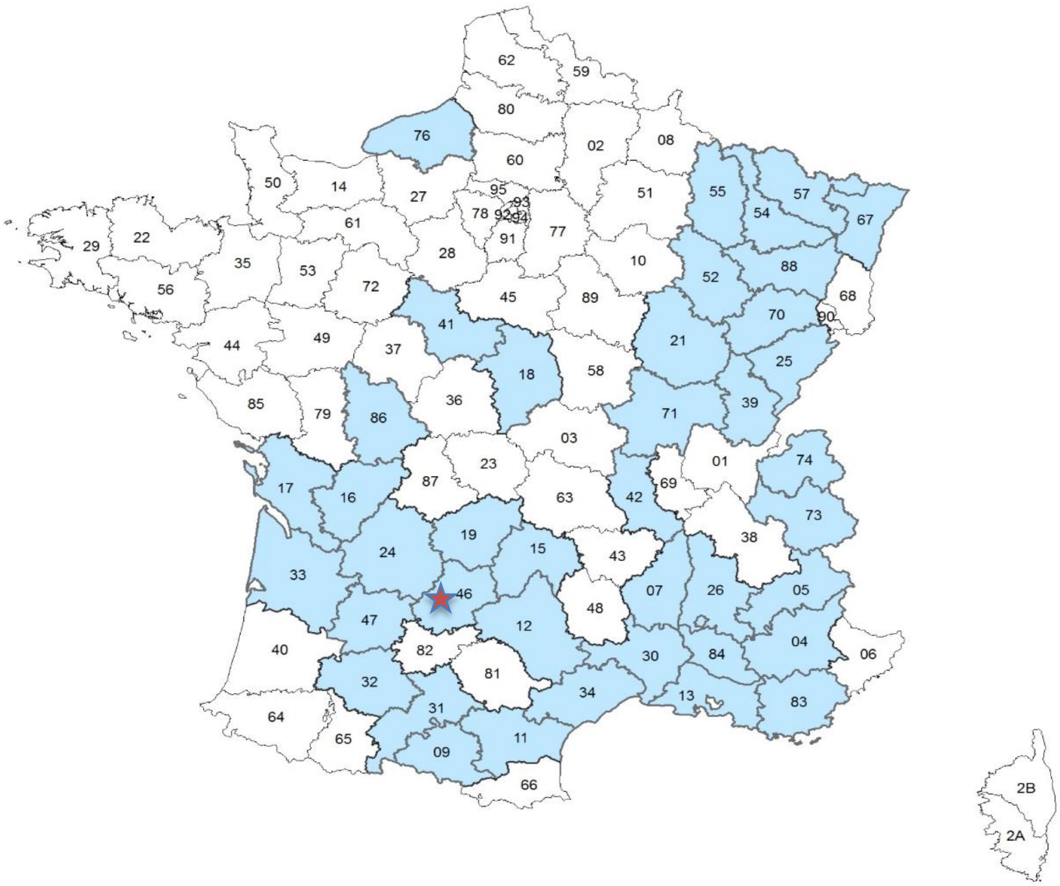



Figure 3.1. Map of the departments of France.
Blue color indicates departments where Paramelle explored for water between 1827 and 1854. Red star indicates Department of Lot.

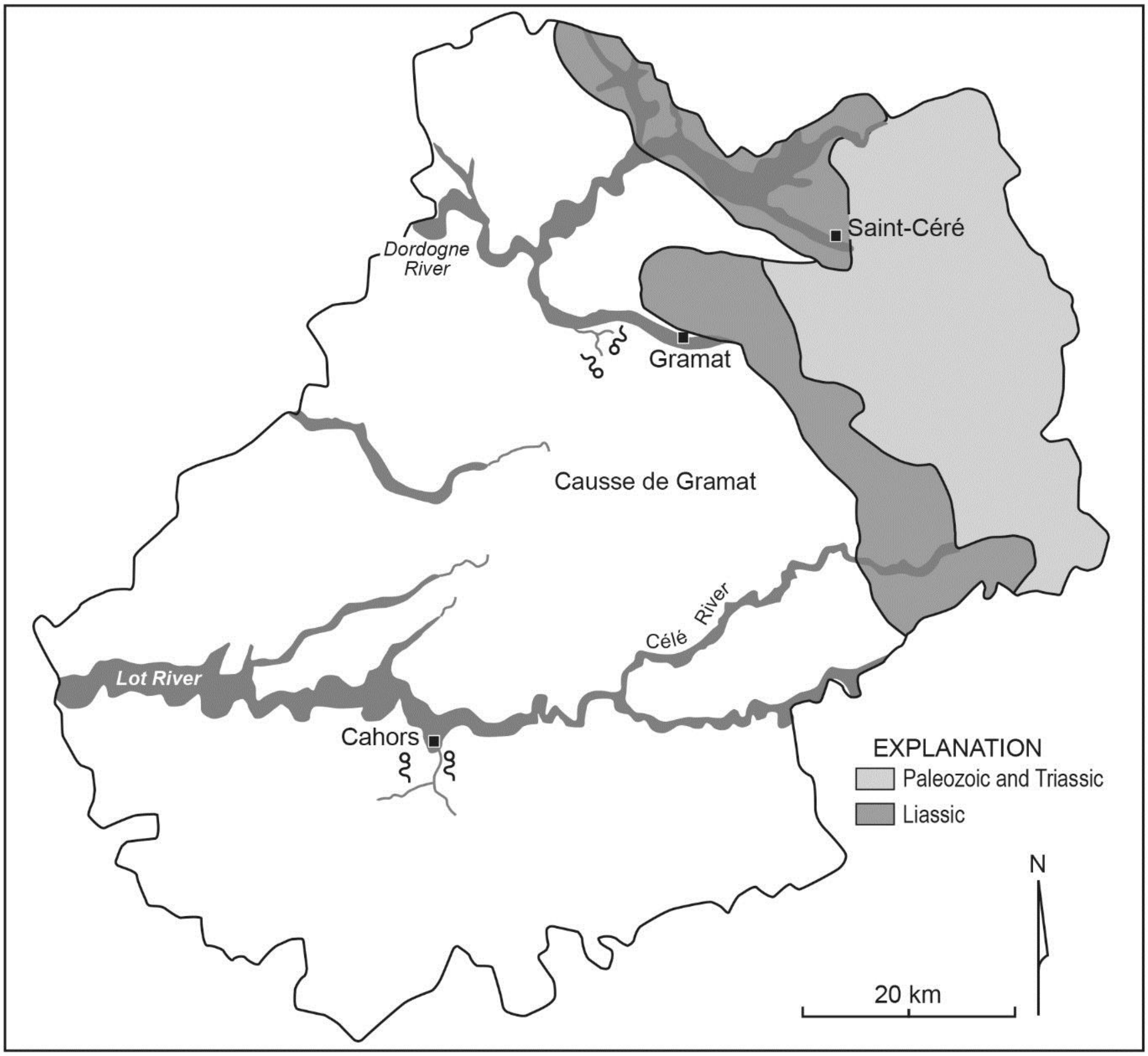
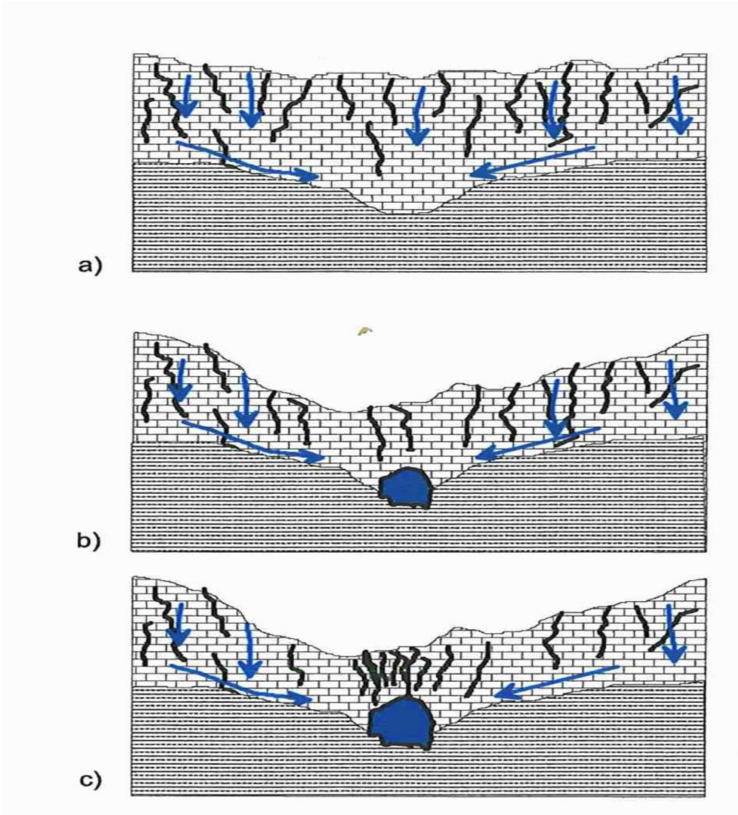



Figure 3.2. Surface geology of the Department of Lot, southwestern France. Paleozoic and Triassic rocks abut the Massif Central to the east. The Liassic surface is clay-rich and hosts numerous springs and streams. The Causse de Gramat is a limestone plateau traversed by the Lot and Dordogne rivers, but devoid of surface water over vast areas. Stream from the east disappear into the subsurface when they reach the limestone.




.

Figure 3.3. Schematic diagram of karst conduit formation.
a) Water passes through fractures in limestone and accumulates at low points in a zone of extreme permeability contrast (related to a lithologic discontinuity or a difference in fracture development.
b) Accumulated water dissolves the limestone until a conduit is created. At the same time, erosion modifies the surface morphology and causes overdeepening.
c) Conduit develops preferentially upward because it is limited at the bottom. A more intense fracture system forms above the conduit, which may explain the reaction of karst features such as the Pouymessen shaft (a vertical shaft connection the conduit to the surface.

Source: Chalikakis, 2006

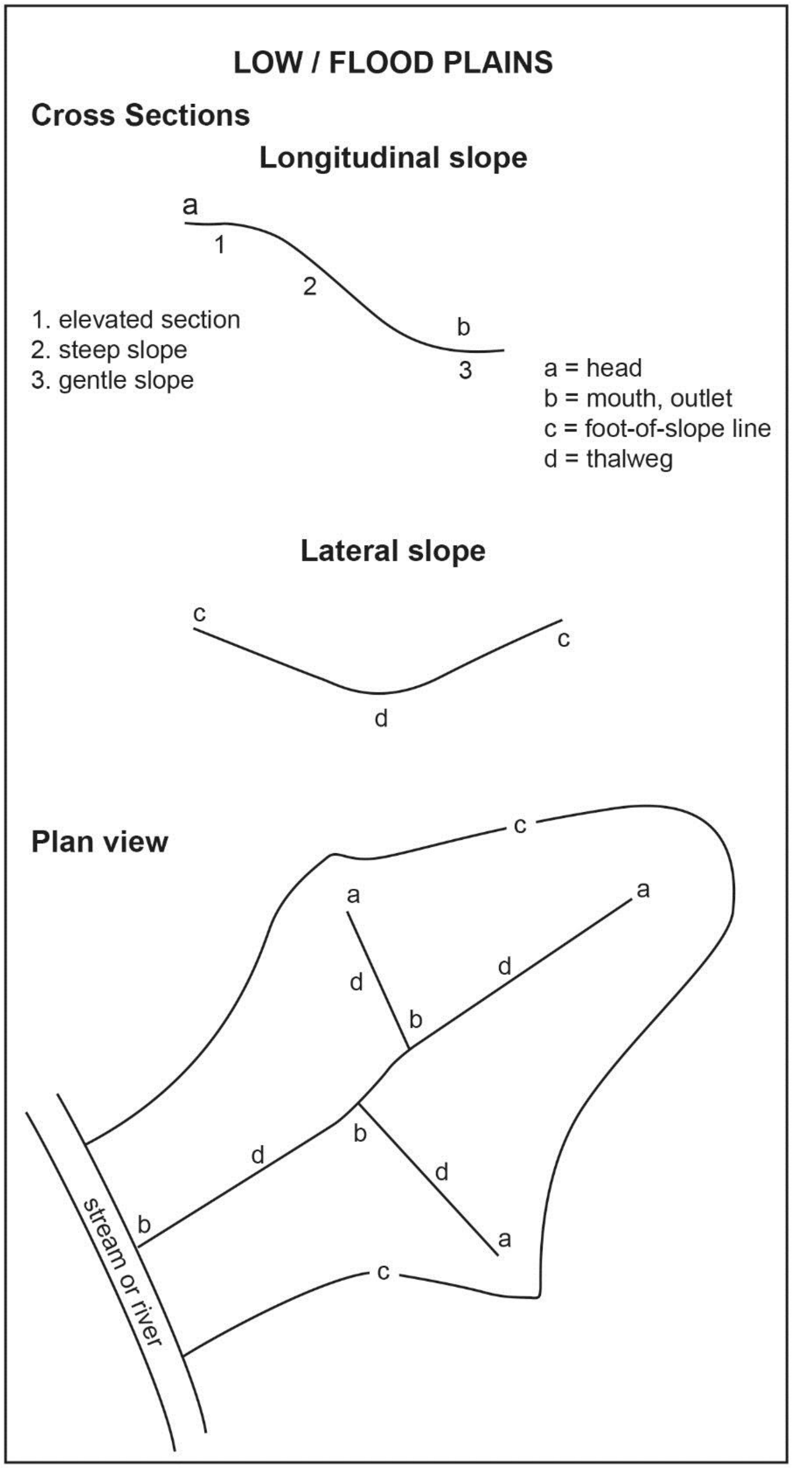



Figure 3.4. Where to look for shallow groundwater on flood plains.
Trickles of water coalesce and infiltrate on elevated dry sections of vales. Water is shallow here, but not abundant. Slopes on cross sections are vertically exaggerated.

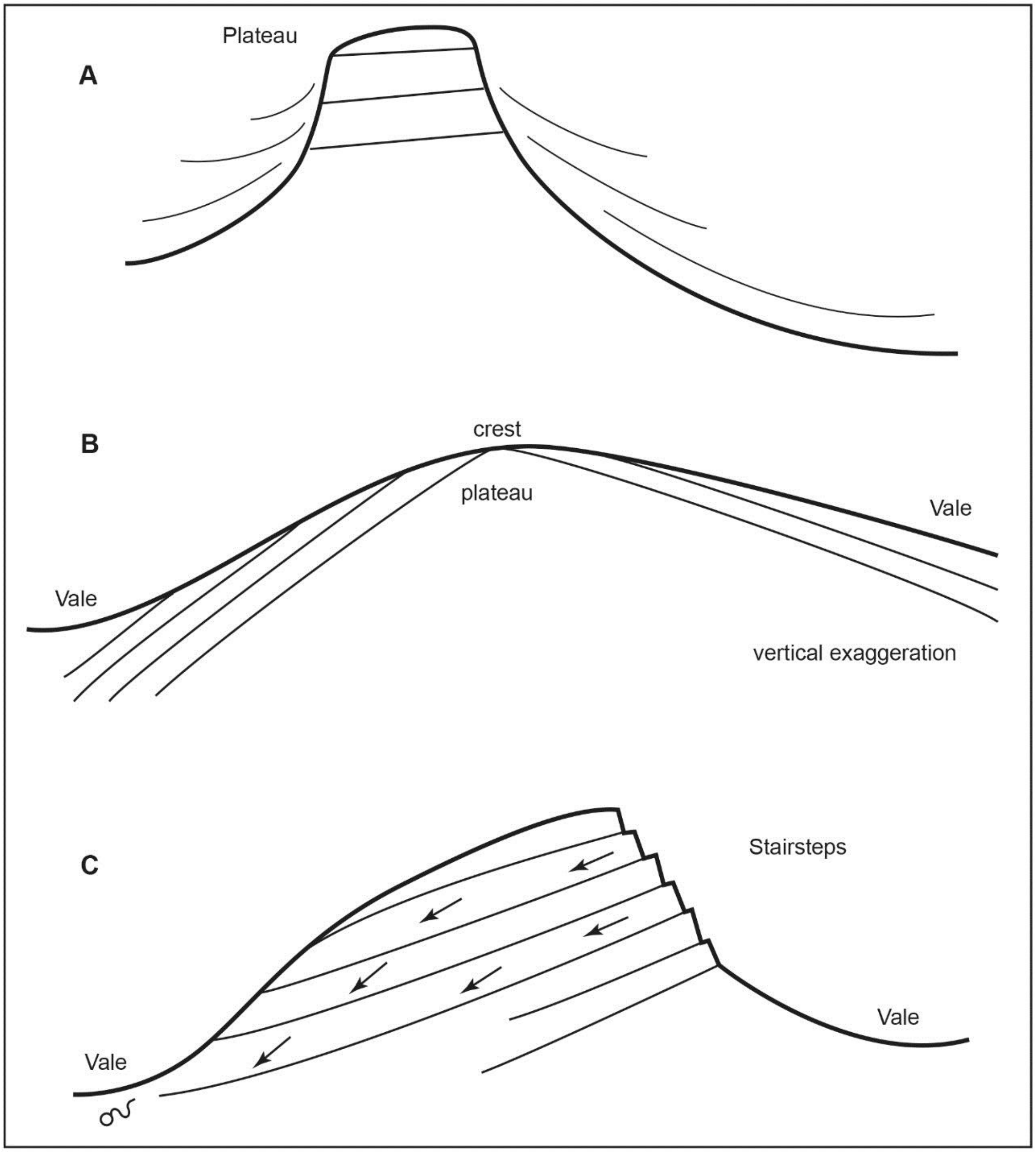



Figure 3.5. Where to look for water on mountains and large hills.
Here the key to finding water is the dip of strata. A. Slightly dipping strata beneath a large surface area can produce groundwater. B. On an anticlinal plateau with watershed divide near the center of the plateau, equal amounts of water flow toward the vales, infiltrating and creating underground watercourses that follow the topography. C. On an asymmetrical plateau with a watershed divide toward one side, the bedding planes on the steep slope form stair steps that collect rainwater and convey it to the base of the opposite side of the plateau.

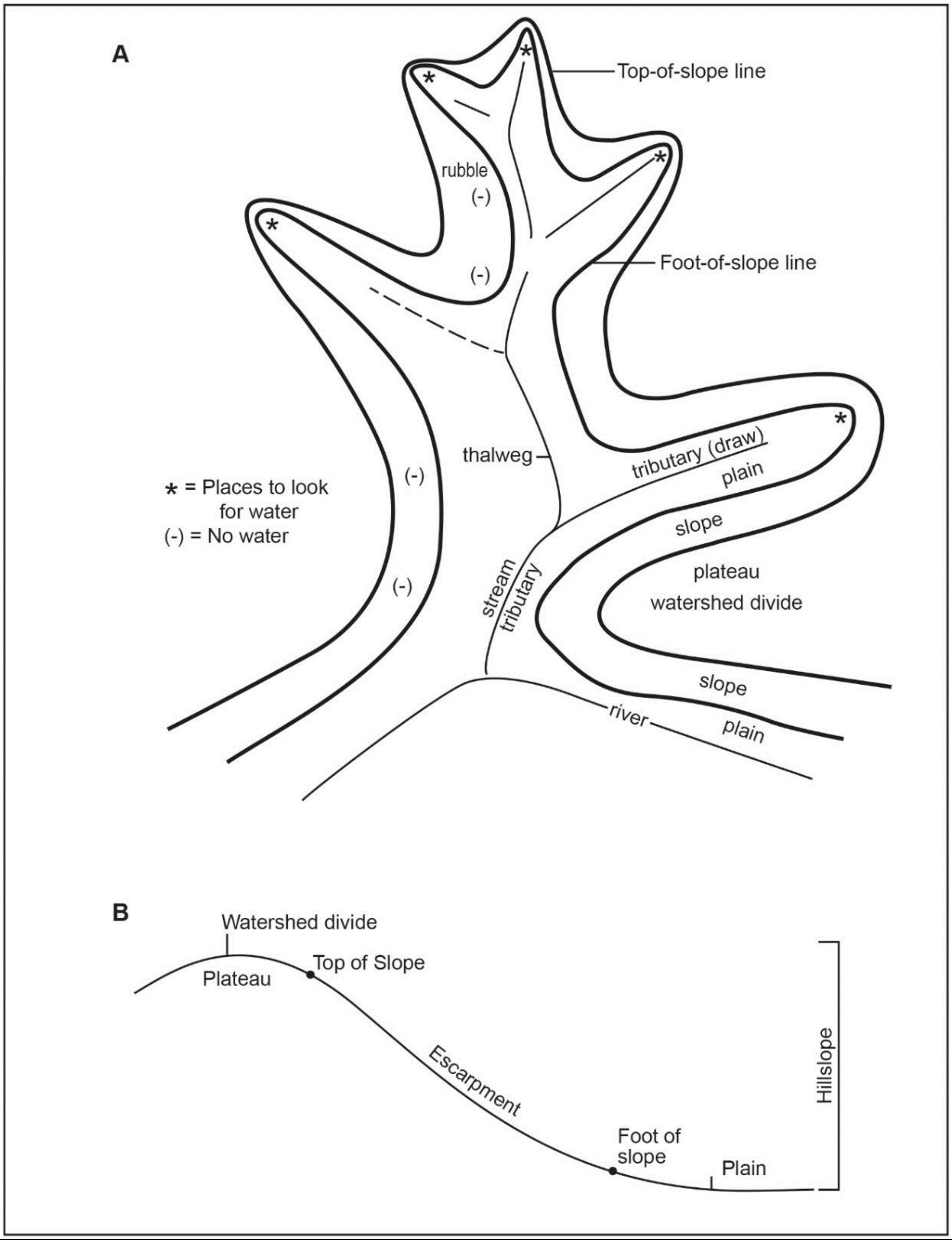
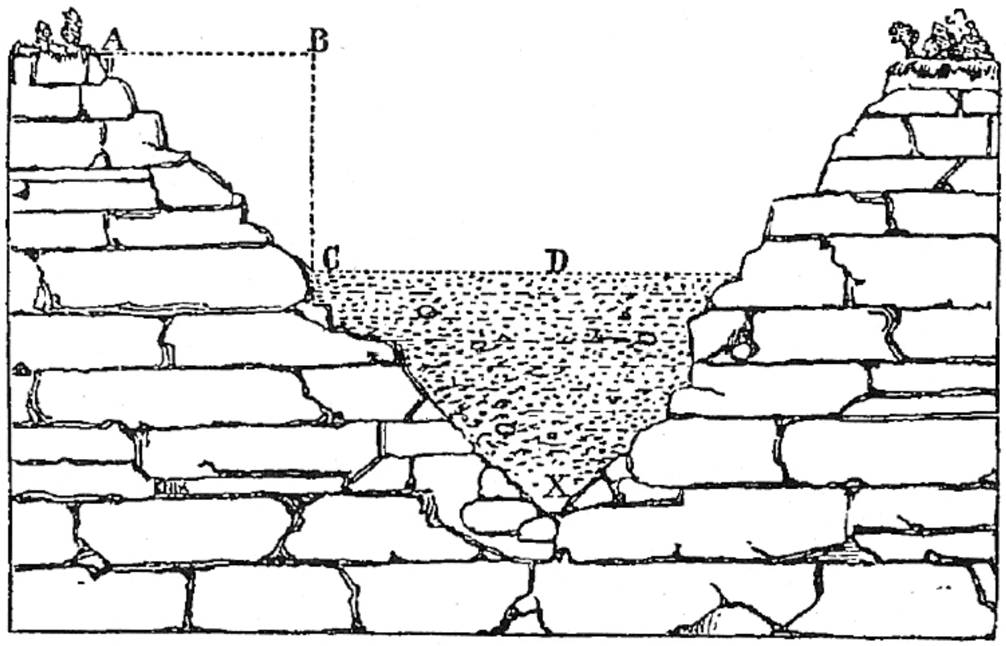



Figure 3.6. Where to look for water on low plains.
On low plains, hidden springs are most numerous, abundant, and shallow on the foot-of-slope line that separates the escarpment from the plain, particularly at the most concealed end of a reentrant, also at the base of a cliff on a low plain.




Coupe d'un vallon dont le fond est comblé par le terrain de transport.

Figure 3.7. How to determine the depth to water in a vale.
Cross section of a vale filled with sediment. This diagram shows Paramelle's geometric method of determining depth to the water at the bottom of the vale. The horizontal distance AB is to the vertical height BC as the horizontal distance CD is to vertical depth DX. Note X at the base of the alluvium in the streambed. Multiplying AB times CD and dividing by AB, one gets the depth from D to X.

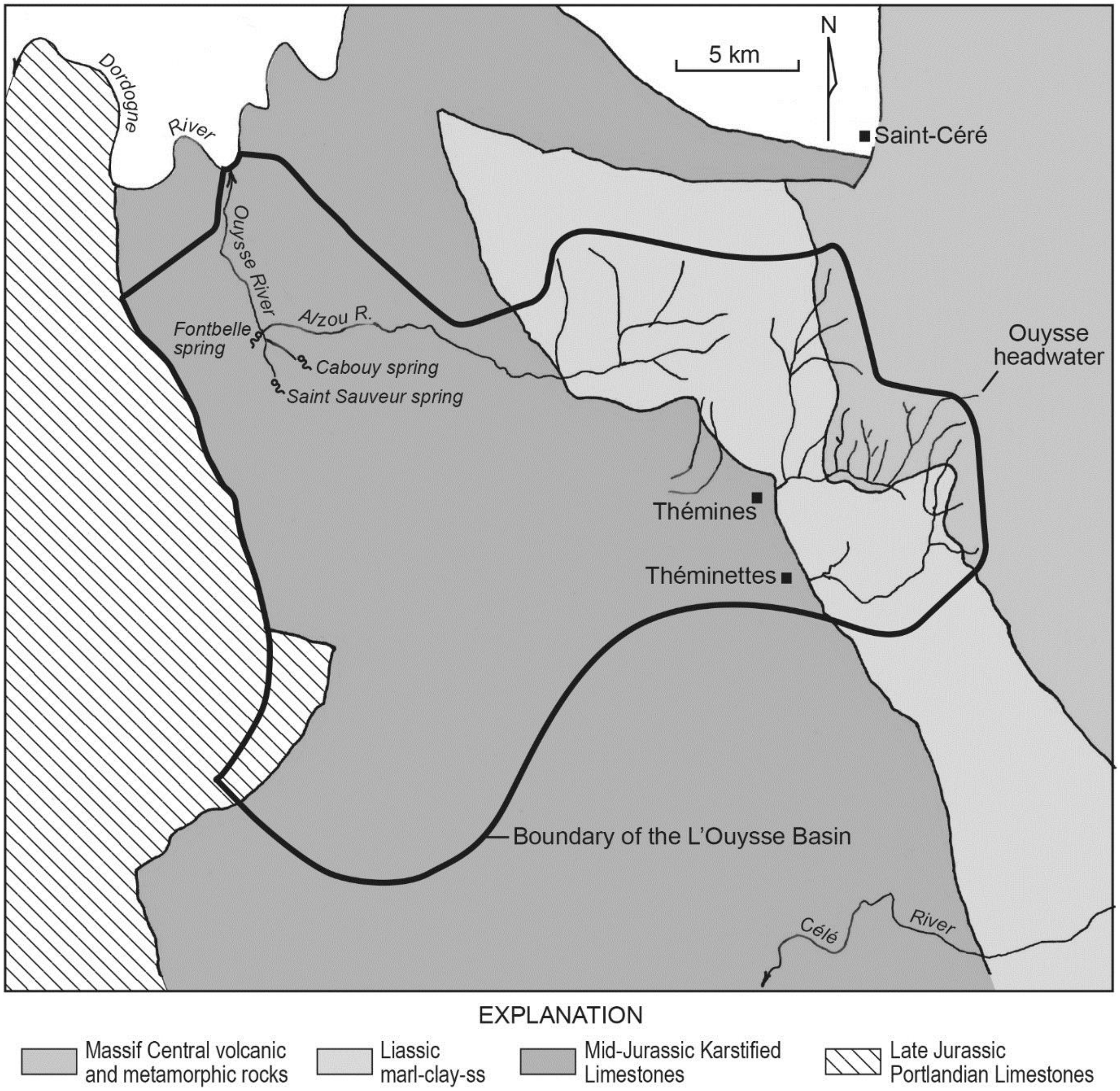



Figure 3.8. The L'Ouysse Basin.
Streams flowing westward from the marly clay of the Liassic sink into swallets when they reach the karst limestone plateau of the Causse de Gramat. The L'Ouysse sinks underground at Thémines and Théminettes and reappear at the Cabouy, Saint Sauveur, and Fontbelle springs to form the L'Ouysse River that flows into the Dordogne.

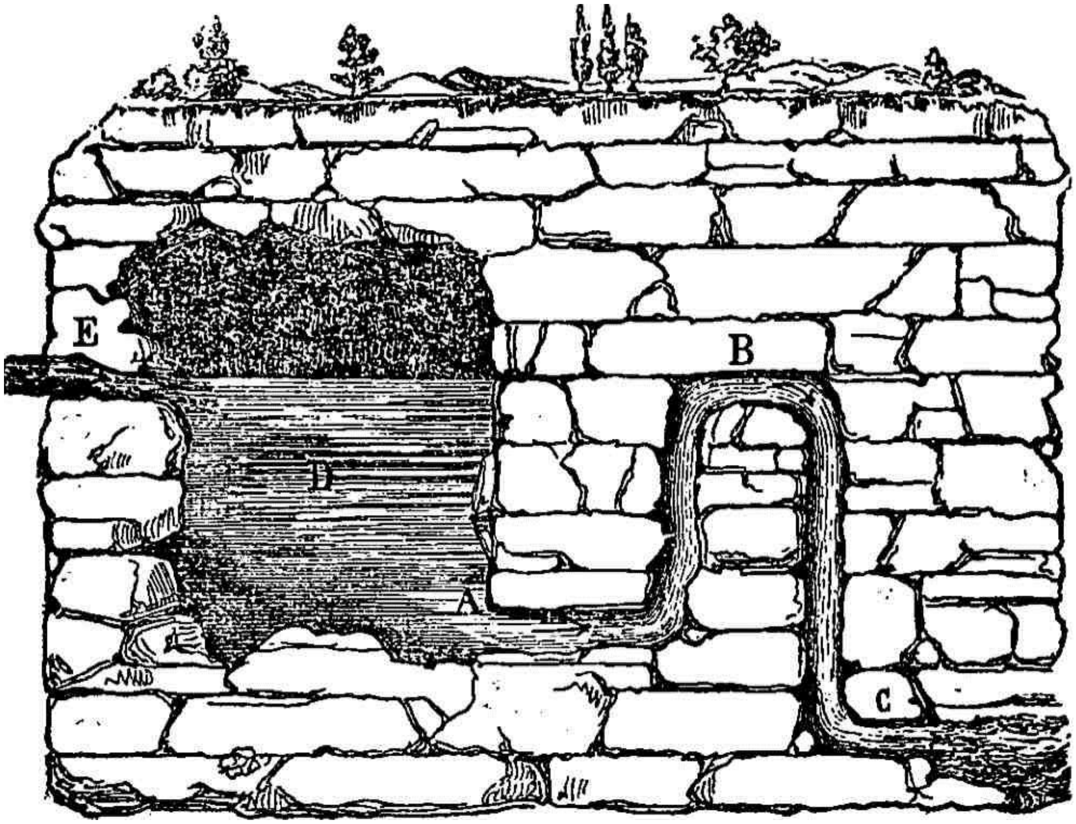
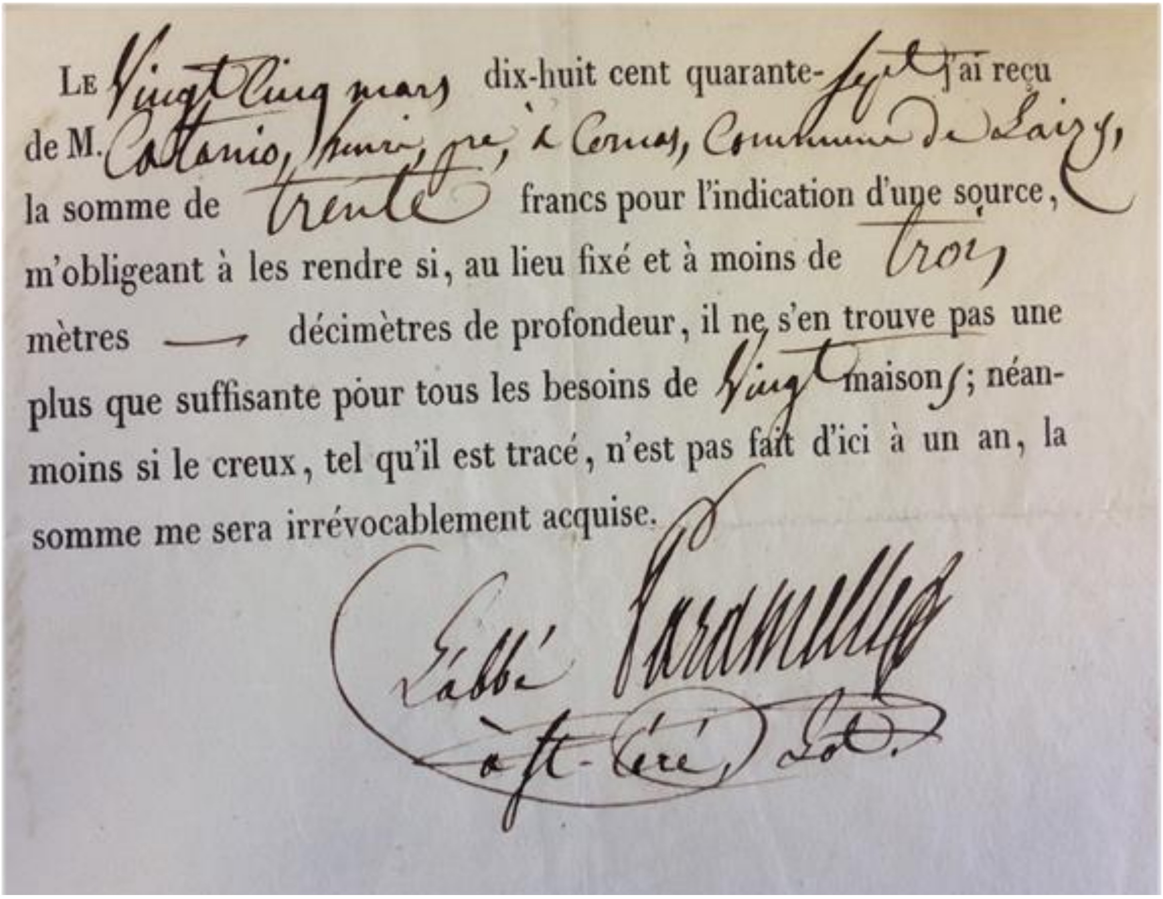



Figure 3.9. Paramelle’s siphon hypothesis as an explanation for the behavior of a periodic spring.
A, Opening of the short branch; B. Elbow; C. Outlet of the long branch; D. Cavity that serves as basin; E. Spring whose water enters the basin and collects there. When basin D is empty, water from spring E fills the basin and rises in the short branch AB. When the basin D and branch AB are full, water flows down branch BC where it noisily pushes out air and continues to flow until the water level falls below the level of the short branch A. Flow ceases and does not begin again until water rises to level B.



Le Vingt Cinq mars dix-huit cent quarante-sept j'ai reçu
de M. Catanio, Henri, pre, à Cernas, Commune de Saisy,
la somme de trente francs pour l'indication d'une source,
m'obligeant à les rendre si, au lieu fixé et à moins de trois
mètres — décimètres de profondeur, il ne s'en trouve pas une
plus que suffisante pour tous les besoins de Vingt maisons; néan-
moins si le creux, tel qu'il est tracé, n'est pas fait d'ici à un an, la
somme me sera irrévocablement acquise.

L'abbé Paramelle
à St-Céré, Lot.

Figure 3.10. Receipt issued by Paramelle for a groundwater indication.
On the twenty fifth of March 1847, I received thirty francs from Mr. Henry Catanio [for a] prairie at [illegible - Cernas?] in the commune of Saisy for the indication of a spring. I will return the fee to the client if he does not find water at the established location at a depth of less than three meters, in sufficient quantity for twenty houses, but if the client does not excavate at the indicated place within a year, I retain the fee.
[Signed] Abbé Paramelle, at Saint-Céré, Lot.

## 3.16. References


Chalikakis, M.K., 2006, *Application des méthodes géophysiques pour la reconnaissance et la protection de ressources en eau dans les milieux karstiques* [Geophysical methods applied to water exploration and protection in karst environments] [PhD thesis]: Paris, Université Paris 6, 217 p.

Darcy, H., 1856, The Public Fountains of the City of Dijon [Translated from *Les Fontaines publiques de la ville de Dijon*: Paris, Dalmont, 647 p.

Gèze, B., 1969, *Le Spéléologue Robert de Joly (1887-1968) et son apport à la science des Cavernes*: *Annales de Spéléologie*, Vol. 24, No. 4, p. 619-638.

Huot, J.-J.-N., 1836, *Memoires de la Société d'agriculture de Seine et Oise* [Report to Société d'Agriculture de Seine-et-Oise]: Versailles, Marlin, p. 109-120.

Mangin, A., 1969, *Etude Hydraulique du Mécanisme d'Intermittence de Fontestorbes*: *Annales de Spéléologie*, Vol. 24, no. 2, p. 253-299.

Martel, E.A., 1894, *Les Abîmes*: Paris, Delagrave, 580 p.

Meinzer, O.E., 1927, Plants as Indicators of Ground Water, USGS Water Supply Paper 577: Washington D.C., US Government Printing Office, 95 p.

Mentelle, [E.], and Malte-Brun, [C.], 1803-1812, *Géogr.*, livre VI [probably *Géographie mathématique, physique, et politique de toutes les parties du monde* [Mathematical, physical, and political geography for all parts of the world: Paris, Tardieu and Laporte.

Paramelle, J-P, 1827, *Mémoire hydrologique et géologique sur le département du Lot* [Hydrologic and geologic report on the Department of Lot], handwritten manuscript submitted to the Conseil General of the Department of Lot, transcribed by J. Taisne and T. Pélissié, published by Spéléo-Club de Paris, 2010.

Paramelle, J.-P., 1859, *L'Art de découvrir les sources* [The Art of Finding Springs], 2nd Edition: Paris, Dalmont et Dunod. 428 p.

Peck, R.B, 1969, Advantages and limitations of the Observational Method in Applied Soil Mechanics: Géotechnique 19, No. 2, 171-187. Reprinted in Institute of Civil Engineers, 1996, The Observational method in geotechnical engineering: London, Thomas Telford Publishing, 223 p.

Pluche, abbé N.A., 1732, *Le Spectacle de la Nature, ou Entretiens sur les particularités de l'Histoire naturelle* [The Spectacle of Nature, or Conversations on the particularities of Natural History], *Entr.* [Discourse] XXI: Paris, Frères Etienne (1764 edition).

Taisne, J., 1986, *L'Abbé Paramelle. Petite histoire d'une statue*: *Grottes et Gouffres*, Bulletin of the Spéléo-Club de Paris, No. 101, September 1986, p. 25-26.

Taisne, J., and Choppy, J., 1987, *Un des premiers hydrogéologues du karst: L'Abbé Paramelle, "Hydroscope"* in Karstologia No. 9, 1987, p. 53-58.

# Chapter 4. Application of Paramelle's observational method to finding groundwater in Texas karst

Abbé Paramelle developed an observational method for finding shallow groundwater on the karst plateaus of southwestern France. He closely observed limestone sinkholes, dry valleys, and springs and used these observations to find small amounts of water for farmers, shepherds, and villages. He was looking for water in the epikarst, the near-surface uppermost weathered zone of the karst. In Paramelle's time, excavation was done by hand, which limited the depth where water could be considered as a resource (Paramelle, 1856). A summary of Paramelle's observations is shown in Table 4.1.

Today's technology makes it possible to drill wells to far greater depths than in Paramelle's time and well drillers and their clients generally seek larger quantities of water than Paramelle's clients. A major question in water well drilling remains the choice of a location that can provide sufficient water to justify well drilling costs.

I applied Paramelle's observations to two karst areas of Texas: the New Braunfels area in Comal and Bexar counties and the Stockton Plateau in Terrell and Val Verde counties. Today we are not limited to exploring for water at shallow depths as Paramelle was. I wanted determine whether wells near surface subsidence features, which may have evolved from sinkholes, were more likely to encounter groundwater than areas farther from such features. This is an investigation of the relationship between karst features and water well productivity in the study areas in Texas.

This investigation was inspired by Lattman and Parizek's (1964) study of the relationship between fracture traces and occurrence of groundwater in carbonate rocks that showed that specific capacity was low in wells located in areas between fractures, that it was higher in wells located on or near single fracture traces in dolomite, and further increased in wells located on or near single fracture traces in limestone. By analogy, this study seeks to determine if zones of solution and subsidence act as pathways for increased weathering and permeability and thus promote vertical groundwater movement and storage. Well data for this study was much more limited than the data available in the Lattman and Parizek study, who were able to drill wells in selected locations.

The research questions are:

1: Do sinkholes correspond to locations of high productivity water wells in karst terrain?

2: By extension, do subsidence areas, areas where sinkholes have coalesced to form larger subsidence areas, correspond to locations of high productivity water wells?

3: Can GIS technology show this correlation?

4: Can GIS technology predict favorable locations for productive water wells?

Based on results of the water well study, an additional research question was added for the Study Area 2:

5. Do Paramelle's observations on the occurrence of shallow groundwater (i.e. springs) apply to the Stockton Plateau?

### 4.1. STUDY AREA 1: NEW BRAUNFELS

For the New Braunfels part of the study, I analyzed an area of the Cretaceous Edwards Aquifer in Central Texas, suggested by Eddie Collins of the Bureau of Economic Geology, where sinkholes are common. The study area is near New Braunfels, Texas between longitudes of 98°00' and 98°30'W, and latitudes of 29°30 and 30°00'N. (Figure 4.1). The map area covers a part of the Balcones Fault Zone, which is the main structural control. Surface geologic units range from Cretaceous limestones, dolomites, claystone, mudstone, and chalk northwest of the fault zone to limestones, marls, claystone, and mudstone southeast of the fault zone (Figure 4.2).

Geologic and Hydrogeologic Setting

The surface geologic units in the study area are primarily the Kainer and Person Formations, shallow water carbonates that make up the Edwards Group. The Kainer, the lower unit, is about 250 ft. (75 m) thick and is composed of limestone, dolomitic limestone, and dolomite deposited in a subtidal to tidal flat environment. Chert, current laminations, and low-angle stratification are present, as is honeycomb porosity. Fossils include rudistids, oysters, gastropods, and miliolids.

The Person Formation, the upper unit, is 130 to 150 ft. (40 to 45 m) thick in outcrop, and is composed of limestone, dolomitic limestone, and dolomite deposited in a similar subtidal to tidal flat environment. Limestone is interbedded with recrystallized dolomitic limestone and argillaceous limestone. This formation is characterized by leached and collapsed intervals, honeycomb porosity, terra rossa, cave and vuggy intervals, solution-widened bedding planes and fractures, and chert. Fossils include pelecypods, gastropods and rudistids. The lower 20 to 30 feet (6-9 m) of the Person Formation, the Regional Dense Member, is a dense argillaceous limestone recognizable in outcrop where it forms a topographic bench at the contact with the Kainer Formation (Collins, 2000).

Faulting developed on top of the buried Ouachita structural belt following consolidation of Cretaceous sediments. The most significant faulting occurred during the Miocene (Hauwert, 2009). Within the fault zone, en echelon normal faults strike mostly N40° to N70°E and mostly dip to the southeast. Fault blocks range in width from two to seven miles (3-10 km) and may be broken up into smaller fault blocks. Fault offset ranges from about 100 to 850 ft. (30-260 m); numerous smaller faults have displacements less than 100 feet (30m) (Collins, 2000). Surface elevation ranges from 600 to 800 ft. (183-244 m) across the study area.

Methods

The goal of the GIS study was to locate aligned and disseminated sinkholes and subsidence areas and analyze the productivity of wells located near these features. I used two type of data to determine subsidence areas. I then compared the results from the two methods to determine if one method generates better results than the other.

The first method involves the use of Stratmap elevation contours to locate surface depressions. This data is available from Texas Natural Resource Information Service (https://tnris.org/data-download/#!/statewide). These digital maps are based on USGS quadrangles; the contour interval is 10 m. Stratmap elevation contours are produced by digitizing map features as line graph elements from USGS quadrangles, at a scale of 1:24,000. After downloading the data from the TNRIS website, I used ArcGIS to find the depression contours and select them.

The second method involved the use of the digitized *Geologic Map of the New Braunfels, Texas, 30 x 60 Minute Quadrangle*, Bureau of Economic Geology Miscellaneous Map No. 39. Preparation of this geologic map included field identification and review of existing geologic literature and aerial photographs. It provides a highly accurate inventory of subsidence features in the study area. I downloaded the version digitized by the Bureau of Economic Geology (BEG).

For water well data, I used Submitted Well Driller Reports from the Texas Water Development Board, (downloaded from [www.twdb.texas.gov/groundwater/data/drillsdb.asp](www.twdb.texas.gov/groundwater/data/drillsdb.asp).)

The Submitted Drillers Report Data Base (SDRDB) lists well reports submitted starting in 2003; it appears to contain in excess of 250,000 well reports for the entire state of Texas; 2395 wells are located within the New Braunfels study area for this project.

Method 1: Stratmap

Stratmap indicates 218 closed depressions within the study area. I identified these closed depressions as subsidence areas in ArcGIS. The closed depressions shown on Stratmap include features such as quarries (Figure 4.3). Using ArcGIS, I created a 100m buffer around the subsidence areas and found six SDRDB wells within this 100m buffer: two industrial wells, two irrigation wells, a test well, and a domestic well (Table 4.2). The two industrial wells are 0.5 km apart and appear to be in the same quarry; another well, listed as domestic, appears to be in a quarry. Well depths range from 400 to 1500 ft. (122 to 457 m). Yields of these six wells range from 10 to 150 gpm (55 to 818 $m^3$/day). Most well reports lack drawdown data, so it was not possible to calculate specific capacity. The highest yielding well of these six is an industrial well (with drawdown data), which has a specific capacity of 0.5 gpm/ft./ft.

Within the study area, 103 wells have yields that range from 100 to 1000 gpm/545 to 5451 $m^3$/day. Table 4.3 shows the highest-yielding wells. A review of these wells indicates that none of them is within 100 meters of a Stratmap subsidence feature. Well depths of high yield wells range from 140 to 1500 ft. (43 to 457 m).

I did not construct a 200m buffer around the Stratmap depressions because I assume that the data would include a similar proportion of man-made depressions, which are not the focus of this study.

Method 2: BEG Miscellaneous Map 39

BEG Miscellaneous Map 39 shows 166 karst or subsidence features within the study area. In ArcGIS, I created 100m and 200m buffer zones around the subsidence features. The 100m buffer zone contains seven out of the 2395 SDRDB wells (Figure 4.4). Yields of these wells range from 0 to 200 gpm (0 to 1090 $m^3$/day) (Table 4.4). Mean yield for these seven wells is 53 gpm (289 $m^3$/day). Well depths range from 600 to 1240 ft. (183 – 378 m). Figure 4.5 is an enlargement of the southwest corner of Figure 4.4. Figure 4.6 is a photograph of land surface in the area of Figure 4.5.

The 200m buffer zone intersects or encloses 18 SDRDB wells (including the seven discussed above) (Figure 4.7). Well yields for these 18 wells range from 0 and 200 gpm (0 to 1090 $m^3$/day). Mean yield is 33 gpm (179 $m^3$/day). Well depths range from 440 to 1240 ft. (134 to 378 m) (Table 4.6). Of the 18 wells, the predominant surface geology units are the Kainer Formation (12 wells), Person Formation (5 wells), and Upper Glen Rose (one well). In addition, all 18 wells lie within 0.5 km of a fault. Most wells with Kainer Formation surface geology are closer to faults than wells whose surface geology is the Person Formation

Yields of wells located outside the 200m buffer of subsidence features range from 0 to 1000 gpm (0-5451 $m^3$/day); the mean is 23 gpm (123 $m^3$/day). Their depths range from 0 to 1540 ft. (0 to 469 m) (Table 4.5).

Submitted Driller Report Well Details

Depths listed for the 2395 SDRDB wells located in the study area range from 0 to 1540 feet (0 to 469 m). Mean depth is 582 feet (177 m). Yields range from 0 (yield is listed as 0 for 141 wells) to 1000 gpm (5451 $m^3$/day); 103 wells have yields greater than 100 gpm (545 $m^3$/day). Mean yield is 24 gpm (131 $m^3$/day).

Results

This study shows that wells located near karst features and subsidence areas have higher yields than wells located farther than 100 meters from these features (Table 4.6).

Discussion

Wells within 100 m buffers of both Stratmap and BEG depressions have higher mean yields than wells located outside buffer areas (56 and 53 gpm compared to 24 gpm/305 and 289 $m^3$/day compared to 130 $m^3$/day). Wells within 200 m buffers of BEG depressions have higher mean yields than wells located outside buffer areas (33 gpm compared to 24 gpm/179 $m^3$/day compared to 130 $m^3$/day). Thus higher well yields correlate with mapped closed depressions, based on this limited study.

The Submitted Drillers Reports database lacks important data for many wells. For example, lack of drawdown data makes it impossible to calculate specific capacity of the wells, and in many cases, yields are not recorded.

The use of ArcGIS provided valuable information aside from the comparison described above. After determining the number of wells with the highest yields (i.e., between 100-1000 gpm/545 – 5451 $m^3$/day) and comparing them visually to the 100m buffer zone around Stratmap closed depressions, ArcGIS showed that none of the 103 highest yielding wells in the study area was within this 100m buffer zone. This raises the question of what factors lead to the high yields from these 103 wells.

ArcGIS shows that a number of wells with higher than mean yields lie within subsidence areas adjacent to faults (Figures 4.4 and 4.7). Thus, it appears that subsidence areas along faults are the most favorable locations for finding high yield water wells in this area.

ArcGIS shows that Stratmap depressions such as quarries are "favorable" locations for high-yield water wells. Two of the three highest-yielding wells within the 100m buffer of Stratmap depressions are located within quarries; well yields here may be higher due to surface water storage and infiltration into a potentially fractured environment. These quarries can be considered anthropogenic subsidence features.

ArcGIS also made it possible to determine the extent of overlap between the Stratmap and BEG depressions. As Figure 4.8 shows, the BEG maps shows numerous small circular karst features whereas the Stratmap depressions are larger and have more irregular shapes; however, in some places they overlap.

Research on this question would benefit from a larger sample size, preferably research in different karst area with more numerous sinkholes and subsidence areas. A comparative study between a highly-faulted area with sinkholes and an area with sinkholes but relatively few faults might provide interesting insights that could be used to study the subsidence and high-yield well correlation; which feature – subsidence or faulting – is a better predictor of a high-yield well location?

As for the comparison of methods, a detailed geologic map provides more focused results than Stratmap. Because Stratmap shows surface depressions of all types, the analyst has to eliminate features not related to karst. In addition, the 10m contour interval is too coarse to show many sinkholes. However, in the absence of a detailed field-checked geologic map, Stratmap can be used for preliminary analysis.

### 4.2. STUDY AREA 2: STOCKTON PLATEAU

The same questions were used in studying the Stockton Plateau.

1: Do sinkholes correspond to locations of high productivity water wells in karst terrain?

2: By extension, do subsidence areas, areas where sinkholes have coalesced to form larger subsidence areas, correspond to locations of high productivity water wells?

3: Can GIS technology show this correlation?

4: Can GIS technology predict favorable locations for high productivity water wells?

Geologic and hydrogeologic setting

The Stockton Plateau is located in the Trans-Pecos area near the southern boundary of the Great Plains physiographic province in Texas. It occupies all of Terrell County, western Val Verde County east to the Pecos River, and eastern Brewster County. The Stockton Plateau lies approximately between 101°15’ and 102°30’ W and between 29°30’ and 30°36’ N. This study focuses on the southern part of the Stockton Plateau, between latitudes 29°30’ and 30°00’N (Figure 4.9). The plateau is on the southern edge of the Edwards Plateau and is composed mostly of limestones of Cretaceous age, which are well exposed due to thin soil and sparse vegetation. Stratigraphic units range from Cretaceous pre-Georgetown Limestone through Austin Chalk overlain by Quaternary gravel and alluvium (Figure 4.10). The relatively undeformed Cretaceous rocks overlie highly deformed Paleozoic formations of the Ouachita system. Elevation within the study area ranges from 2680 ft. (817 m) in southeastern Brewster County part of study area to 960 ft. (293 m) in Val Verde County along the Rio Grande. The following geologic descriptions are from Freeman (1968).

The oldest Cretaceous rocks in the area are (in ascending order) the Glen Rose, Maxon Sand, Walnut Clay, Comanche Peak Formation, Edwards Formation, and Kiamichi, which underlie the Georgetown Limestone. The thickness of these oldest Cretaceous units totals about 700 ft. (213 m). The overlying Georgetown Limestone, 450-600 ft. (137-183 m) thick, is the most widely exposed formation in the area; it crops out along the Rio Grande and its main tributaries in most of the map area. It forms vertical cliffs and large reentrants with overhanging roofs. It erodes along the bedding plane, resulting in a flat surface away from canyons.

Upper Cretaceous rocks overlie the Georgetown: Del Rio Clay, Buda Limestone, Boquillas Flags, and Austin Chalk. The Del Rio Clay ranges in thickness from 0 to 85 ft. (0 to 26 m) and consists of 4 rock types, claystone (60-80%), siltstone (25%), coquina limestone, and nodular limestone. In the field the Del Rio occupies a flat surface on the Georgetown, forms a brown moderate to steep slope, and is capped by the resistant Buda Limestone. *Exogyra arietina* is a characteristic fossil. The Del Rio Clay was deposited in a shallow continental sea at a depth below storm waves; the sediment source was to NE or NW.

The Buda Limestone, with a total thickness ranging from 50 to 90 ft. (15 – 27 m), consists of three units: a lower step-forming unit, moderate-to-steep-slope-forming middle unit, and a hard, vertical step-forming upper unit. In the field the Buda appears as a white band above the dark Del Rio and below the dark base of the Boquillas. The top and bottom layers are micritic limestone, with a porcelaneous texture and fetid odor; these units are nearly pure calcite. The middle unit is a clayey micritic limestone that weathers nodular. Fossils include ammonites, corals, hemiaster, and *Exogyra*. The top of the Buda is an unconformity; it was deposited in a shallow marine continental environment that received its terrigenous sediment from a distant source.

The Boquillas Formation, also called Boquillas Flags, and called Eagle Ford farther east, has a total thickness ranging from 160 to 220 ft. (49 to 67 m). It is composed of four lithologic units: a resistant lower pinch-and-swell unit that forms steep faces and mesas, a flagstone unit, ledgy unit, and an upper laminated unit. The Boquillas is a dark gray in color, predominantly clastic (90% calcarenite and shell fragments), and fossiliferous.

The Austin Chalk, the youngest Cretaceous unit in the area, forms a large surface outcrop in the central portion of the Stockton Plateau. The unit has been eroded and only the bottom 200 ft. (61 m) of the Austin Chalk remain. The Austin Chalk caps hills and forms vertical cliffs along streams. Two lithologies are present, a hard, pale orange limestone and thin interbeds of laminated clayey limestone, but the formation is not subdivided. It contains *Inoceramus* and conformably overlies the Boquillas.

Methods: Water Wells

I used the Geology of the Comstock-Indian Wells Area Val Verde, Terrell, and Brewster Counties, Texas, USGS Professional Paper 594-K, which contains a geologic map and overlay map showing extensive areas of subsidence (Freeman, 1968). Subsidence areas located west of the Pecos River are elongate and oriented predominantly NE to SW; eastward, toward the Pecos River the orientation trends toward N-S. Large subsidence areas are present east of the Pecos River in the Baker's Crossing and Shumla quadrangles, (45°N and 101°00 – 101°30W); one large irregularly shaped feature oriented approximately E-W measures 7 km N-S and 16 km E-W (Figure 4.11).

The boundaries of the study area were set at 101°15’ to 102°00’ W and from 29°30’ to 30°00’N so as to use readily available data. Elevations within the area range from 920 ft. (280 m) to 2060 ft. (629 m).

The Submitted Drillers Report Data Base (SDRDB) lists 88 wells within the study area, ranging in depth from 95 to 1040 ft. (29 to 317 m); mean well depth is 510 ft. (155 m).

For the analysis I established a 200m buffer around the SDRDB wells and displayed them on the subsidence overlay to determine if any buffer zone overlapped a subsidence feature (Figure 4.12).

Results

No buffer zones overlapped any subsidence feature. The well with the shortest distance to subsidence feature is SDRDB well 85451 located in near the northern boundary of the study area, at latitude 29.989722 longitude -101.583611 (8 km W of intersection of -101.5 meridian and the Pecos River (Figure 4.13). Well 85451 is located between two subsidence features, 450 m from the small subsidence area to the SW and 530 m from the larger subsidence area to the NE. On Figure 4.12, the blue dot indicates the 200m buffer zone surrounding the well. Subsidence features are from a scanned copy of the map overlay (Freeman, 1968).

Discussion

The lack of water wells located near subsidence areas is consistent with the small number of water wells in the Stockton Plateau area. This is a sparsely populated area. Also, as in Paramelle’s time, water wells are sited for convenience (e.g. proximity to dwelling), not in locations where groundwater is most readily abundant. Given the hydrogeology of the Stockton Plateau, it is likely that groundwater is found at depths determined by flow paths developed in response to factors that are different than those present in the New Braunfels area. In New Braunfels, the Edwards is present at the surface but on the Stockton Plateau, another 100-200 feet of Cretaceous limestones overlie the Edwards. Resistant limestones at the plateau surface, a long period of erosion, and the nature of karst features on the Stockton Plateau created a hydrologic system that promotes rapid downward movement of infiltrating water to conduits that carry the water down-gradient to the Pecos and Rio Grande.

On the Stockton Plateau, the primary source of groundwater is the Edwards Trinity Plateau Aquifer, essentially the Fredericksburg (Edwards). The geomorphology of the Stockton Plateau is dominated by the Pecos River and the Rio Grande, which planed the region during the Tertiary and began incising the Cretaceous during the Pleistocene (Veni, 1991). This unconfined aquifer is recharged throughout the outcrop that extends to northern Pecos County (Figure 4.15) and by streams flowing from the Glass Mountains and Marathon Basin located to the west and northwest (Figure 4.10). Water table elevation ranges from 1060 m in the west to 320 m at the downdip end. Recharge occurs though direct infiltration of surface water in streams; most water enters and moves through the aquifer along fractures and solution features such as sinkholes, swallets, and caves. Groundwater discharges via springs and water wells. Major groundwater withdrawal of this aquifer has occurred on the northwestern portion of the Stockton Plateau, to the point of drying up of Comanche Springs, once the largest springs in West Texas. Groundwater naturally discharges from the Stockton Plateau into the Rio Grande and along the Pecos River. Brune (1981) found that the largest springs discharge to the Pecos. Pecos River springs and Rio Grande springs flow from the Buda and Fredericksburg (Edwards).

Veni (1991) reviewed Freeman's map of subsidence features on the Stockton Plateau. He states that no solution sinkholes have been documented on the Stockton Plateau, but that numerous collapse sinkholes are present. Solution sinkholes result from abundant runoff and soluble lithology, conditions which are not present on the Stockton Plateau. Collapse sinkholes form when a cave ceiling is no longer able to support its own weight; this usually occurs as the cave grows in size or conditions in the cave change from phreatic to vadose. Veni cites White's (1988) classification of collapse sinkholes into three types: (basic) collapse sinkhole, subsidence sinkhole, and subsidence shaft; Veni defines subsidence sinkholes as collapses into deep cavities in which upward stoping of strata breaches the surface and collapse materials fill the sinkhole (Figure 4.14).

White's third category, subsidence shafts, are not known to occur on the Stockton Plateau, likely because the shafts have been eroded away.

According to Veni, the oldest and largest collapse features on the Stockton Plateau are subsidence sinkholes. Freeman (1968) mapped 175 subsidence sinkholes within 24 km of the Rio Grande and estimated that about 1/3 are circular and 100 – 200 m in diameter; 1/3 are linear, 100-200 m wide and 2-3 km long; and 1/3 are 100-200 m wide and average 500 – 700 m long. Vertical displacement of strata is commonly 12-15 m and more than 70 m in places. Veni claims that most of these sinkholes have no topographic expression because erosion has removed evidence of depressions that may have formed on the land surface, which is confusing because Freeman mapped these areas as subsidence areas. Veni adds that some sinkholes may have filled with Plio-Pleistocene gravels.

According to Kastning (1987), subsidence sinkholes on the Stockton Plateau probably formed by collapse into phreatically-formed cavities to a depth of 90-120 m below the top of the Fredericksburg Group (Edwards). The following reasons support this horizon as the suspected solution zone: no displacement has been found below this level and this level corresponds to the top of the marly Sue Peaks Formation which would restrict downward groundwater flow and promote the development of horizontal passages.

The N60-70°E orientation of the sinkholes does not align with major fracture trends in the study area; Veni thinks that sinkhole orientation may align with paleo-flow conduits discharging to the Pecos River, which was a major active river since the late Eocene (Thomas, 1972, in Veni). In the pre-Pleistocene, the Pecos is thought to have been entrenched to a lower elevation than the Rio Conchos (now a tributary to the Rio Grande) and that the head difference between the rivers favored groundwater movement down the potentiometric gradient to the Pecos (Veni, 1991) (Figure 4.16). As a result, water from the Rio Conchos infiltrated into the Edwards and discharged into the ancestral Pecos River. As groundwater flow paths enlarged their roofs they lost structural support and groundwater support. Veni interprets the dissimilar pattern of sinkholes east of the Pecos River as slow groundwater movement along an ill-defined gradient.

Regarding basic collapse sinkholes, Veni says that all of them present on the Stockton Plateau involve collapse of the Boquillas Formation into Buda voids. The (basic) collapse sinkhole is smaller than subsidence sinkholes and collapse sinkholes form from the top down.

Based on stratigraphic controls observed in cave development, Veni noted that the basal Del Carmen Limestone (equivalent to the Fort Terrett member, or the Kainer of New Braunfels) is less permeable than overlying limestone and that groundwater perches on that unit and thus enhances solution.

After rivers incised into the Edwards Group and created outlets for groundwater discharge, the initially steep potentiometric surface encouraged drainage until continued incision reduced the potentiometric surface and reduced drainage, resulting in collapse of conduits.

Based on the results of this part of the study, I decided to examine shallow groundwater on the Stockton Plateau.

Methods: Springs

I also examined groundwater discharge at springs. One of Paramelle's recommendations for finding groundwater is to look in areas near springs; this is likely a recommendation to a landowner who lives adjacent to a spring, but does not own the spring property. Springs often occur in clusters, and Paramelle notes that the landowner may find shallow groundwater (or a hidden spring) near a known spring.

To review locations of known and mapped springs on the basis of conditions Paramelle considered favorable for springs (Table 4.1), I downloaded Texas springs data from the Texas Parks and Wildlife Department [personal communication, 2017] and plotted spring locations on study area maps (Figure 4.17). Table 4.7 is a list of springs located within the study area. I used Gunnar Brune's *Springs of Texas* (1981) for additional information on springs.

Results

The following discussion is a review of geologic and topographic setting of these springs, from west to east: Coe, Luis Guerra, Indian Wells, Buena, Cedars, unnamed spring west of Guy Skiles Spring, and Dead Man Spring.

Coe Springs in eastern Brewster County (Figures 4.18 and 4.19) illustrates Paramelle's observation that water is present in recesses in vales and at the base of steep slopes. On mountain slopes, the inclination of layers is the most important factor; water is not present when layers slope into the mountain. Water can be found at the base of the edge of a plateau, if the plateau is large enough, that is, if there is a large enough recharge area. Brune (1981) noted that in 1976 wet weather seepage at Coe Springs supported both plants and animals: walnut trees, blackbrush, creosote bush, prickly pear, deer, javelina, rabbits, doves, and house finches. Pictographs in caves in the nearby limestone bluff attest to a long period of habitation in ancient times.

Luis Guerra (also known as Chupadera) Springs (Figures 4.20 and 4.21) flow from Buda Limestone, less permeable than the overlying strata, concordant with Paramelle's basic principle that groundwater is found on top of a confining layer at the base of permeable rocks. The spring is on a slope, and for this reason, I surmise that the strata dip gently to the south or southeast, per Paramelle's observation that if the strata dipped into the mountain, there would be no spring. The spring is located at the foot of a steeper slope, in and near a recess (Figure 4.22). Brune (1981) recorded the longtime owner and resident as saying that these springs and others nearby used to flow all winter each year, providing water for a distance of 1.6 kilometers downstream, but that overgrazing and destruction of natural vegetation have caused the springs to fail. Panthers and javelina were common in 1976. Numerous artifacts, mounds, and paintings attest to a long period of habitation and use of the springs.

Indian Wells, also called Indian Pot Hole, flows from the Boquillas Formation (Figure 4.23). Brune (1981) describes it as being located at the head of McClain Canyon. This spring appears to be on a flat area at an elevation of 2220 ft. (677 m), about 1.1 km southeast of a plateau that rises to 2280 ft. (695 m) and is capped with Boquillas. The flat area is a saddle in the Boquillas. The spring is located on the slope of a recess that opens out downstream into a faulted subsidence area. Because the water is trapped in the Boquillas, whose bottom contact appears to be around 2140 ft. (652 m), the spring probably collects water from rainfall on the plateau and discharged it downgradient at this location. At this location thickness of the Boquillas is about 140 ft. (43 m).

The upper units of the Boquillas are likely more permeable than the lower or middle layers that stop the infiltration of precipitation and create the springs; this is Paramelle's basic tenet that water is found where permeable surface units overlie a confining layer. Again, the size of the plateau is large enough to create groundwater; Paramelle's idea of recharge zone, given enough rainfall. Although the springs were dry in 1976, they are reported to flow in wet weather. Native American paintings in shelters around the pool indicate habitation of the springs over time.

Buena Springs (Figure 4.24) flow to the surface at the contact between the Buda and Boquillas formations. This situation illustrates Paramelle's observations on the presence of water where permeable units overlie a confining bed, and the presence of water at the base of a slope. The spring is located in an area of steep topography (Figure 4.25), in a slight recess in a large reentrant (Figure 4.26), similar to the base-of-slope line where Paramelle found water on low plains. The topographic map shows the contours V'ing upstream to the west of spring; this may represent a surface thalweg which Paramelle considered a key to finding the hidden thalweg below. The high area to west of spring is large enough to accumulate abundant water; water can be found at base of the ledge of the plateau. Severe overgrazing in the area has reduced ground cover to creosotebush, catclaw and mesquite (Brune 1981).

Cedars Spring, (Figure 4.27) flows from the Austin Chalk in a recess along a slope at an elevation of 1840 ft. (561 m). Water flows to a creek located to south, which flows southeast to Lozier Canyon. The spring lies between two surface alluvium-filled streams that have incised to depth of 1780 ft. (542 m) (Figure 4.28). Northwest of the spring between the streams is an area roughly 4.5 x 3 km or 1350 hectares, which is likely the recharge area of the spring. The elevation difference is about 80 ft. (24 m). Paramelle estimated that a 5-hectare recharge area with a 10m thick aquifer could supply 4 liters per minute (approx. 1 gpm) at a spring, so with sufficient rainfall the 1350-hectare recharge area could supply a spring. The Austin Chalk allows water to infiltrate and a layer of clayey limestone likely inhibits the downward infiltration of the water and conveys it along the clayey surface to the spring location. According to Brune (1981) these springs were very important to early settlers and in 1976, although declared to be dry, 0.35 lps was flowing from other small springs upstream. A large willow tree still stood at the site in 1976 when Brune visited.

Two springs were located near Langtry Creek, an unnamed spring and a spring named Guy Skiles (Figure 4.29 and Figure 4.30). They are now covered by the Amistad Reservoir. The unnamed spring flowed from the most recessed end of a vale (Figure 4.31), from the Georgetown, which is overlain by the Buda at a horizontal distance of 50 meters and a vertical distance of 20 ft. (6 m) up the vale.

On the eastern margin of the Stockton Plateau, Dead Man Spring (Figure 4.32) flows from the Georgetown Limestone along a steep slope in a vale that empties eastward into the Pecos River. About 300 m west of the spring, the Buda crops out on top of the Georgetown but does not cap the entire surface of the Georgetown. The spring is at an elevation of between 1380 and 1400 ft. (421 and 427 m), and the base of the Buda is at 1460 ft. (445 m) (Figure 4.33). The elevation of the hilltop located west and northwest of the spring reaches 1500 ft. (457 m) over a width of about one kilometer before decreasing westward. An unknown thickness of terrace gravel lies in a N-S band adjacent to the Buda and on top of the Georgetown. Based on Paramelle's observations, the size of the hilltop is large enough to supply the spring, although the spring water may actually be regional groundwater flowing within the Georgetown.

Discussion

The locations of the springs discussed above share three major features: they are all on slopes (gentle to steep) or protuberances within recesses. The land surface rises to the northwest, the hydrologically upgradient direction. Field observations indicate that plants are present near springs that still flow or seep.

### 4.3. CONCLUSIONS

In the New Braunfels area, sinkholes and subsidence areas correlate with high yield wells and GIS can be used to show this correlation. Thus, GIS analysis can suggest favorable locations for productive water wells in karst terrain. For the analysis, a detailed geologic map with mapped subsidence features provides more focused results than Stratmap, which uses 10 m contour intervals to display surface depressions of all types, including man-made features. The use of ArcGIS technology is an extension of the observational method; it provides a powerful visual tool for observing correlations of geologic features and high-yield wells. Just as Paramelle used the most advanced maps of his day to observe geological phenomena and find water, the use of 21st century map technology with its large databases can lead to success in siting water wells.

On the Stockton Plateau, no water wells are located within 200 m of subsidence areas; thus this method did not show that wells near subsidence areas are more productive than wells located farther from subsidence areas. For an alternative approach to applying Paramelle's observational method to the Stockton Plateau, I analyzed spring locations to see if they confirm his observations on suitable locations for finding shallow groundwater. Although the Stockton Plateau has a hydrogeologic history that differs from the limestone and karst regions of France, Paramelle's observations can be used to find shallow water in karst areas of Texas, as shown by the presence of springs. The locations of Stockton Plateau springs support Paramelle's observations that:

- Water is present at shallow depths in vales.
- Water is present in recesses in vales.
- Water is found where a vale joins a stream or river.
- Water is present at the bottom of drop-offs in ravines and vales.
- Water is present at concealed ends of recesses along the foot-of-slope line.
- Water is found at the base of steep slopes.
- Groundwater perches on permeability contrasts.
- Underground water is in constant motion and roughly follows topography.
- A recharge area narrower than 500 m will not produce springs.
- Aquatic plants can be good indicators of groundwater.

Table 4.1. Summary of Paramelle's hydrogeologic observations

**GEOLOGY/LITHOLOGY**

Geology basics: classification of rocks as permeable and impermeable, concept of porosity, understanding of alluvial and colluvial deposits

Water is present in porous, permeable rocks

Water is present in places where permeable surface units overlie a confining bed (clay); repetitions of these layers increase water quantity.

Lithologies **likely** to contain water, if underlain by an impermeable layer.

- Alluvium
- Sands in general, plus greensand (glauconitic sand) and millstone grit (coarse sand)
- Limestones: oolitic, siliceous, shelly, marly
- Travertine (indicates presence of a spring)
- Crystalline rocks (if covered by permeable rocks) may yield small springs.
- Fractured crystalline rocks may yield small springs.
- Stratified rocks yield large but not numerous springs

Lithologies and geologic environments/features **unlikely** to contain water:

- Bare unfractured crystalline rocks
- Most limestones (low porosity, deep water tables, difficult digging)
- Dolomite (impermeable)
- Volcanic rock (low porosity, deep water tables, difficult digging)
- Clays (impermeable)
- Chalk (water drains through)
- Shales and siltstones
- Landslide and slump deposits (disorganized, no thalweg present)
- Rocks with extensive vertical fracturing (allow water to sink to depth)
- Steeply dipping strata, fissured rocks, and large blocks
- Subsidence areas, landslides and slumps

**TOPOGRAPHY/MORPHOLOGY**

**Vales:**

Water is present at shallow depths in vales.

Vale of a certain size will host shallow groundwater (idea of recharge area).

Water is present in reentrants/recesses in vales.

The thalweg is the best guide to water in vales, where depth to thalweg is shallow.

Water is found where vale joins stream or river.

Water is present in depressions at the head of a vale where water infiltrates to form groundwater, but it is not abundant there.

Water is present at the bottom of drop-offs in ravines and vales.

Groundwater is abundant and shallow downstream in a vale, further along the path of the watercourse, because a watercourse grows as it flows.

Groundwater is abundant where a plain extends across a vale, if the vale is full of consolidated sediment and underlain by an impermeable layer. Multiple layers mean more water.

Paramelle proposed a geometric method to find depth to groundwater in alluvium in vales.

**Low/flood Plains:**

Groundwater is present in the most concealed ends of recesses along the foot-of-slope line on low plains, but not along salients or under rubble.

Presence of water is indicated by places water accumulates during rains and presence of phreatophytes.

**Thalweg**:

Groundwater is often present at the intersection of thalweg and stream/river.

Water is present at the base of steep slopes.

Water is not found at the top of hillslopes.

Thalweg is key to water in carbonate systems: aligned dolines mark out the thalweg

Surface water flow during heavy rain indicates thalweg direction.

Groundwater is shallow at the base of a drop-off along the visible thalweg.

**Mountains**:

There are no springs on mountain tops because there is no recharge area.

Mountains receive more precipitation than lowlands; therefore more water is present.

Mountain slopes: inclination of layers is the most important factor in finding water.

**GROUNDWATER**

Groundwater forms where permeable, porous rock overlies an impermeable layer.

The concept is also valid description of discontinuous water in epikarst.

Underground water in constant motion, follows topography

Water cycle: infiltration, evaporation, transpiration.

Water quality: granite provides best water

Groundwater has better quality than surface water

Groundwater protection: Water that has flowed under contaminated areas should be rejected.

Turbidity in groundwater results from flow under agricultural land and vineyards; shallow water are more susceptible.

In limestone, sinkhole alignment indicates an underground watercourse and caverns.

Groundwater is shallow where water flows to surface at the end of its underground pathway, i.e., near a spring.

**Recharge**

Size of recharge area determines amount of water present. Paramelle calculated a 5-hectare watershed with 10-m thick aquifer supplies 4 liters per minute at a spring.

Impermeable rock over a 100-hectare recharge area may produce no groundwater.

On clay hills topped with LS plateau 8-15 m thick, water can be found at the base of the edge of the plateau where springs are often hidden in recesses.

Minimum size of recharge area: hills that are 400-500 meters wide at base are not large enough to produce springs.

On limestone plateaus, discrete recharge into disseminated sinkholes supplies springs to rivers and streams.

Water is found in discharge zones rather than recharge zones.

Groundwater is shallow in the infiltration (recharge) area, but not abundant.

**Water Table.** To determine the depth to groundwater,
Observe water levels in adjacent wells, pits.
Survey the elevation of impermeable layers in hillside and determine depth by measuring slope and distance to a well site on a plain.

**Karst observations**
Swallet-resurgence connection
Dolines on plateaus form springs in rivers, no surface flow
Dolines are aligned over conduits, caverns.

**Plants as surface manifestation of flow**
Phreatophytes, particularly in vales, are good indicators of water.

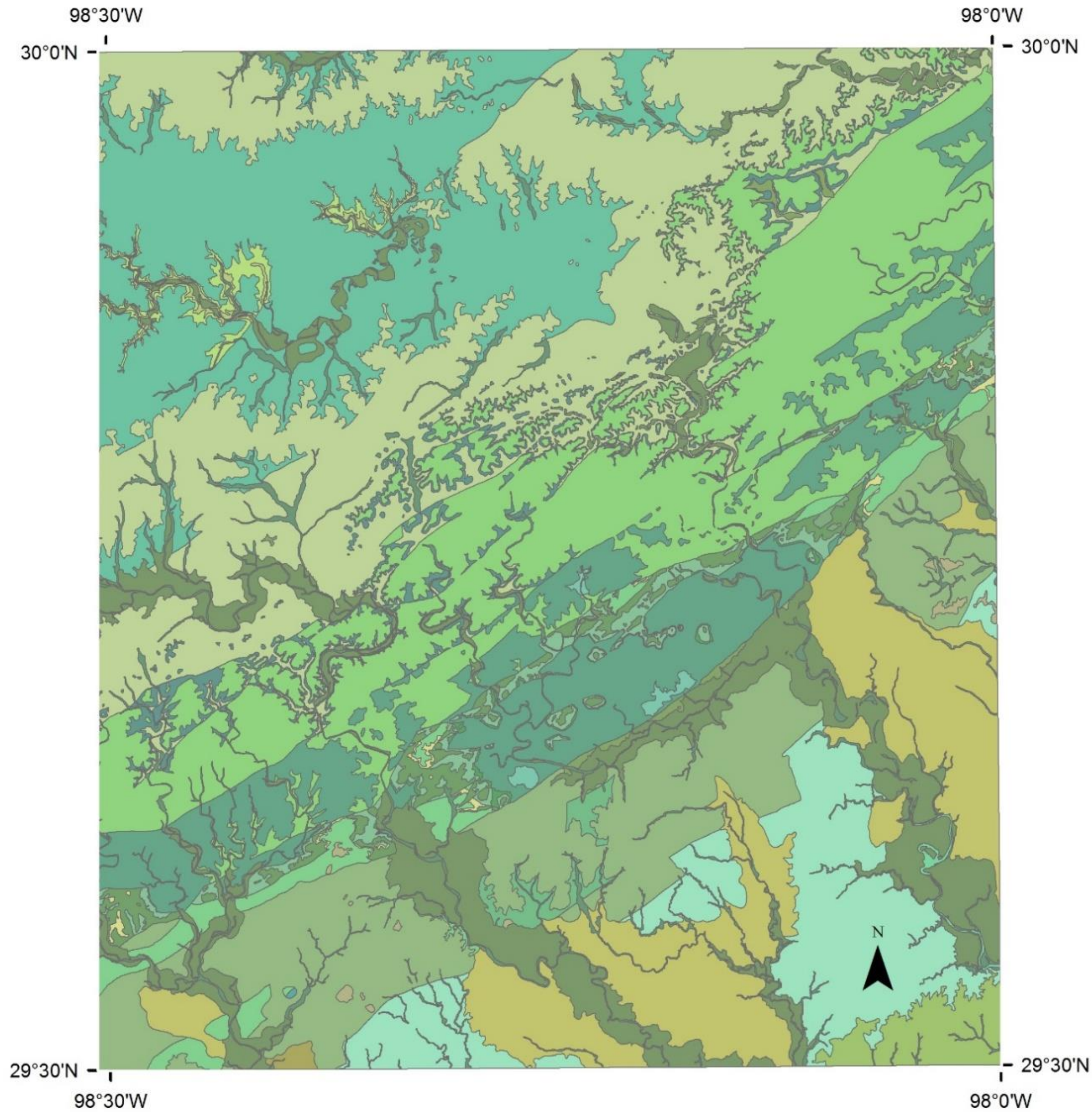
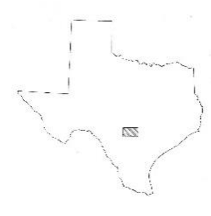



Figure 4.1. Geologic map of the New Braunfels study area.



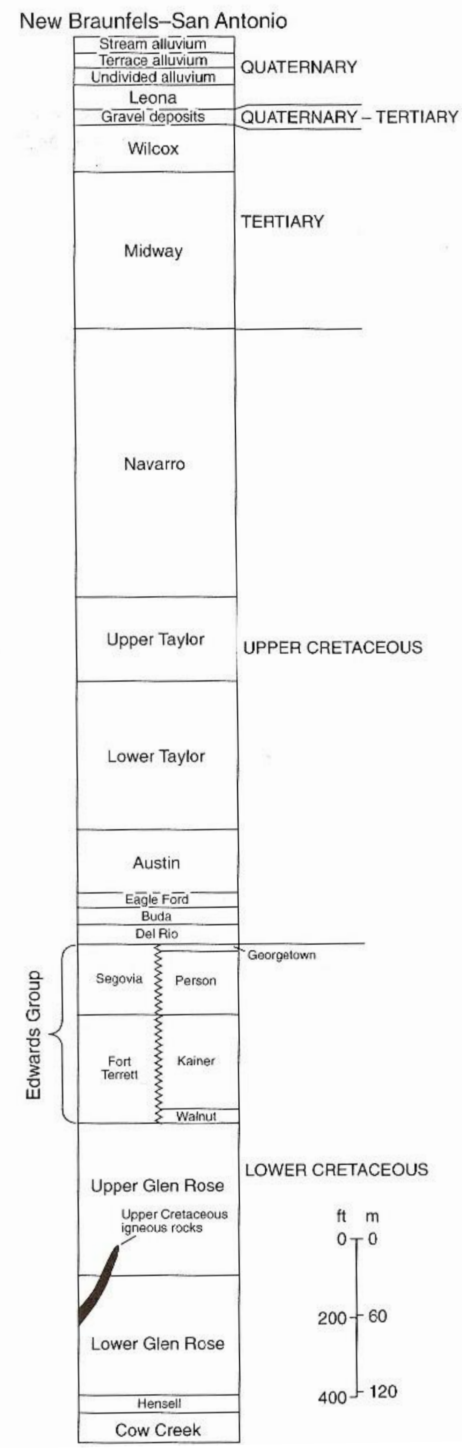



Figure 4.2. Stratigraphic column of units present in the New Braunfels area.

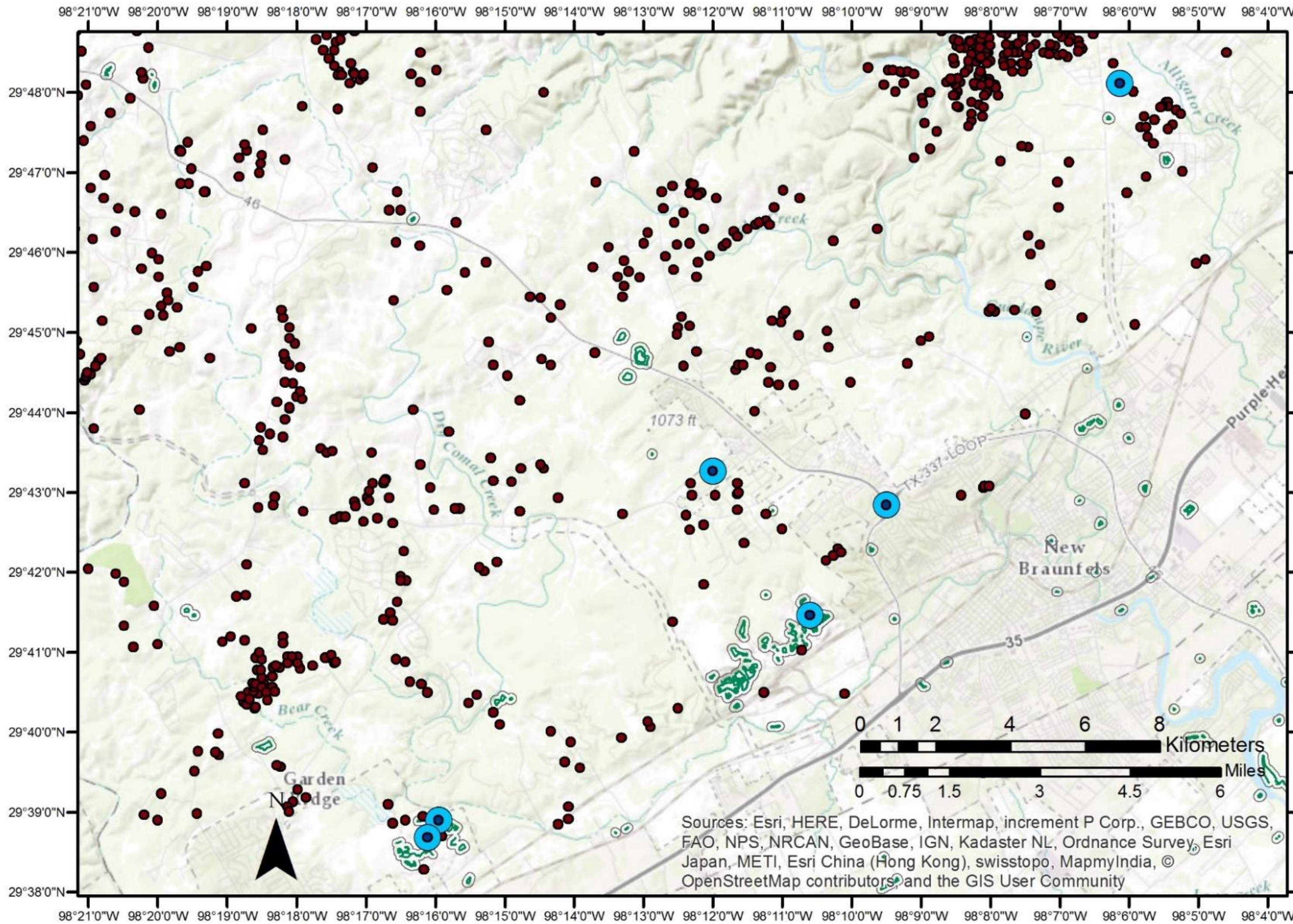



Figure 4.3. Map of Stratmap depressions, 100 m buffer zones, and SDRDB wells.
Depressions are depicted in green, 100 m buffer surrounding Stratmap depressions are outlined in black, SDRDB well locations depicted as red circles. The six SDRDB wells that lie within 100 m of Stratmap depressions are shown as blue circles with dark centers. The large green areas at the bottom of the map are quarries.

Table

SDR_yield_BufferClip

| OBJECTID * | WR_Track_N | Proposed_U | County | Well_Owner | Well_City | Well_Zip_C | Latitude_D | Long_DD | Date_W_Com | BH_Depth__ | Yield2 | WellReport | TestType | Yield | Drawdown |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 15259 | Domestic | Comal | Millinium Homes | Bulverde | 78132 | 29.691111 | -98.176667 | 24-Sep-02 | 480 | 15 | 15259 | Jetted | 15 | 0 |
| 2 | 114263 | Industrial | Bexar | HANSON AGGREGATES | Garden Ridge | 78266 | 29.648334 | -98.265834 | 25-Jan-07 | 1500 | 150 | 114263 | Pump | 150+ | 300 |
| 3 | 169450 | Irrigation | Comal | Newcombe Development | New Braunfels | 78132 | 29.721111 | -98.200001 | 7-Jan-09 | 800 | 30 | 169450 | Pump | 30 | 0 |
| 4 | 184313 | Industrial | Comal | Hanson | Garden Ridge | 0 | 29.644722 | -98.268611 | 16-Sep-04 | 1480 | 50 | 184313 | Estimated | 50 | 0 |
| 5 | 203258 | Test Well | Comal | Avalon Lakes c/o Peter Serebrenik | New Braunfels | 78132 | 29.801945 | -98.102223 | 14-Dec-09 | 600 | 80 | 203258 | Pump | 80 | 0 |
| 6 | 212589 | Irrigation | Comal | MILO BURDETTE | NEW BRAUNFEL | 78132 | 29.714167 | -98.158334 | 16-Mar-10 | 760 | 10 | 212589 | Jetted | 10 | 0 |

Table 4.2. SDRDB wells within 100 meters of Stratmap subsidence features.

Details of the six (6) SDRDB wells shown on Figure 4.3. The wells lie within the 100 m buffer of Stratmap depressions in the study area. Note the yield and drawdown information on these wells.

| FID | WR_Track_N | Proposed_U | County | Well_Owner | Well_City | Well_Zip_C | Latitude_D | Long_DD | Date_W_Com | BH_Depth__ | Yield2 | WellReport | TestType | Yield | Drawdown | Hours |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2239 | 397435 | Industrial | Comal | Capital Aggregate | New Braunfels | 78132 | 29.668889 | -98.215556 | 19-Apr-15 | 1003 | 1000 | 397435 | Pump | 1000 | 150 | 3 |
| 1378 | 170285 | Public Supply | Bexar | Bexar Met. Water District | San Antonio | 78225 | 29.679722 | -98.491111 | 19-Apr-04 | 860 | 997 | 170285 | Pump | 997 | 20 | 36 |
| 1296 | 156122 | Public Supply | Bexar | Water Exploration Co.,LTD. | | 0 | 29.688611 | -98.410556 | 26-Mar-03 | 920 | 800 | 156122 | Unknown | 800 | 0 | 1 |
| 1616 | 217397 | Public Supply | Bexar | Bexar Met Water District | San Antonio | 0 | 29.698334 | -98.4925 | 3-Dec-07 | 700 | 725 | 217397 | Pump | 725 | 16.6 | 43 |
| 1297 | 156125 | Public Supply | Bexar | Water Exploration Co.,LTD. | | 0 | 29.688334 | -98.411112 | 27-Mar-03 | 920 | 700 | 156125 | Unknown | 700 | 0 | 1 |
| 2238 | 397433 | Industrial | Comal | Capital Aggregate | New Braunfels | 78132 | 29.671667 | -98.208334 | 9-Mar-15 | 1302 | 680 | 397433 | Pump | 680 | 300 | 3 |
| 1423 | 177191 | Industrial | Comal | Cemex CT3 | New Braunfels | 78132 | 29.689722 | -98.209723 | 30-Mar-04 | 1340 | 600 | 177191 | Pump | 600 | 475 | 0 |
| 1873 | 292626 | Public Supply | Comal | Green Valley Special Utility District | Garden Ridge | 78266 | 29.629722 | -98.280555 | 13-Jun-12 | 660 | 560 | 292626 | Pump | 560 | 85 | |
| 2234 | 396956 | Public Supply | Comal | Canyon Lake Water Service Company | Canyon Lake | 78133 | 29.845278 | -98.261667 | 4-Jun-15 | 560 | 555 | 396956 | Pump | 555 | 70 | 36 |
| 1615 | 217394 | Public Supply | Bexar | Bexar Met Water District | San Antonio | 0 | 29.698889 | -98.490556 | 3-Dec-07 | 720 | 550 | 217394 | Pump | 550 | 254 | 36 |
| 1938 | 314834 | Stock | Comal | CUSHING LAND AND CATTLE | NEW BRAUNFELS | 78133 | 29.857501 | -98.315001 | 26-Feb-13 | 385 | 550 | 314834 | Pump | 550 | 20 | 36 |
| 857 | 88326 | Public Supply | Bexar | BexarMet Water District | San Antonio | 0 | 29.683055 | -98.490278 | 8-Jun-06 | 860 | 507 | 88326 | Pump | 507 | 178 | 36 |
| 902 | 94566 | Public Supply | Hays | Wimberley Water Supply | Wimberley | 78676 | 29.982778 | -98.122222 | 6-Apr-03 | 615 | 500 | 94566 | Jetted | 500+ | 0 | |
| 1298 | 156157 | Public Supply | Bexar | Water Exploration Co., LTD | | 0 | 29.683611 | -98.411945 | 27-Mar-03 | 1140 | 500 | 156157 | Unknown | 500 | 0 | 1 |
| 1421 | 177153 | Domestic | Hays | Alan & Katy Prigge | Wimberley | 78320 | 29.981111 | -98.119444 | 4-Jul-06 | 540 | 500 | 177153 | Jetted | 500+ | 0 | |
| 1607 | 215209 | Public Supply | Comal | Holcim LP | New Braunfels | 78132 | 29.667778 | -98.215001 | 14-Jun-07 | 1300 | 500 | 215209 | Estimated | 500 | 0 | 1 |
| 2039 | 353695 | Public Supply | Comal | New Braunfels Utilities | New Braunfels | 78132 | 29.705001 | -98.17 | 14-Jan-14 | 520 | 500 | 353695 | Estimated | 500+ | 0 | |
| 2096 | 367180 | Domestic | Comal | New Braunfels Utilities | New Braunfels | 78132 | 29.704167 | -98.169167 | 21-May-14 | 620 | 500 | 367180 | Estimated | 500+ | 0 | |
| 2143 | 378160 | Public Supply | Bexar | SAN ANTONIO WATER SYSTEM | SAN ANTONIO | 0 | 29.706667 | -98.455834 | 28-Jan-01 | 790 | 500 | 378160 | Pump | 500 | 111 | 72 |
| 2345 | 415822 | Public Supply | Comal | CITY OF GARDEN RIDGE | GARDEN RIDGE | 78266 | 29.650206 | -98.301756 | 7-Jan-16 | 701 | 450 | 415822 | Pump | 450 | 0 | 36 |
| 1266 | 149068 | Public Supply | Comal | KT Development Well #2 | Garden Ridge | 0 | 29.699167 | -98.275 | 11-Apr-04 | 1350 | 415 | 149068 | Pump | 415 | 19 | 36 |
| 1304 | 156549 | Public Supply | Comal | KT Development Well # 2 | Garden Ridge | 0 | 29.698334 | -98.275 | 11-Apr-04 | 1350 | 415 | 156549 | Pump | 415 | 19 | 36 |
| 1908 | 308119 | Test Well | Hays | Greg LaMantia | Wimberley | 78676 | 29.970278 | -98.034445 | 12-Nov-12 | 850 | 400 | 308119 | Pump | 400 | 30 | 24 |
| 1951 | 317171 | Irrigation | Hays | GREG LAMANTIA | WIMBERLY | 78676 | 29.970833 | -98.034445 | 24-Feb-13 | 800 | 400 | 317171 | Pump | 400 | 30 | 24 |
| 2235 | 397020 | Public Supply | Comal | Canyon Lake Water Service Company | Canyon Lake | 78133 | 29.845556 | -98.260556 | 21-May-15 | 560 | 395 | 397020 | Pump | 395 | 314 | 36 |
| 202 | 16713 | Industrial | Bexar | G. G. Gail | San Antonio | 0 | 29.713334 | -98.479722 | 2-Jan-03 | 650 | 366 | 16713 | Pump | 366 | 161 | 6 |
| 1303 | 156493 | Public Supply | Comal | K T Development Well #1 | Garden Ridge | 78226 | 29.698334 | -98.273611 | 3-Mar-04 | 1260 | 348 | 156493 | Pump | 348 | 106 | 36 |
| 1407 | 176593 | Public Supply | Comal | CANYON LKAE WATER SUPPLY | NEW BRAUNFELS | 78132 | 29.792222 | -98.254445 | 28-Sep-07 | 1080 | 300 | 176593 | Estimated | 300 | 0 | 2 |
| 1526 | 193314 | Domestic | Comal | Haroldson, Don | Bulverde | 78163 | 29.8275 | -98.236667 | 21-May-08 | 680 | 300 | 193314 | Estimated | 300 | 0 | 2 |
| 2061 | 359175 | Public Supply | Comal | New Braunfels Utilities | New Braunfels | 78132 | 29.703612 | -98.171111 | 29-Mar-14 | 520 | 300 | 359175 | Estimated | 300+ | 0 | |
| 1212 | 138752 | Industrial | Comal | Brian Forrester | New Braunfels | 0 | 29.810556 | -98.045834 | 21-Mar-05 | 1280 | 275 | 138752 | Pump | 275 | 365 | 24 |
| 2354 | 420204 | Irrigation | Comal | Mackie McCrea | Canyon Lake | 78133 | 29.852092 | -98.299081 | 25-Jan-16 | 440 | 250 | 420204 | Jetted | 250+ | 0 | |
| 1614 | 217390 | Public Supply | Comal | Bluegreen Southwest | Bulverde | 0 | 29.773055 | -98.261667 | 27-Apr-07 | 1000 | 242 | 217390 | Pump | 242 | 418 | 72 |
| 1206 | 137058 | Domestic | Comal | Cypress Falls Farms | Canyon Lake | 78133 | 29.860278 | -98.182778 | 11-May-06 | 185 | 205 | 137058 | Jetted | 205+ | 0 | |
| 281 | 24979 | Domestic | Hays | Bobby McNeil Custom Homes | San Marcos | 0 | 29.913056 | -98.069444 | 7-Jul-03 | 930 | 200 | 24979 | Estimated | 200+ | 0 | |
| 438 | 40980 | Domestic | Hays | Angel Pacheco | San Marcos | 0 | 29.9225 | -98.070278 | 11-Aug-03 | 780 | 200 | 40980 | Estimated | 200 | 0 | |
| 642 | 63438 | Domestic | Hays | ROGER BALLENTINE | WIMBERLEY | 78676 | 29.971944 | -98.121111 | 12-Jun-05 | 530 | 200 | 63438 | Jetted | 200+ | 0 | |
| 858 | 89091 | Domestic | Hays | Stephanie Rothstein | Wimberley | 78676 | 29.998611 | -98.115001 | 11-Jun-06 | 515 | 200 | 89091 | Jetted | 200 | 0 | |
| 1057 | 114774 | Industrial | Bexar | Hanson Aggregates | Garden Ridge | 78266 | 29.638056 | -98.269444 | 31-Mar-07 | 1195 | 200 | 114774 | Pump | 200+ | 0 | |
| 1179 | 132709 | Test Well | Comal | Southerland Communities | New Braunfels | 78132 | 29.735834 | -98.246389 | 25-Dec-07 | 1240 | 200 | 132709 | Estimated | 200+ | 0 | |
| 1205 | 136904 | Industrial | Bexar | Lattimore Ready Mix | San Antonio | 78260 | 29.732778 | -98.4975 | 26-Dec-07 | 453 | 200 | 136904 | Jetted | 200+ | 0 | |
| 1767 | 265702 | Irrigation | Hays | J.D. FIELDS | WIMBERLEY | 78676 | 29.988056 | -98.108889 | 20-Jun-11 | 530 | 200 | 265702 | Jetted | 200 | 0 | |
| 1903 | 306173 | Public Supply | Comal | DANK PROPERTIES & INVESTMENTS | New Braunfels | 78132 | 29.838056 | -98.073055 | 23-Sep-12 | 1240 | 200 | 306173 | Estimated | 200+ | 0 | |
| 2069 | 362870 | Domestic | Hays | JOHN MATHIS & PETRA GEORGE | SAN MARCOS | 78666 | 29.940278 | -98.071389 | 19-Feb-14 | 600 | 200 | 362870 | Jetted | 200+ | 0 | |
| 2075 | 363720 | Domestic | Hays | GRADY BURNETTE BUILDERS/ENDRES JOB | SAN MARCOS | 78666 | 29.953334 | -98.105278 | 24-Feb-14 | 830 | 200 | 363720 | Jetted | 200+ | 0 | |
| 2142 | 378158 | Public Supply | Bexar | SAN ANTONIO WATER SYSTEM | SAN ANTONIO | 0 | 29.716389 | -98.455278 | 27-Nov-00 | 907 | 200 | 378158 | Pump | 200 | 100 | 720 |
| 54 | 4267 | Domestic | Bexar | Bill Krog | San Antonio | 0 | 29.716112 | -98.404445 | 13-Jan-02 | 500 | 150 | 4267 | Jetted | 150 | 0 | 1 |
| 734 | 74631 | Domestic | Hays | Michael Echart | San Marcos | 78666 | 29.995556 | -98.004723 | 3-May-04 | 550 | 150 | 74631 | Jetted | 150+ | 0 | |
| 1054 | 114263 | Industrial | Bexar | HANSON AGGREGATES | Garden Ridge | 78266 | 29.648334 | -98.265834 | 25-Jan-07 | 1500 | 150 | 114263 | Pump | 150+ | 300 | |
| 1401 | 176232 | Domestic | Comal | Jason and Allison Nitsch | New Braunfels | 78132 | 29.766389 | -98.123611 | 22-Apr-09 | 320 | 150 | 176232 | Estimated | 150 | 0 | |
| 1885 | 296734 | Domestic | Hays | STROBEL CONSTRUCTION | WIMBERLEY | 78676 | 29.964167 | -98.064445 | 1-Aug-12 | 890 | 150 | 296734 | Jetted | 150 | 0 | |
| 2355 | 420206 | Irrigation | Comal | Mackie McCrea | Canyon Lake | 78131 | 29.825106 | -98.301733 | 28-Jan-16 | 620 | 150 | 420206 | Jetted | 150 | 0 | |
| 2381 | 424063 | Domestic | Hays | HGGS Homes LLC | Wimberley | 78676 | 29.942083 | -98.083167 | 7-Jun-16 | 850 | 150 | 424063 | Other | 150 | 0 | |
| 889 | 92548 | Industrial | Comal | Chemical Lime Ltd. | New Braunfels | 78132 | 29.683889 | -98.178611 | 10-Aug-06 | 1060 | 134 | 92548 | Pump | 134 | 290 | 24 |
| 275 | 24804 | Domestic | Comal | Ager Barrett | Bulverde | 78163 | 29.751112 | -98.360834 | 10-Aug-03 | 686 | 120 | 24804 | Jetted | 120+ | 0 | |
| 1748 | 258866 | Domestic | Comal | LEE WHITE | CANYON LAKE | 78133 | 29.860278 | -98.191667 | 29-Jun-11 | 140 | 120 | 258866 | Estimated | 120 | 0 | |
| 44 | 3647 | Domestic | Bexar | Angela Weissgarber | San ANtonio | 78261 | 29.706667 | -98.407501 | 14-Nov-01 | 520 | 100 | 3647 | Jetted | 100 | 0 | 2 |
| 50 | 4023 | Domestic | Comal | Bill Elmer | San Antonio | 78266 | 29.715834 | -98.305278 | 29-Nov-01 | 660 | 100 | 4023 | Jetted | 100 | 0 | 1 |
| 110 | 8368 | Domestic | Comal | Lea wendtlandt | New Braunfels | 78132 | 29.676667 | -98.27 | 13-Jun-02 | 520 | 100 | 8368 | Jetted | 100 | 0 | 1 |

Table 4.3. High yield SDRDB wells ranked according to yield.
None of these wells lie within 100m of a Stratmap subsidence feature.

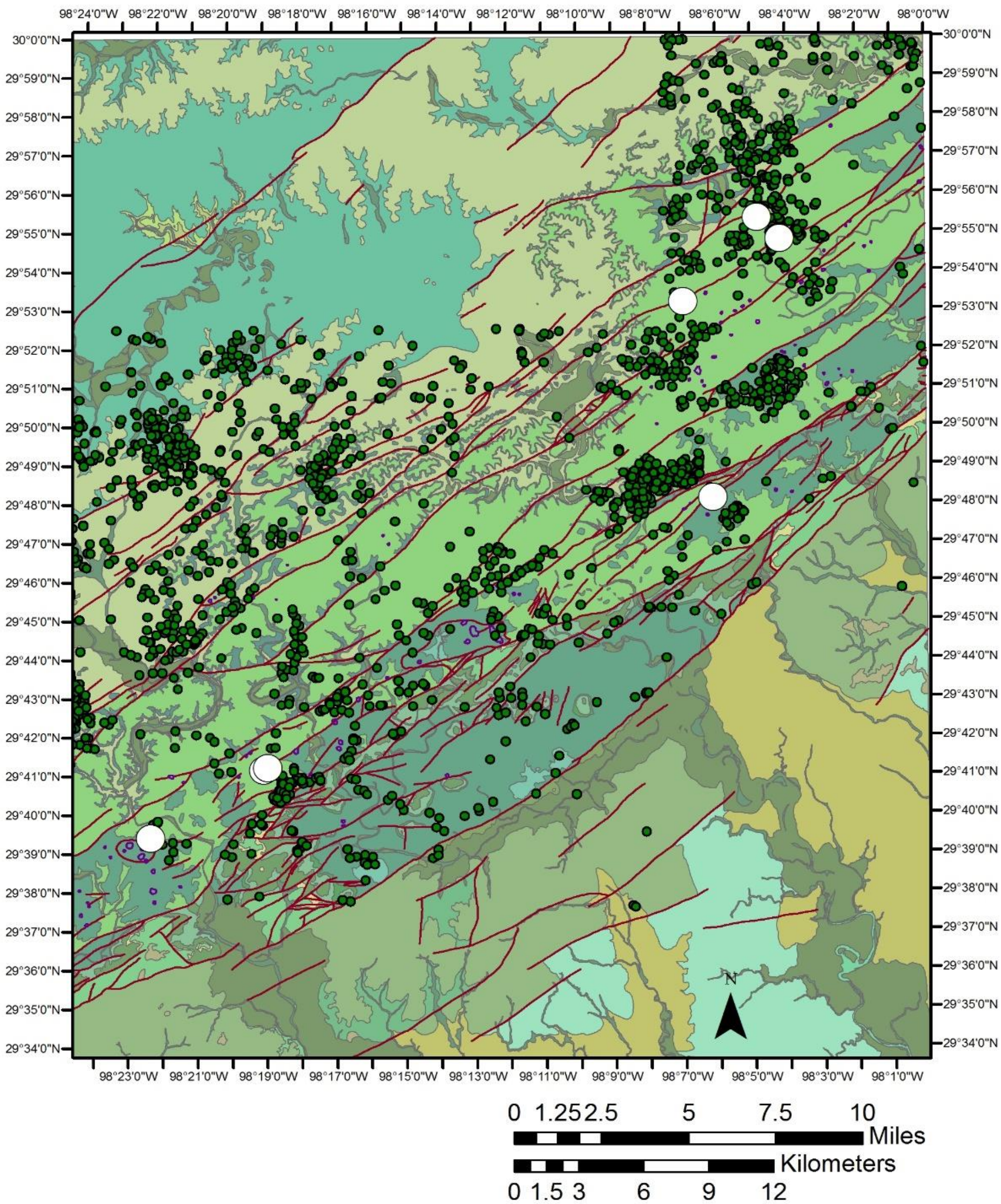



Figure 4.4. Map showing SDRDB wells whose 100 m buffer zones intersect karst features. Buffer zones surrounding seven wells intersect karst depressions depicted on BEG map. Note two wells superimposed at the lower center of the map.

Table

Wells100mBuffer

| FID | WR_Track_N | Proposed_U | County | Well_Owner | Well_City | Well_Zip_C | Latitude_D | Long_DD | Date_W_Com | BH_Depth__ | Yield2 | WellReport | TestType | Yield | Drawdown | Hours |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 24979 | Domestic | Hays | Bobby McNeil Custom Homes | San Marcos | 0 | 29.913056 | -98.069444 | 7-Jul-03 | 930 | 200 | 24979 | Estimated | 200+ | 0 | |
| 1 | 32303 | Domestic | Hays | JARED HERZOG | KYLE | 78640 | 29.922222 | -98.080278 | 29-Dec-03 | 938 | 50 | 32303 | Jetted | 50 | 0 | |
| 2 | 43255 | Domestic | Bexar | Don & Dina Fry | San antonio | 78266 | 29.656667 | -98.371944 | 15-Aug-04 | 600 | 15 | 43255 | Jetted | 15 | 0 | 1 |
| 3 | 158997 | Domestic | Comal | David Brown | New Braunfels | 0 | 29.886111 | -98.115834 | 23-Sep-08 | 720 | 0 | 158997 | Jetted | | 0 | |
| 4 | 203258 | Test Well | Comal | Avalon Lakes c/o Peter Serebrenik | New Braunfels | 78132 | 29.801945 | -98.102223 | 14-Dec-09 | 600 | 80 | 203258 | Pump | 80 | 0 | |
| 5 | 404380 | Domestic | Comal | Wuest Legacy Partners | San Antonio | 78266 | 29.685556 | -98.317778 | 4-May-15 | 700 | 5 | 404380 | Estimated | 4-6 | 0 | |
| 6 | 404381 | Domestic | Comal | Wuest Legacy Partners | San Antonio | 78266 | 29.686667 | -98.315834 | 7-May-15 | 1240 | 20 | 404381 | Estimated | 20+ | 0 | |

Table 4.4. Details of SDRDB wells whose 100 m buffer zones intersect BEG karst depressions, as shown in Figure 4.4.

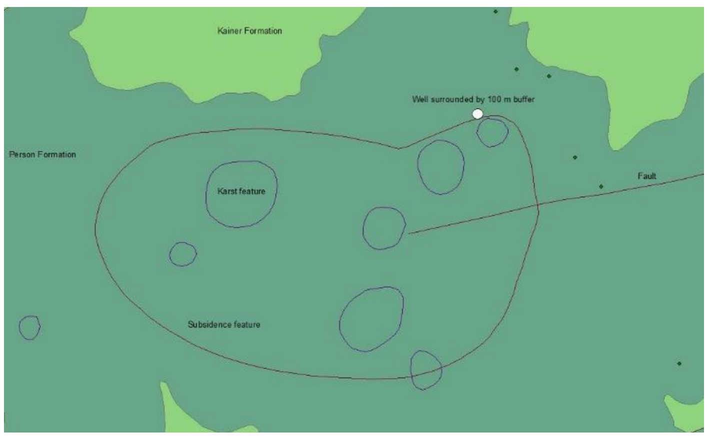



Figure 4.5. Enlargement of SW corner of Figure 4.4. Intersection of the 100 m buffer zone of an SDRDB water well (white dot) with a subsidence feature (red circle). Seven karst features (blue outlines) lie within a larger subsidence feature (outlined in red) that is also the location of the end of a fault (red line). Additional karst features can be seen to the south and west of the subsidence area; additional faults are also present nearby. Table 4 shows that the yield on the highlighted well is 15 gpm (82 $m^3$day).

Figure 4.6. Photograph of karst, subsidence, and faulted area shown in Figure 4.5. Looking west from Hanging Oak Road, Bexar County.

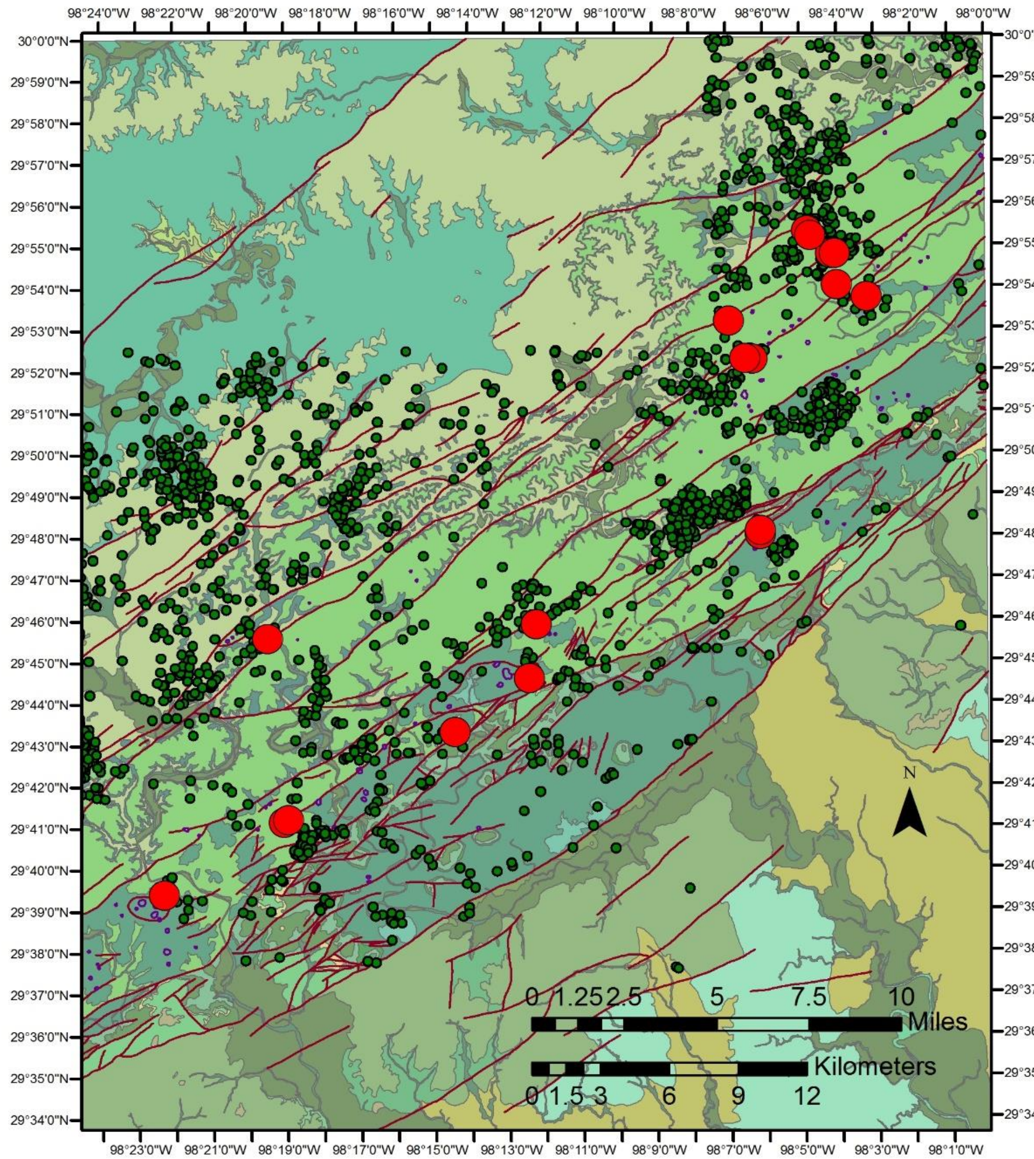



Figure 4.7. Map showing SDRDB wells whose 200 m buffer zones intersect karst features. Red dots indicate the location of the 18 SDRDB wells.

Table

Wells200mBuffer

| FID | WR_Track_N | Proposed_U | County | Well_Owner | Well_City | Well_Zip_C | Latitude_D | Long_DD | Date_W_Com | BH_Depth__ | Yield2 | WellReport | TestType | Yield | Drawdown | Hours |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 24979 | Domestic | Hays | Bobby McNeil Custom Homes | San Marcos | 0 | 29.913056 | -98.069444 | 7-Jul-03 | 930 | 200 | 24979 | Estimated | 200+ | 0 | |
| 1 | 32303 | Domestic | Hays | JARED HERZOG | KYLE | 78640 | 29.922222 | -98.080278 | 29-Dec-03 | 938 | 50 | 32303 | Jetted | 50 | 0 | |
| 2 | 43255 | Domestic | Bexar | Don & Dina Fry | San antonio | 78266 | 29.656667 | -98.371944 | 15-Aug-04 | 600 | 15 | 43255 | Jetted | 15 | 0 | 1 |
| 3 | 57984 | Domestic | Comal | Alan Svoboda | Canyon Lake | 78132 | 29.870833 | -98.105278 | 27-Feb-05 | 700 | 10 | 57984 | Estimated | 10 | 0 | |
| 4 | 60090 | Domestic | Comal | Dawn Triche | New Braunfels | 78133 | 29.800278 | -98.102223 | 27-Nov-04 | 1100 | 20 | 60090 | Estimated | 20++ | 0 | |
| 5 | 91867 | Domestic | Comal | Steve Southwell | Bulverde | 78163 | 29.759445 | -98.324722 | 25-Jul-06 | 840 | 8 | 91867 | Estimated | 8 | 40 | 1 |
| 6 | 123370 | Domestic | Hays | Jared Keith Herzog and Julie | San Marcos | 78666 | 29.913056 | -98.067778 | 27-Aug-07 | 980 | 15 | 123370 | Estimated | 15 | 0 | |
| 7 | 144125 | Domestic | Hays | Cheryl Doane | San Marcos | 76666 | 29.895556 | -98.053612 | 1-Jun-08 | 840 | 30 | 144125 | Estimated | 30 | 0 | |
| 8 | 158997 | Domestic | Comal | David Brown | New Braunfels | 0 | 29.886111 | -98.115834 | 23-Sep-08 | 720 | 0 | 158997 | Jetted | | 0 | |
| 9 | 203258 | Test Well | Comal | Avalon Lakes c/o Peter Serebrenik | New Braunfels | 78132 | 29.801945 | -98.102223 | 14-Dec-09 | 600 | 80 | 203258 | Pump | 80 | 0 | |
| 10 | 220066 | Domestic | Comal | Magdelena Murrillo & Katherine McGarity | New Braunfels | 78132 | 29.764723 | -98.203612 | 20-May-10 | 440 | 9 | 220066 | Estimated | 8-10 | 0 | |
| 11 | 271692 | Domestic | Hays | JASON FISCHER/ENDRES JOB | SAN MARCOS | 78666 | 29.900556 | -98.066944 | 19-Oct-11 | 930 | 100 | 271692 | Jetted | 100+ | 0 | |
| 12 | 292873 | Domestic | Comal | NICK SMITH | New Braunfels | 78132 | 29.721667 | -98.240556 | 27-May-12 | 600 | 12 | 292873 | Pump | 12 | 0 | |
| 13 | 296130 | Domestic | Comal | DAVID & KATHRYN BRYANT | NEW BRAUNFEL | 78133 | 29.871111 | -98.108612 | 11-Aug-12 | 580 | 5 | 296130 | Estimated | 4-6 | 0 | |
| 14 | 311031 | Domestic | Hays | Jimmy Lummas | San Marcos | 78666 | 29.920278 | -98.078889 | 28-Jan-13 | 600 | 5 | 311031 | Estimated | 5 | 0 | |
| 15 | 404380 | Domestic | Comal | Wuest Legacy Partners | San Antonio | 78266 | 29.685556 | -98.317778 | 4-May-15 | 700 | 5 | 404380 | Estimated | 4-6 | 0 | |
| 16 | 404381 | Domestic | Comal | Wuest Legacy Partners | San Antonio | 78266 | 29.686667 | -98.315834 | 7-May-15 | 1240 | 20 | 404381 | Estimated | 20+ | 0 | |
| 17 | 400103 | Domestic | Comal | David Wiedenfeld | New Braunfels | 78132 | 29.743056 | -98.206944 | 15-Jul-15 | 490 | 12 | 400103 | Estimated | 10-15 | 0 | |

Table 4.5. Details of wells whose 200 m buffer zones intersect BEG subsidence areas, as shown in Figure 4.7.

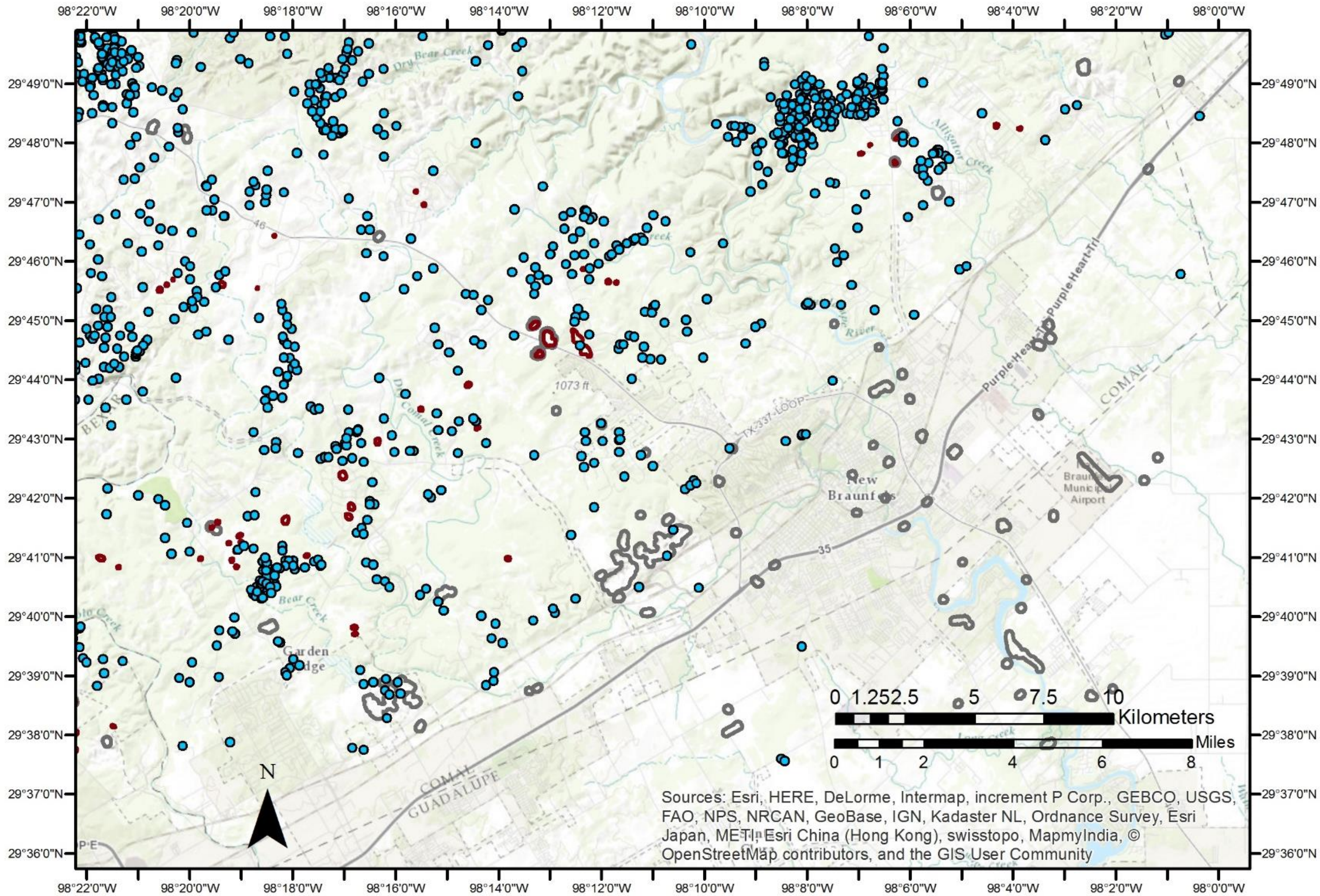



Figure 4.8. Comparison map showing Stratmap depressions, BEG karst features, and SDRDB wells.
Stratmap depressions are shown as gray outlines, BEG karst features as red outlines, and SDRDB wells as blue dots.

Table 4.6. Summary of data.

| Category | Depth Range in ft. | Depth Range in m | No. of Wells | Yield gpm | Yield $m^3/d$ | Mean Yield gpm | Mean Yield $m^3/d$ |
|---|---|---|---|---|---|---|---|
| Stratmap 100 m Buffer | 400-1500 | 122-457 | 6 | 10-150 | 55-818 | 56 | 305 |
| BEG 100 m Buffer | 600-1240 | 183-378 | 7 | 0 - 200 | 0-1090 | 53 | 289 |
| BEG 200 m Buffer | 440-1240 | 134-378 | 18 | 0 - 200 | 0-1090 | 33 | 179 |
| Outside Buffer Areas | 0-1540 | 0-469 m | 2317 | 0 - 1000 | 0-5451 | 23 | 123 |

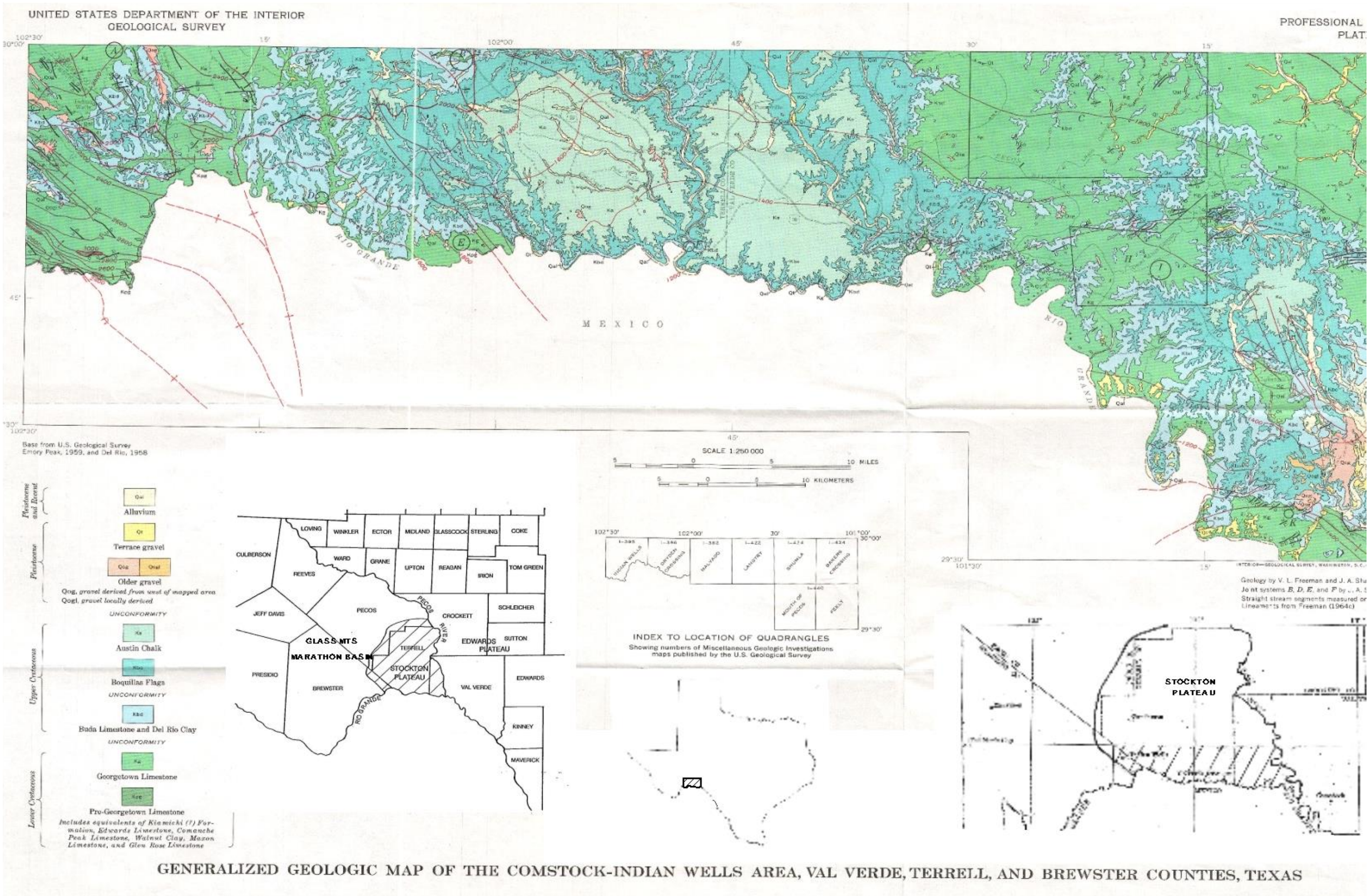



Figure 4.9. Geologic map of the southern Stockton Plateau.
From Freeman, 1968.

| System | Series or Group | Stockton Plateau stratigraphic units | | |
|---|---|---|---|---|
| | | Southwest | Central | Southeast |
| Quaternary | Pleistocene | Gravels, undifferentiated | | |
| Tertiary | Pliocene | Gravels, undifferentiated | | |
| Cretaceous | | Austin Chalk | | |
| | | Boquillas Formation | | |
| | Washita | Buda Limestone | | |
| | | Del Rio Clay | | Del Rio Clay |
| | | Georgetown | | |
| | Fredericksburg/ Edwards | Santa Elena LS | Segovia Member | Devils River LS |
| | | Sue Peaks Fm. | | Devils River LS |
| | | Del Carmen LS | Fort Terrett Member | Devils River LS |
| | Trinity | Maxon Sand | | |
| | | Glen Rose Formation | | |
| | | Basal Sand | | |

Figure 4.10. Geologic Units of the Stockton Plateau.
Modified from Veni (1991), Freeman (1968), and Bureau of Economic Geology Geologic Atlas of Texas Del Rio Sheet, 1977.

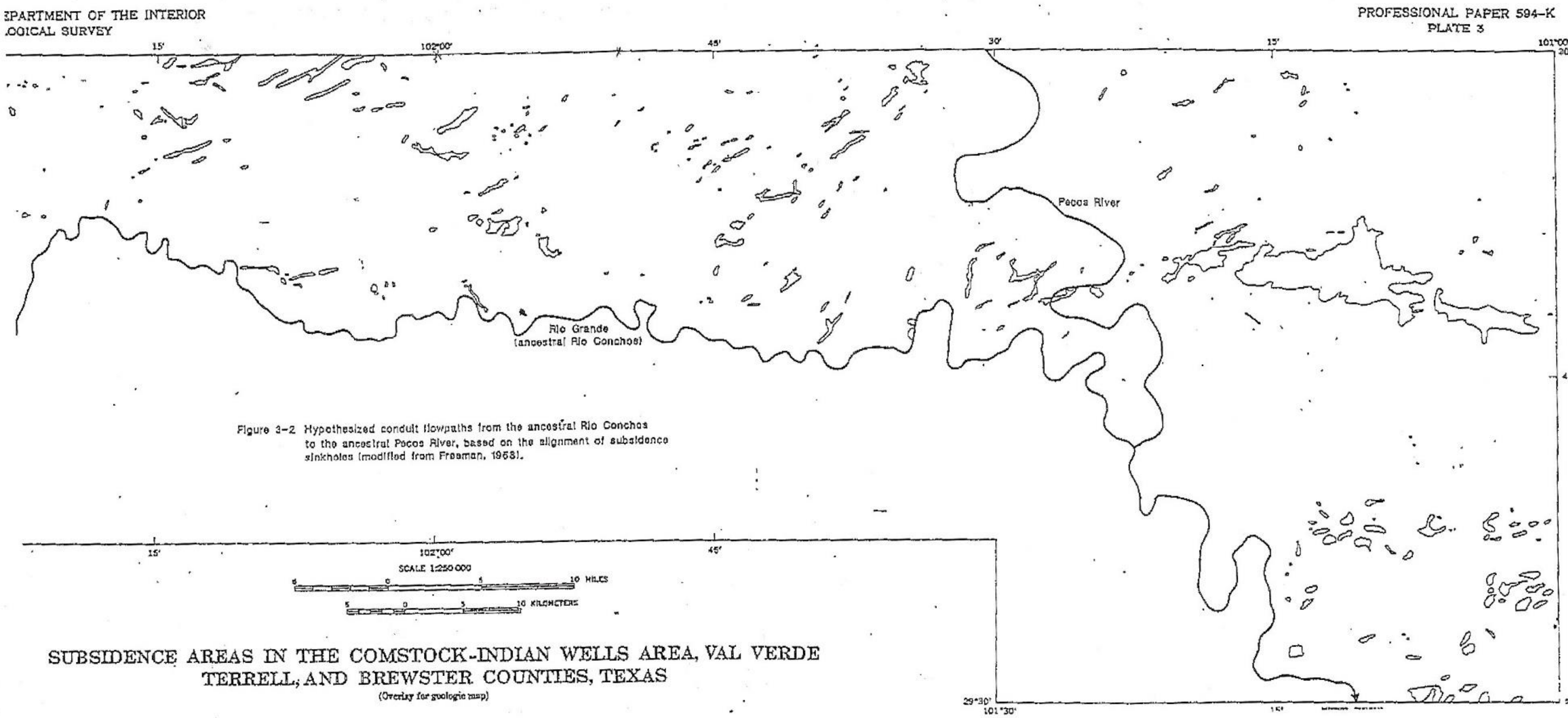



Figure 4.11. Subsidence areas in the Comstock-Indian Wells Area Modified from Veni (1991) and Freeman (1968).

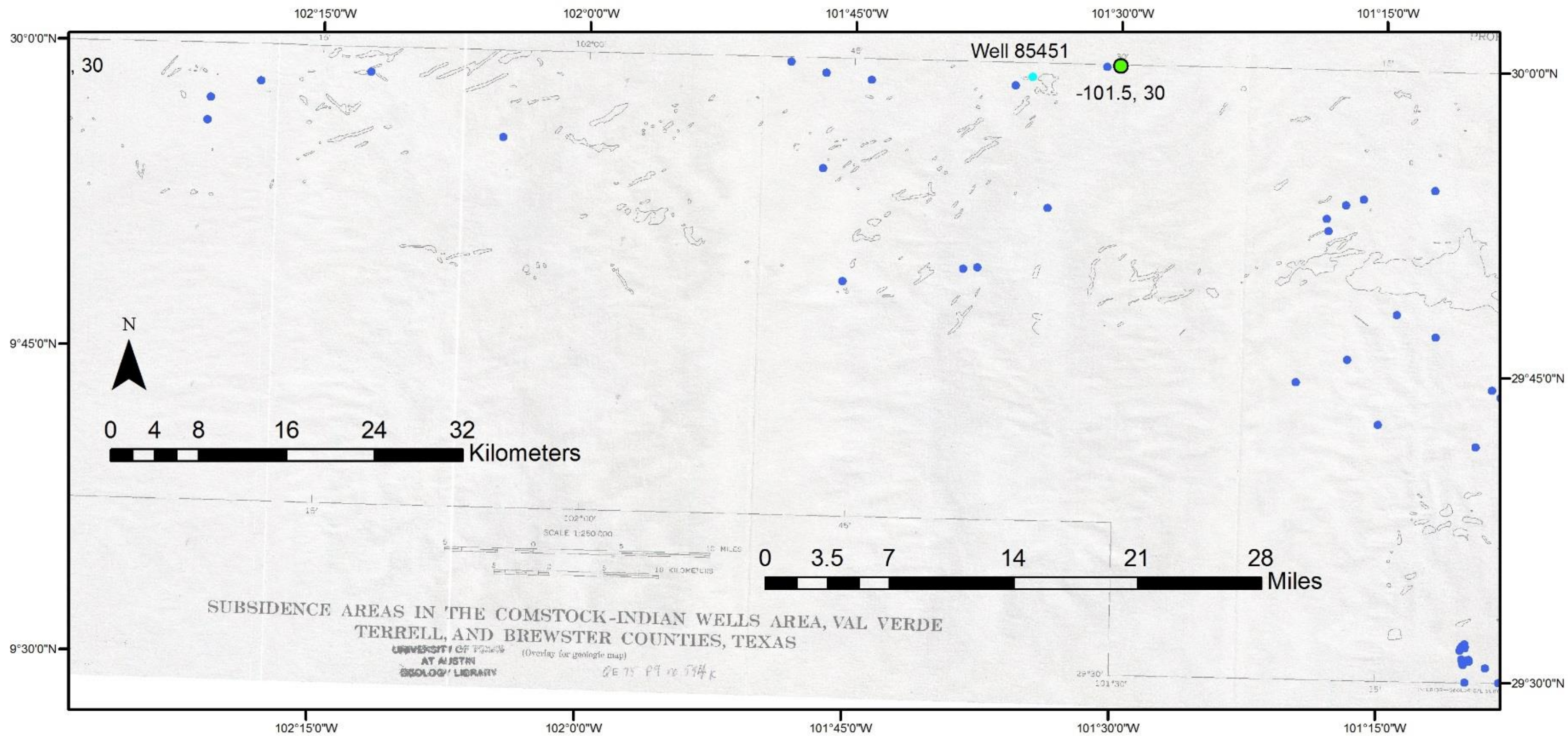



Figure 4.12. Stockton Plateau subsidence areas and SDRDB wells.
Wells are surrounded by a 200m buffer colored blue. No 200 m buffer zones around SDRDB wells intersect subsidence areas.
Location of Well 85451 is at top of map. Modified from Freeman (1968).

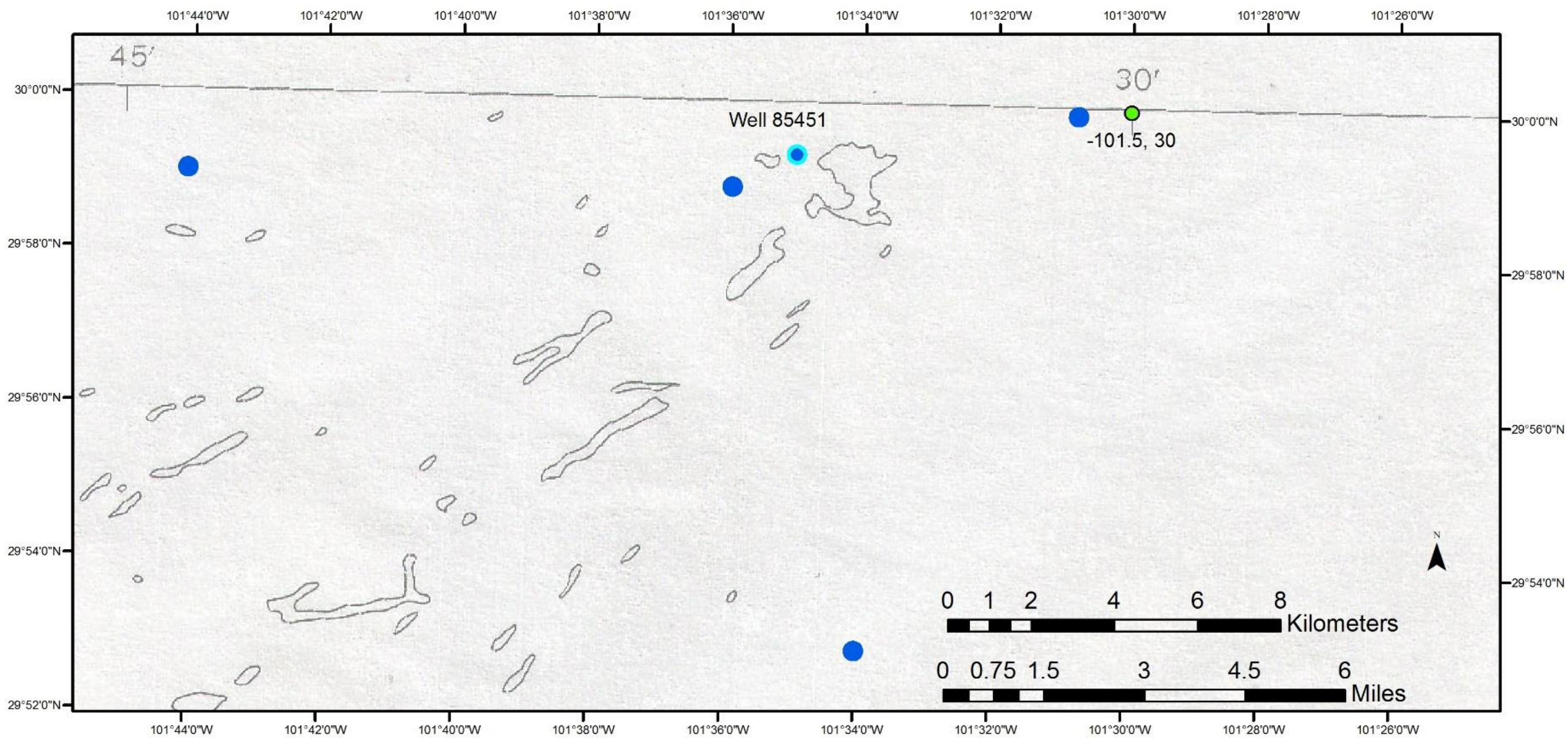



Figure 4.13. Enlargement of Figure 4.12.
Well 85451 is located between two subsidence areas. Modified from Freeman (1968).

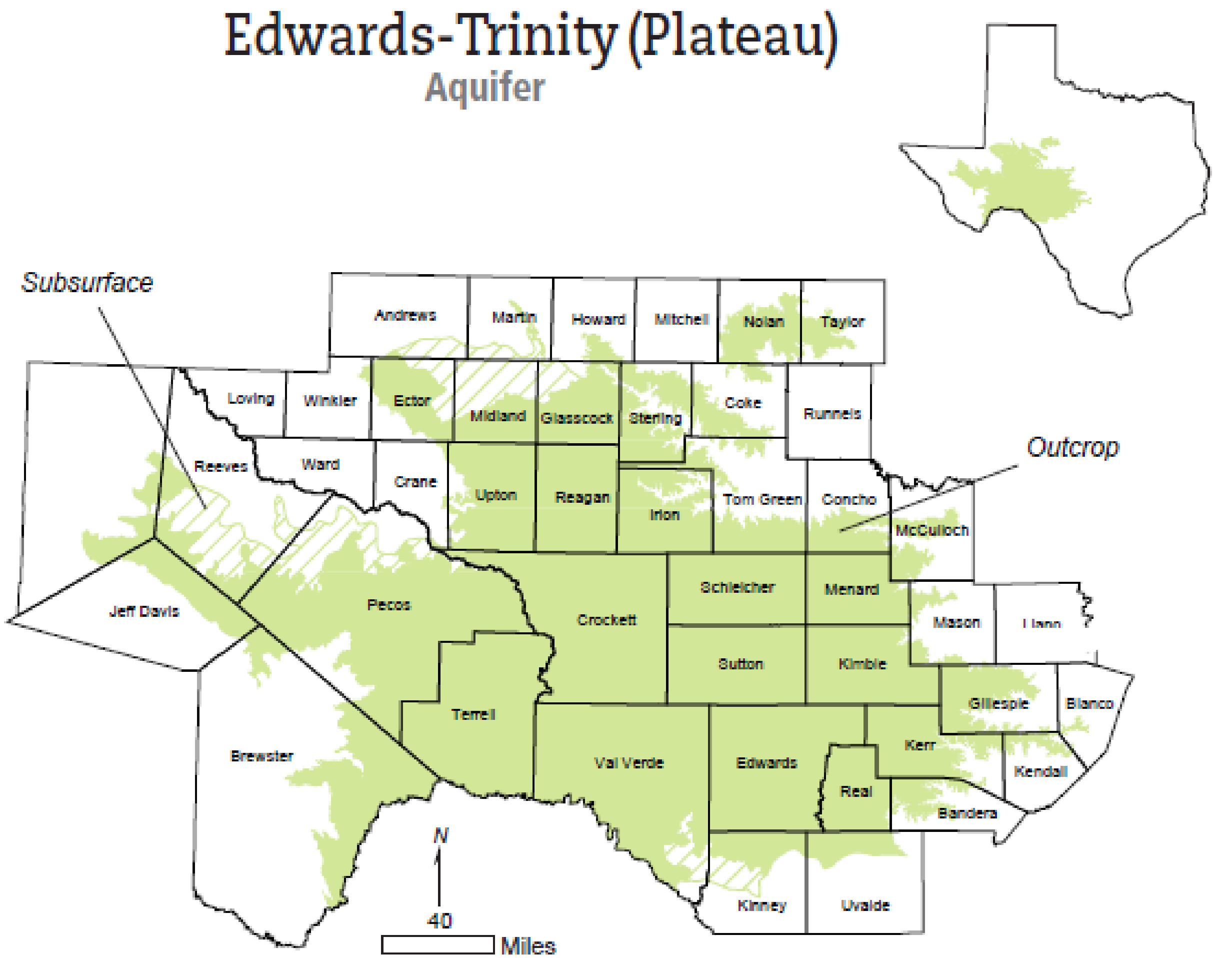



Figure 4.14. Surface outcrop of Edwards Trinity Plateau Aquifer.
Source: Texas Water Operators (http://texaswateroperators.com.)

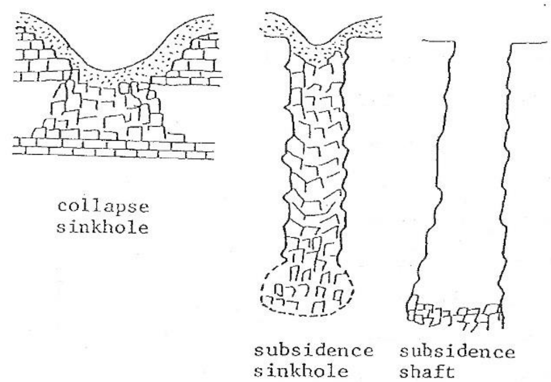



Figure 4.15. Three types of collapse sinkholes.
Source: Veni (1991) and White (1988).


Figure 4.16. Rio Conchos, tributary of the Rio Grande.
The Rio Conchos flows into the Rio Grande west of Big Bend, outside the study area. Source: Wong et al., 2007.

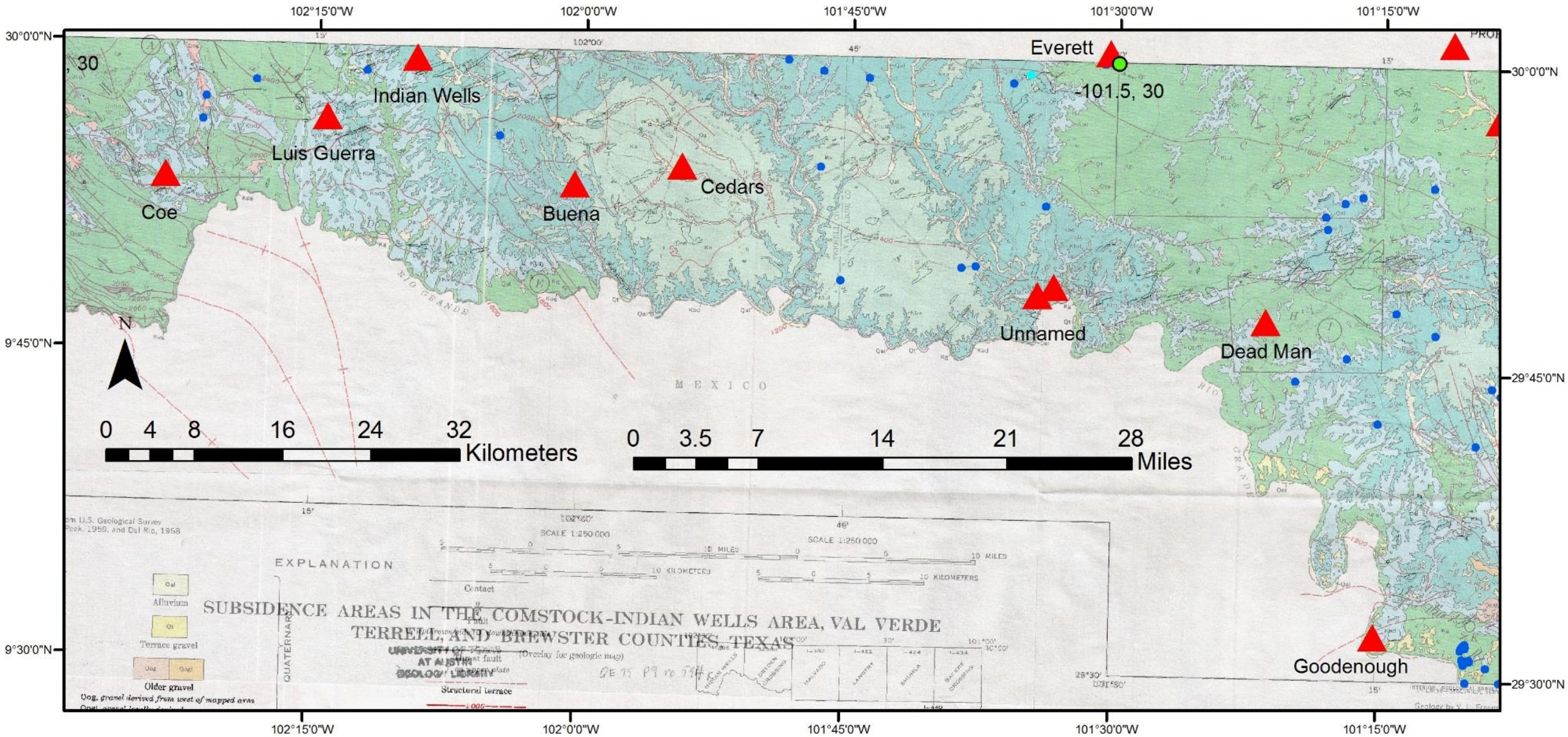



Figure 4.17. Stockton Plateau study area geology, subsidence areas, SDRDB wells and TPWD springs. Subsidence areas are indicated as black outlines, SDRDB wells shown in blue (surrounded by 200 m buffer zone) and TPWD springs indicated as red triangles. Goodenough Springs is shown on the map because of their historical significance; prior to being covered by Amistad Reservoir, they were the third largest springs in Texas. It is not discussed in the text because it is east of the Pecos River, outside the study area. Modified from Freeman (1968).

Table 4.7. Stockton Plateau study area springs.

Source: Texas Parks and Wildlife Dept. (TPWD). County: B = Brewster, T = Terrell, VV = Val Verde. Comments from Brune (B).

| Spring Name | Latitude | Longitude | County | Comments |
|---|---|---|---|---|
| Coe Springs | 29.891863 | -102.39209 | B | Located on San Francisco Creek, now dry. Depicted on 1898 US Engineer Office map. Springs maintained a water hole in early times. In 1976, wet weather seepage supported walnut trees, black brush, creosote bush and prickly pears. Deer, javelina, and rabbits present in 1976. Indian pictographs nearby. (B) |
| Luis Guerra, also known as Chupadera | 29.941863 | -102.242085 | T | 18 km SW of Dryden at the head of Red House Canyon. Used to flow 1.6 km down canyon. Seeps were present in 1976; javelina and panthers common. (B) |
| Cedar Springs | 29.90 | 101.90 | T | On Cedar Creek, these springs were dry in 1976 but 0.35 liter per second were flowing from other small springs in the Austin chalk upstream. Large willow nearby in 1976. (B) |
| Indian Wells, also Indian Pot Hole Springs | 29.991862 | -102.158742 | T | 9 km SW of Dryden, at head of McClain Canyon. Water scoured a hole out of Buda LS, dry in 1976. Depicted on Livermore's (1883) Military Map of Rio Grande Frontier (B) |
| Buena Springs | 29.891866 | -102.008736 | T | 18 km SE of Dryden, near Buena Creek, numerous seeps in Buda LS. In 1976, 0.1 lps flowing into gravel in Buena Creek. (B) |
| unnamed spring | 29.809923 | -101.573172 | VV | covered by Amistad Lake (TPWD) |
| Guy Skiles | 29.816593 | -101.557892 | VV | adjacent to unnamed spring, covered by Amistad Lake (TPWD) |
| Dead Man Spring | 29.791876 | -101.358717 | VV | According to Brune, four springs of this name are present on east side of Pecos River north of the Southern Pacific railroad, near Pecos high bridge, now under 17 m of water when Amistad Reservoir is at conservation pool level. In 1939 discharge was 120 lps and 1971 discharge was 91 lps. But TPWD mapped Dead Man Spring on west side of Pecos River. I used the TPWD location in this study, and I don't cite Brune's comments because they do not appear to refer to the TPWD Dead Man Spring |

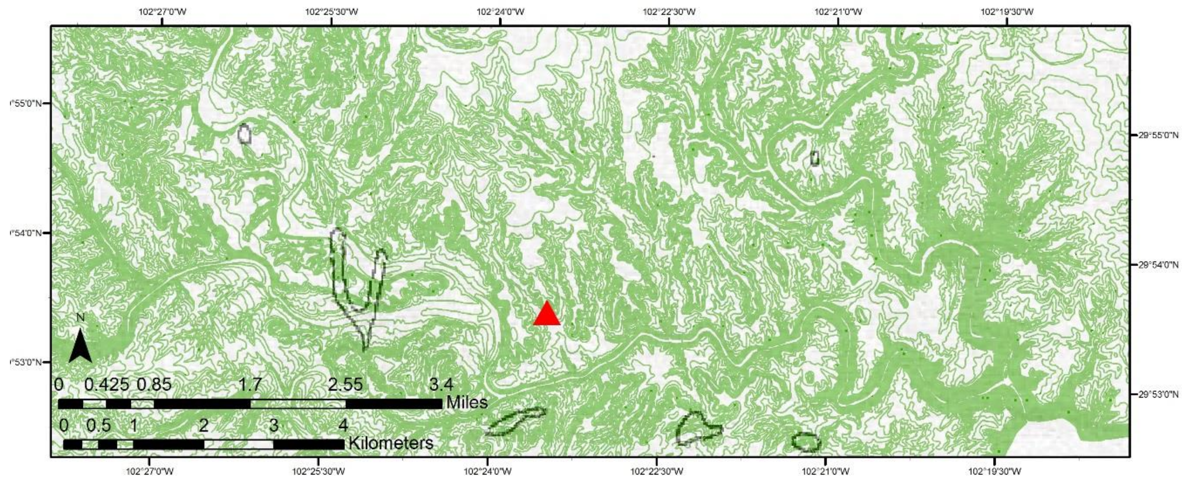



Figure 4.18. Coe Springs Topographic Map.
Coe Springs are located in a structural low northeast of an area of NW-SE folding in eastern Brewster County. The geologic map shows the springs flowing from Buda Limestone. Areas outlined in black are subsidence features mapped by Freeman (1968).

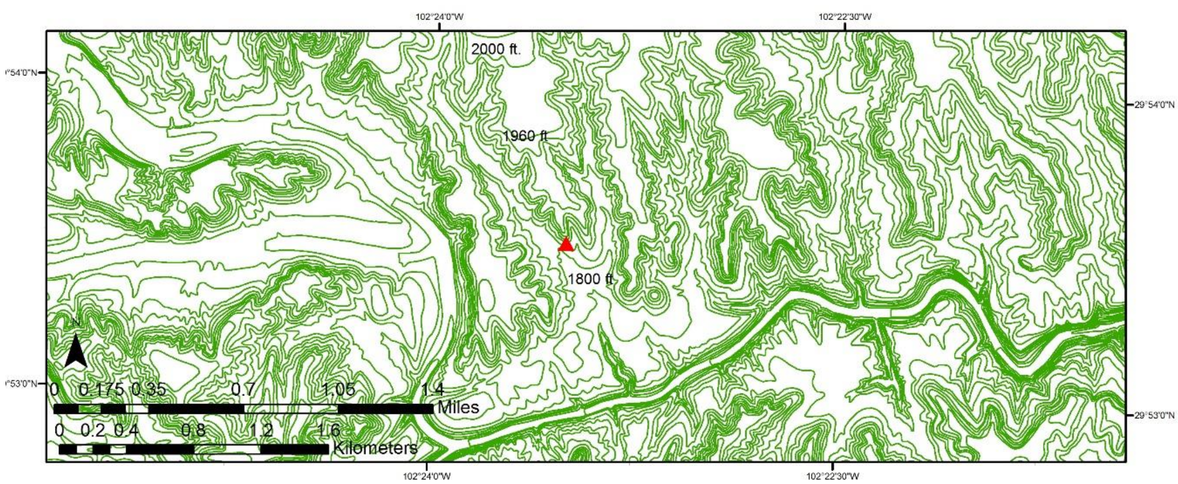



Figure 4.19. Coe Springs topographic map enlargement.
Coe Springs lies between the elevations of 1820 (555 m) and 1840 ft. (561 m) on a hillside in a recess and at the base of a steep slope. To the north (hydrologically upgradient) is a plateau at an elevation of 2000 ft. (610 m). To the south, the river is at an elevation of 1660 ft. (506 m).

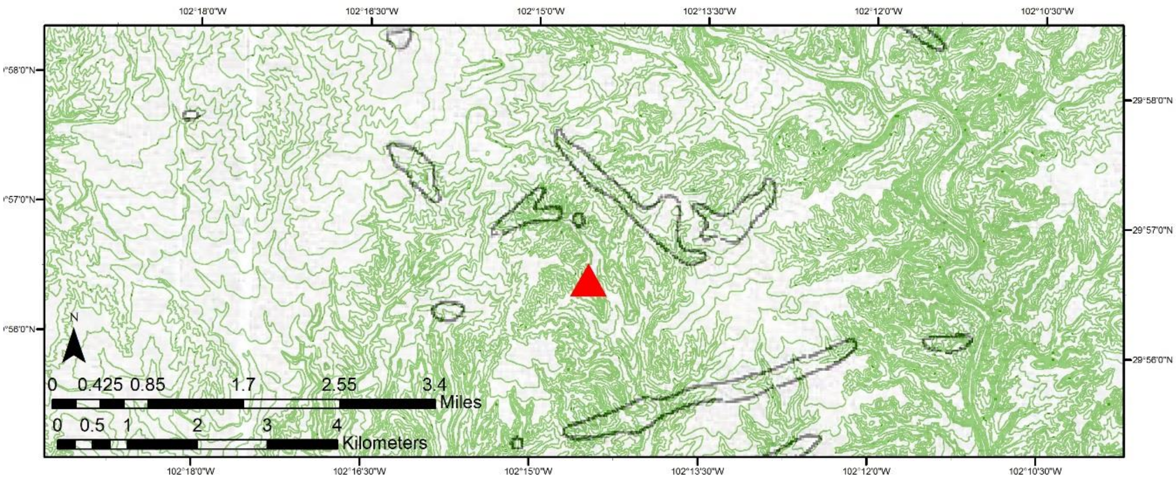



Figure 4.20. Luis Guerra (Chupadera) Spring.
Spring is in Leona Canyon between 2080 ft. (634 m) and 2100 ft. (664 m) to the east of a plateau. The closest subsidence area is 900 m north.

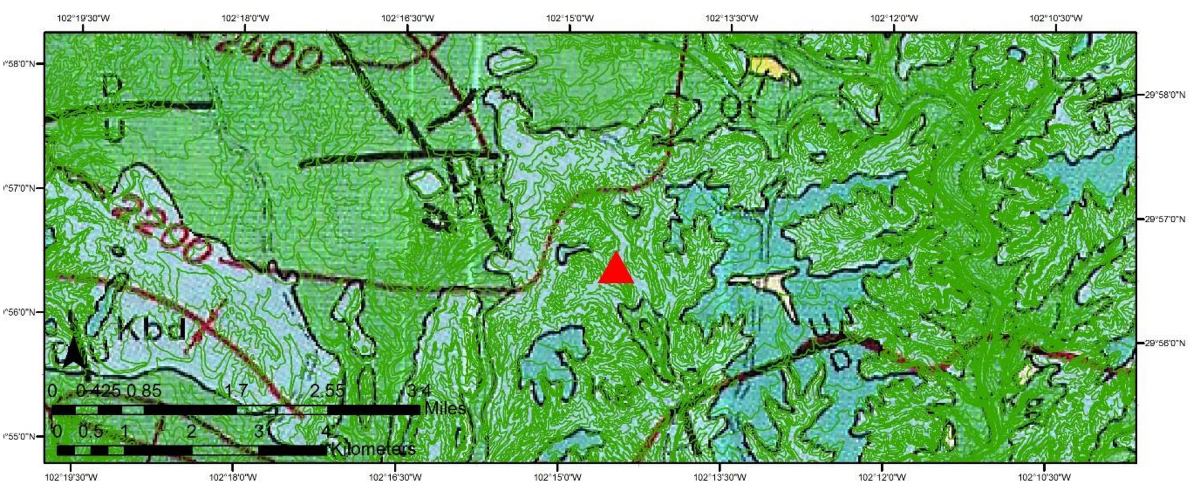



Figure 4.21. Luis Guerra Spring geologic setting.
Spring flows from Buda Limestone.

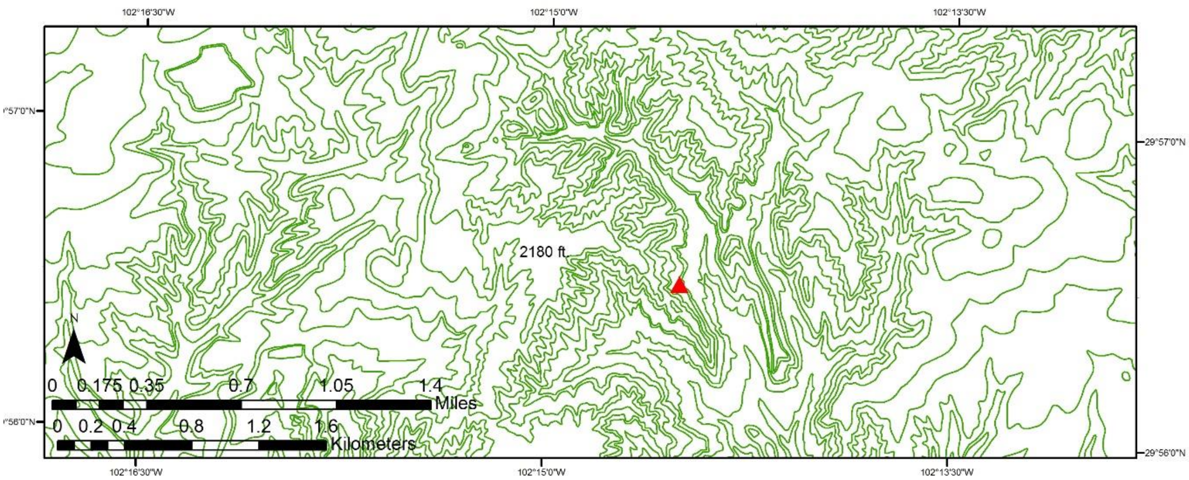



Figure 4.22. Luis Guerra Spring topographic enlargement.
The spring is located southeast of a plateau with an elevation of 2180 ft. (664 m).

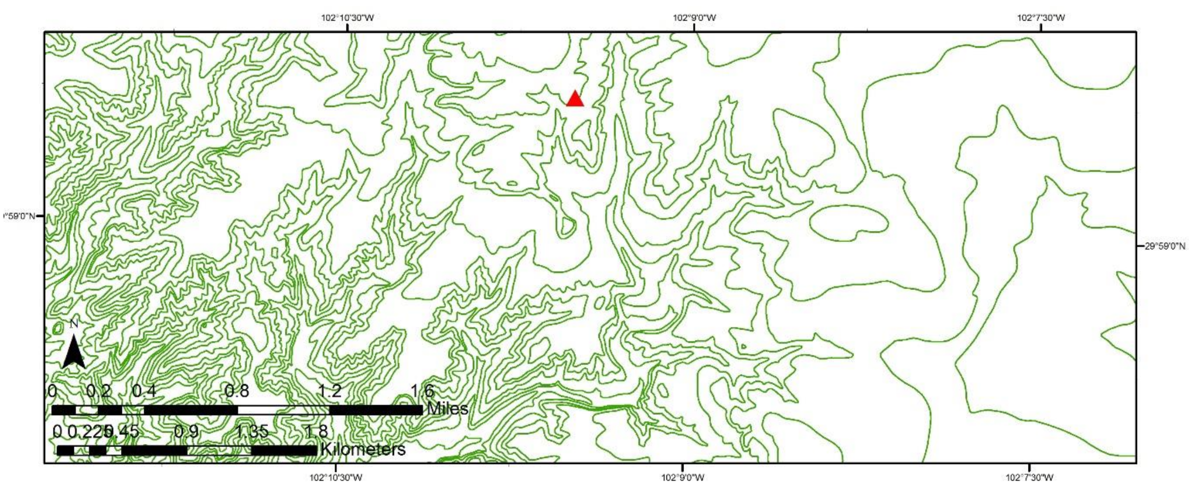



Figure 4.23. Indian Wells, also known as Indian Pothole.
Spring scoured out a hole in Boquillas Limestone. The spring is located on southeastern end of topographic high, on a flat to the between two recesses/draws.

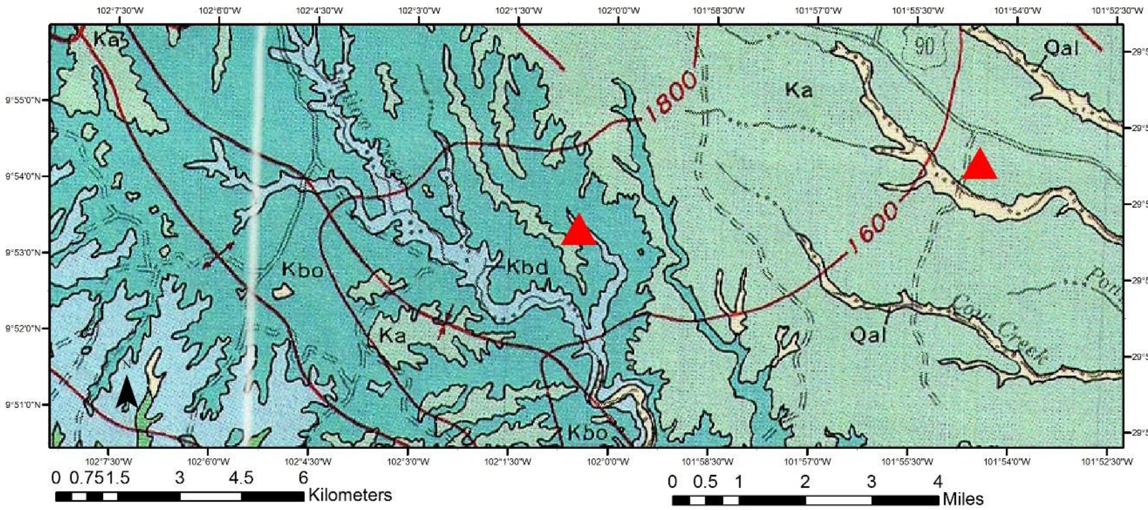



Figure 4.24. Buena Springs geologic map.
Springs are located at the contact of the Buda and Boquillas at an elevation of 1720 ft. (524 m). An elongate high west of the spring is at an elevation of 1920 ft. (585 m).  Cedars Spring is to the east.

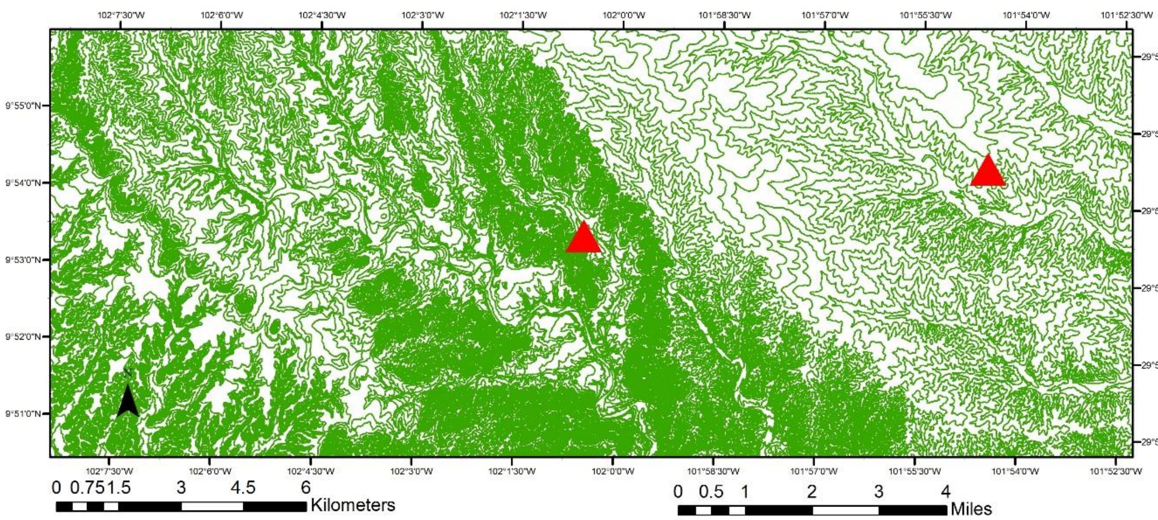



Figure 4.25. Buena Springs topographic map.
Springs are located in a region of steep topography.

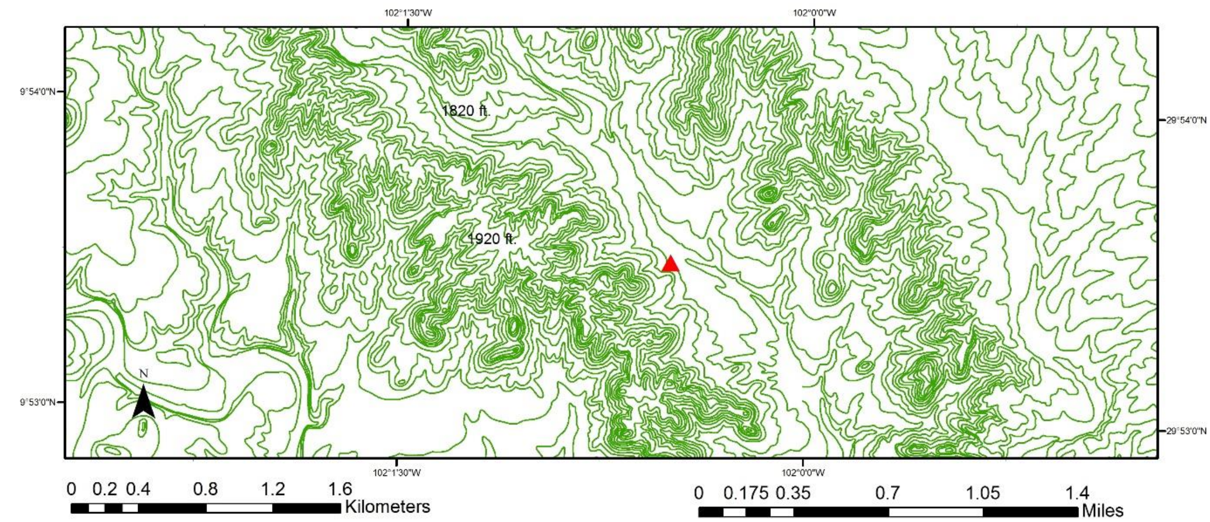



Figure 4.26. Buena Springs topographic map, enlarged.
The springs are at the base of the slope and beginning of plain, below a steep stope, in a tributary to Indian Creek, in a downgradient location based on regional slope.

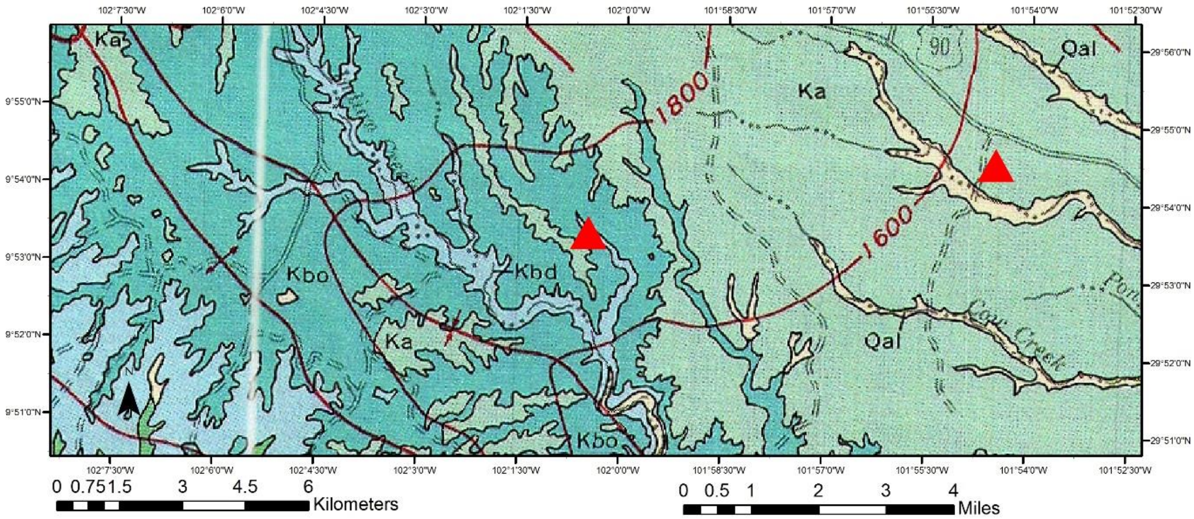



Figure 4.27. Cedars Springs geologic map (same as Figure 4.23).
Cedars Springs, shown on the east side of this map, flows from the Austin Chalk near the 1840 ft. (561 m) topographic contour. Buena Spring is located to the west of Cedars Spring.

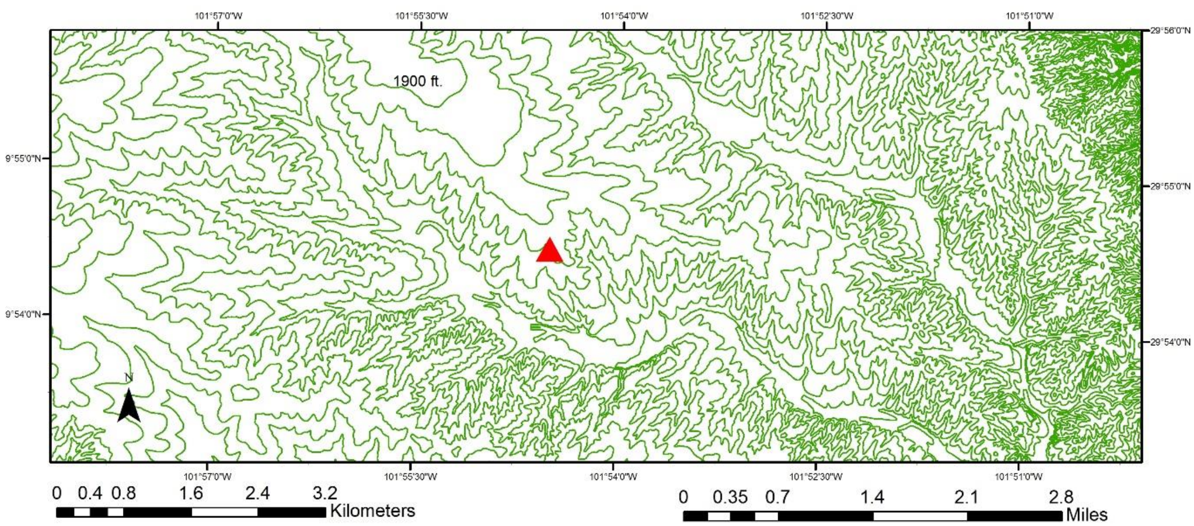



Figure 4.28. Cedars Spring topographic map.
Spring is located in a recess along a flat slope, with creek to south that flows southeast to Lozier Canyon. Springs lie between two alluvium-filled creeks that have incised to 1780 ft. A 1900 ft. (579 m) plateau lies to the northwest.

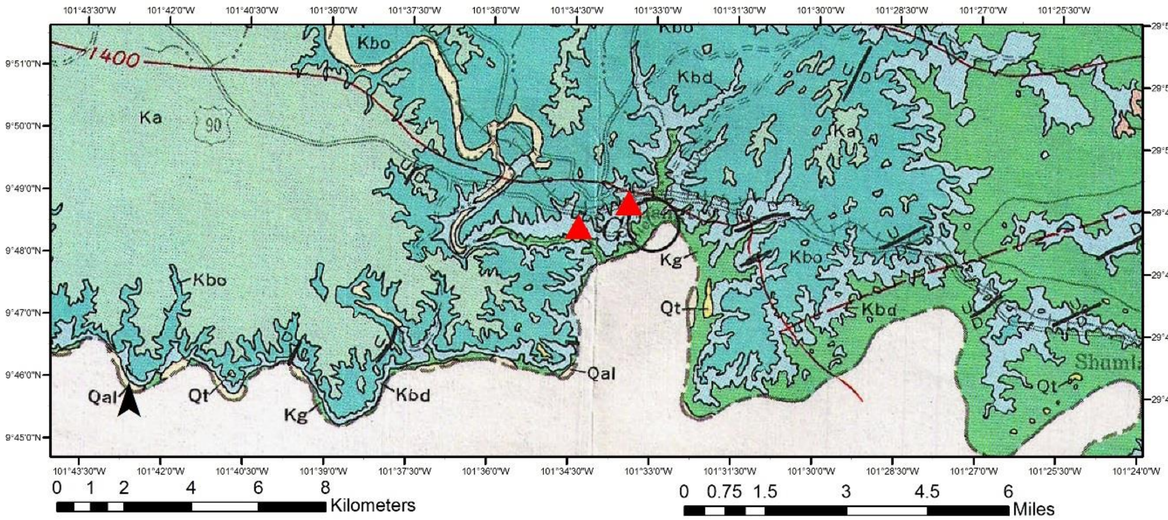



Figure 4.29. Geologic map of two springs near Langtry Creek.
Spring to the west is unnamed, spring to the east is called Guy Skiles. Both are now covered by Amistad Reservoir. Unnamed spring flows from Georgetown Limestone. Circle marked with letter G refers to the location of a set of visible joint readings and a rose diagram showing mostly N-S readings (Freeman, 1968).

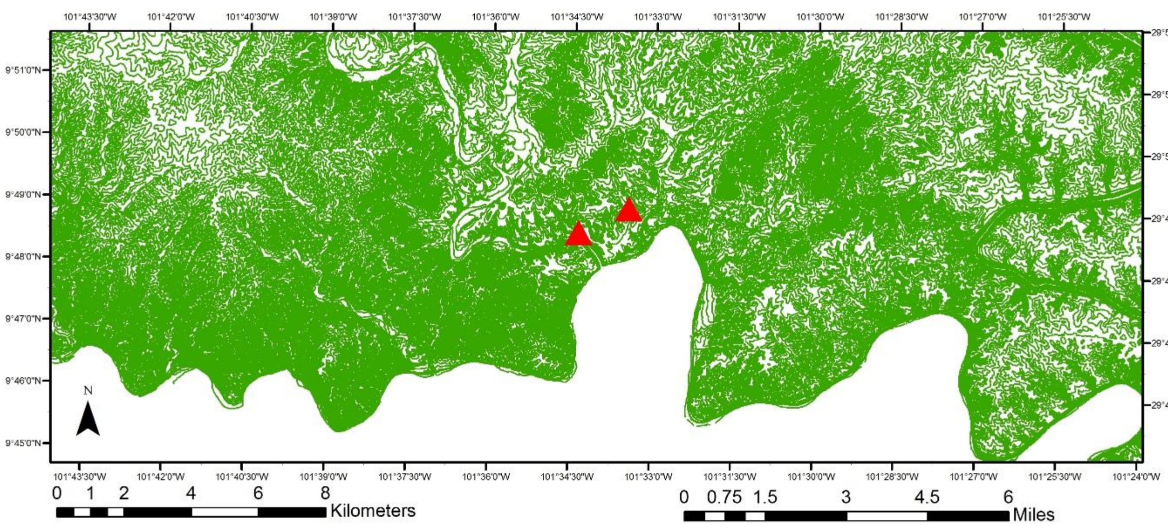



Figure 4.30. Topographic setting of Unnamed and Guy Skiles springs.

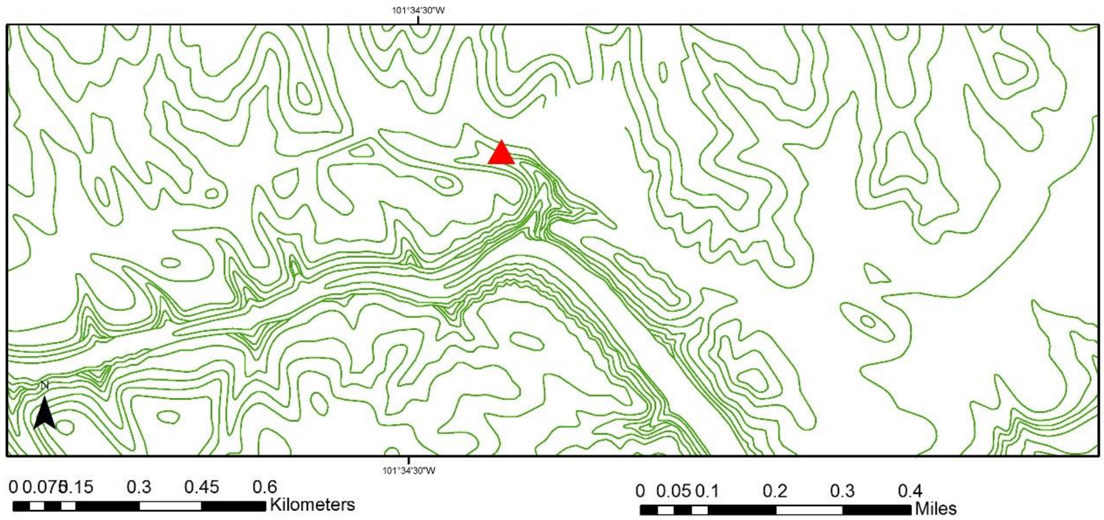



Figure 4.31. Enlargement of topographic map Figure 4.30.
Unnamed spring is in a recess, on a slope at 1280 ft. (390 m), highs to NW are at 1520 ft. (463 m).

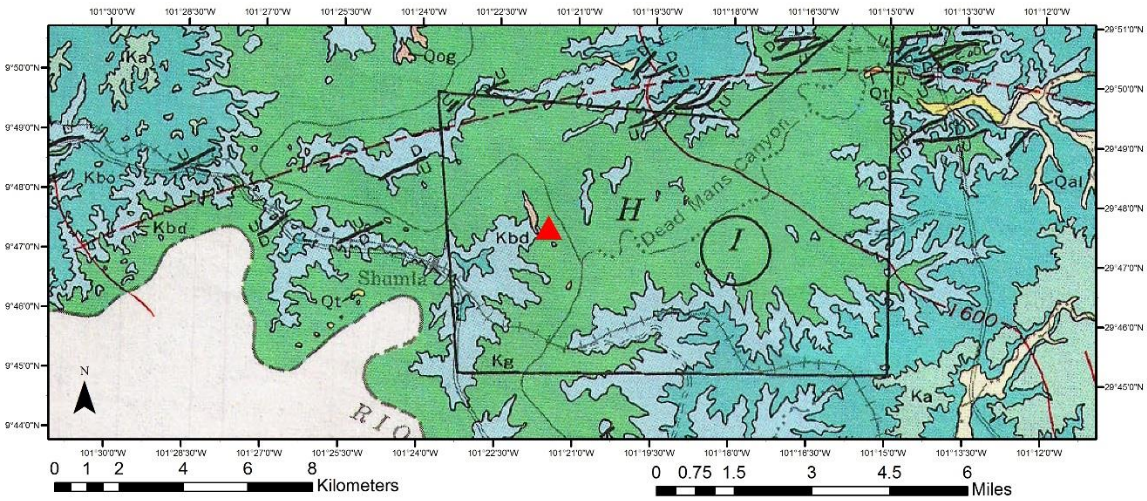



Figure 4.32. Dead Man Spring geologic setting.
Dead Man Spring flows from Georgetown Limestone. The area labeled H refers to locations of lineament and straight stream segment readings. The area labeled I refers to locations of visible joint readings. (From Freeman, 1968).

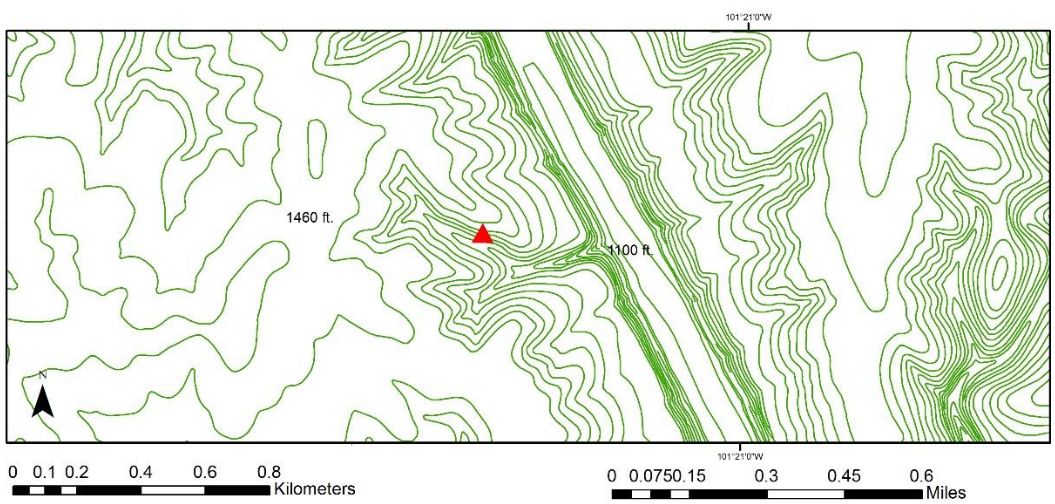



Figure 4.33. Dead Man Spring topographic map.
Spring lies on a steep slope in a recess NW of Pecos River. Spring is located between elevations of 1380 -1400 ft. (420 -427 m). An area of high elevation (1480 ft./451 m) lies to the NW of the spring. The contour in the Pecos River is 1100 ft. (335 m).

### 4.4. References


Brune, G., 1981, Springs of Texas, Volume 1, 2nd edition: College Station, Texas A&M University Press.

Bureau of Economic Geology Geologic Atlas of Texas Del Rio Sheet, 1977

Collins, E., 2000, Geologic Map of the New Braunfels, Texas, 30 x 60 minute Quadrangle: Bureau of Economic Geology Miscellaneous Map No. 39, Scale 1:100,000, 1 sheet, 28 pages text.

Freeman, V., 1968. Geology of the Comstock-Indian Wells Area Val Verde, Terrell, and Brewster Counties, Texas, USGS Professional Paper 594-K: Washington, D.C., United States Government Printing Office, 26 p.

Hauwert, N.M., 2009, Groundwater Flow and Recharge within the Barton Springs Segment of the Edward Aquifer, Southern Travis and Northern Hays Counties, Texas. [PhD. Thesis] Austin, University of Texas, 328 p.

Kastning, E.H., 1987, Solution-subsidence-collapse in central Texas: Ordovician to Quaternary *in* Barry F. Beck and William L. Wilson, eds., Karst hydrogeology: engineering and environmental applications: Boston, A.A. Balkema, p. 41-45.

Lattman, L.H., and Parizek, R.R., 1964, Relationship between Fracture Traces and the Occurrence of Ground Water in Carbonate Rocks: Journal of Hydrology Vol. 2, No. 2, 1964, p. 73-91.

Paramelle, J.-B., 1856. *L'Art de découvrir les sources* [*The Art of Finding Springs*]: Paris, Victor Dalmont, 376 p.

Texas Natural Resource Information Service (http://tnris.org/data-download/#!/statewide)

Texas Parks and Wildlife Department Springs Database. Lynne Hamlin, personal communication, February 2017.

Texas Water Development Board (www.twdb.texas.gov/groundwater/data/drillsdb.asp)

Texas Water Operators (http://texaswateroperators.com.)

Thomas, R.G., 1972, The geomorphic evolution of the Pecos River system: Baylor Geological Studies Bulletin, No. 22: Waco, Texas, Baylor University, 40 p.

Veni, G., 1991. Draft report: Evolution of the Stockton Plateau, prepared for Intera, Austin, Texas.

White, W.B., 1988, Geomorphology and hydrology of karst terrains: New York, Oxford University Press, 464 p.

Wong, C.M., Williams, C.E., Pittock, J., Collier, U. and Schelle, P., 2007, World's top 10 rivers at risk: Gland Switzerland, WWF International. (wwf.panda.org/about_our_earth/about_freshwater/freshwater_problems/river_decline/10_rivers_risk)

# Chapter 5. Summary and Discussion

Chapter 1 of this dissertation is an overview of the dissertation and an introduction to Jean-Baptiste Paramelle. It includes a description of Paramelle's business model. In addition, it contains photographs of two water systems built in the mid-19$^{th}$ century on the basis of his discoveries.

In Chapter 2, I present my translation of Abbé Paramelle's major work, *The Art of Finding Springs*, a best-selling 19th century book on how to find groundwater. Paramelle popularized groundwater and promoted it as a healthy, economical and indispensable resource. During his 31-year career, he "indicated" groundwater in about half the territory of France. The 32 chapters of the book include topics such as definitions of landforms, rock types, advice on how to observe geology and landforms in the field, definition of springs, discussion of water cycle and spring formation, how to find water on limestone plateaus, how to determine the depth and volume of groundwater, where to look and where not to look for groundwater, how to exploit groundwater, mineral and periodic springs, water quality, and ancient methods of finding groundwater. Paramelle also discusses how he developed his method and the groundwater discoveries he made during his working career from 1832 until 1853.

In Chapter 3, I summarize Paramelle's method by distilling the 412-page book down a single chapter. I summarize the topics covered in the book (listed in the preceding paragraph). I highlight Paramelle's use of observation to refute widely accepted but unsubstantiated ideas on groundwater and his use of observation to predict groundwater occurrences from Cassini maps. I discuss peer review by 19th and 20th century scientists, including speleologist E.A. Martel. I offer additional information on Paramelle's personality, his role as a teacher, and his business practices. New illustrations of Paramelle's ideas help the reader visualize his ideas on how groundwater forms and moves and how to find it. Paramelle's observations are summarized in Table 4.1 in Chapter 4.

In Chapter 4, I apply Paramelle's observations to two karst areas in Texas, New Braunfels and the Stockton Plateau. I expand Paramelle's concept of sinkholes as markers of groundwater to subsidence areas, i.e., coalesced sinkholes, to determine if high productivity water wells are located in proximity to subsidence areas. I used GIS to observe water wells with 100 m and 200 m buffers that intersect or are located within mapped subsidence areas. I analyzed the yields of wells located within the buffers and compared them to yields of wells located farther away. In the New Braunfels area, I found a positive correlation based on 18 wells. On the Stockton Plateau, an area of sparse water wells, no well buffers intersect any subsidence areas so no conclusions could be drawn. To draw some information from the Stockton Plateau study, I analyzed springs according to Paramelle's observations on the occurrence of shallow groundwater. I found that springs occur in recessed valleys or on the sides of these valleys, at the base of steep slopes, at the intersection of an overlying permeable rock and an underlying impermeable rock, and downgradient of an area large and thick enough to act as a recharge area, in accordance with Paramelle's observations.

### 5.1. Paramelle's Accomplishments

In closing, I summarize Paramelle's impact on hydrogeology and karst studies and list the remarks of some contemporaries and later hydrogeologists on his impact.

Abbé Paramelle's list of scientific firsts and accomplishments between 1818 and 1854 is impressive. Paramelle

- taught himself the geologic principles of the day by reading widely,
- developed a scientific observational method to find springs and groundwater that was widely used until the 1970s,
- was more popular than his contemporary Henry Darcy in mid-19th century France,
- contributed to karst science before karst science existed,
- contributed to speleology by noting aligned dolines as common features in dry valleys, surface valleys overlying underground streams, and the swallet-resurgence link,
- found water on the waterless karst plateau of the Causses du Quercy, Department of Lot,

- found water in 40 of 86 French departments,
- indicated groundwater in 10,275 places in France, and Paramelle estimates that 90% of these indications were verified by drilling,
- wrote a best-selling book to explain his method; the 1st edition was reprinted once and in all 6 editions were published, the last in 1926,
- enabled water seekers to find water per his instructions after his death,
- compiled a 3000-volume library of geology books,
- ran a consulting business that refunded his client's money if groundwater was not found at the depth and volume he predicted, and
- left a legacy of small groundwater systems in France.

Paramelle accomplished the above with the few tools available in his day, primarily his skill at observation at all scales, as he describes in his book and as summarized in Chapter 2 of this dissertation. He used all available technology, which was limited to 18th-19th century Cassini maps. He used these maps to find water at locations he determined to be favorable and to predict springs that he had never seen, causing some on-lookers to call him the New Moses. An 1842 newspaper article noted that Paramelle mentally analyzed the geological anatomy of the ground, looking at the ground surface, geology, uneven features, and rock type (*Courrier du Gard*, 1842). It is clear that Paramelle would have made full use of aerial photography, geologic maps, geophysics and other types of technology to aid in the search for water, had they been available.

### 5.2. Paramelle's Impact

Among French geologists and scientists, Paramelle's name was well known early in his career and remains so today. Henry Darcy, who published *The Public Fountains of the City of Dijon* in 1856, devoted several pages of his book to discussions of Paramelle's method and his book. The following are a few comments by French scientists on Paramelle's contributions to hydrogeology.

In 1836, J-J-N. Huot, geologist, lecturer, and author of an 1837 geology textbook, addressed the *Société d'Agriculture de Seine-et-Oise* on the subject of Paramelle and his water discoveries. Speaking early in Paramelle's career, Huot established that Paramelle explored for water in a scientific way, based on physics, physical geography, and a remarkable observational ability that he had developed with experience. Attached to this speech is an 1836 letter from the Prefect of the Department of Lot talking of Paramelle's early career and stating that of 51 wells dug according to Paramelle's theory, 48 were successful. (Huot, 1836).

In 1836 "the great naturalist Etienne Geoffroy Saint-Hilaire addressed a paper to the French Academy of Sciences stating that Paramelle's success was based 'on science and observation'" (Margat et al., 2013).

In 2003, Ghislain de Marsily said, "In Darcy's time, hydrogeology was still arguing about the Greek water cycle, from the sea to the continents. Father Paramelle's famous book "The art of discovering springs" (1856, 1859), with no mention of Darcy's work, was the best seller, not Darcy's" (De Marsily, 2003).

The European Academies Science Advisory Council (undated) states a similar idea: "… the most famous 19th century hydrogeologist in France was not Darcy, but Father Paramelle (1856) whose treaty on "The art of discovering springs" was determinative in making groundwater popular in France and exploiting it for domestic water supply." (Barraqué et al., date unknown)

In 2007, Renard pointed out,

> The birth of quantitative hydrogeology is generally considered to be the year 1856 when Henry Darcy published the Fountains of the City of Dijon (Darcy 1856), which contained the first description of the law governing the flux of water through porous media. Interestingly the same year Paramelle published a book entitled The Art of Discovering Ground Water (Paramelle 1856). Paramelle's book was descriptive, analyzing ground water occurrence in thousands of places in France and developing empirical rules to infer the presence of ground water from geological and geomorphological observations. Paramelle's book was the best seller at the time (not Darcy's book).
>
> (Renard, 2007)

In an article on the relative roles of Darcy and Paramelle in the foundation of modern hydrology, Tixeront, an engineer, compares Darcy's work of simplification, that is, simplification of natural phenomena for engineering purposes, to Paramelle's focus on the infinitely variable natural conditions in which groundwater is found. Tixeront claims that to find notable progress beyond Paramelle's methods, aside from Darcy's law, scientists had to wait for Schlumberger and 20th century geophysicists. Tixeront notes Paramelle's broad knowledge of the hydrologic literature. Tixeront also noted that Paramelle described geology not as an exact science, but a science of general rules that sometimes involve exceptions. Tixeront notes that this "probability" is a precursor to statistics. In summary, he considers Darcy and Paramelle as the precursors of the two scientific currents that have led to hydrology as a modern geophysical science (Tixeront, 1956).

Paramelle did not lack critics. E.A. Martel (1859-1938), often called the father of modern speleology, summarized Paramelle's concept of aligned sinkholes as "*jalonnement*," roughly translated "marking out," as in marking out a path. Martel rejected Paramelle's observation that aligned sinkholes in dry valleys mark out underground watercourses; Martel agreed there was some truth to the idea, but that it was an exception rather than the rule (Martel, 1894). Martel believed that sinkholes formed primarily as a result of erosion by whirlpools. He rejected the idea that underground caverns are formed by rock collapse or that a watercourse often flows under aligned sinkholes and he repeatedly rejected the idea of "*jalonnement*". In his 1921 book entitled *Nouveau traité des eaux souterraines* [New treatise on groundwater], Martel does not include Paramelle in a series of 19th century authors who had contributed to hydrogeologic knowledge even though the sixth edition of Paramelle's book would be published in 1926. Martel includes Paramelle in a list of authors who believed, as Martel did, that large underground reservoirs did not exist in limestones. As Michel Bakalowicz states, "Martel does not have a hydrogeologic vision, as Paramelle did. He was an explorer, capable of excellent morphological observations, and full of certainties" (Bakalowicz, personal communication 2016).

Among the international community, O.E. Meinzer quoted Paramelle extensively in his USGS Water Supply Paper on Plants as Indicators of Ground Water. Meinzer translated a paragraph on the topic of vegetation in the thalweg from Paramelle's *The Art of Finding Springs* (Meinzer 1927).

In another publication, Meinzer again cites Paramelle in discussing the development of groundwater hydrology. He says,

> About the middle of the century there appeared a number of publications, chiefly in France, based on extensive research in different phases of the subject of ground water, and it should perhaps be considered that ground-water hydrology, as a branch of science, had its beginning at this time. I refer especially to the work of the following men:

Meinzer includes Paramelle in the list with Belgrand, Dupuit, and Darcy (Meinzer 1934).

Appendix C contains more references to Paramelle's contribution to hydrogeology.

### 5.3. PARAMELLE, THE PERSISTENT OPTIMIST AND TEACHER

Heir to the Enlightenment and imbued with the 19th century can-do spirit, Paramelle sought to improve human living conditions and insisted that people should enjoy a certain quality of life, which included nearby water, clean water filtered through stone filters, and water wells with mechanical methods of raising the water. Paramelle says,

> It is still possible to find many villages with common wells that lack any type of mechanism for drawing water and whose inhabitants have never known or wanted to get together to set one up. … This condition of things is fit for barbarians or for the first people who inhabited the earth.
>
> (Chapter XXVII, *Art of Finding Springs*)

Paramelle exhibited amazing perseverance in the search for water. In 1818 when he set out to find water for his thirsty parishioners, he was responding to dire necessity. He spent nine years walking the limestone plateaus and riverbanks, and the springs and streams in primitive rocks in the Department of Lot looking for water. He traveled to 40 of the 86 departments of France that existed at the time, including Savoie, which at that time was not part of France. His career predated the construction of railroads; he traveled on horseback in all types of weather for seven months of the year, from March through June and September through November, beginning in 1832 and continuing until his retirement in 1854.

Paramelle continued his education by reading widely. If we compare the list of references in his 1827 memoire (Appendix A) to that of his 1856 book (Appendix B), we see how extensively Paramelle read over the years. Most of his reference books are in French but he read Englishman Henry de la Bèche in a French translation. We can assume that many of the references listed in *The Art of Finding Springs* were in his 3000-volume library.

Paramelle shares with most 21st century geologists a belief in the importance of fieldwork. Paramelle repeatedly recommends fieldwork and provides detailed instructions on where to go, what to look at, and how to look at it. He points out the groundwater divide that crosses France and encourages students to seek out the groundwater divides that cross their departments. In response to people who claimed he had supernatural powers, Paramelle responded that with a few months study of geologic theory and three months in the field, anyone could do what he did. Paramelle would probably echo the words, “The best geologists are the ones who have seen the most rocks.”

## 5.4. REFERENCES


Barraqué, B., Chery, L., Margat, J., de Marsily, G., and Rieu, T., (undated), Ground Water in the Southern Member States of the European Union: an assessment of current knowledge and future prospects, Country Report for France, European Academies Science Advisory Council (EASAC).

*Courrier du Gard*, 1 April 1842.

De Marsily, G., 2003, About Darcy's Law: Geological Society of America Abstracts with Programs (Annual Meeting), v. 35, p. 448.

Huot, J.-J.-N., 1836, *Memoires de la Société d'agriculture de Seine et Oise* [Report to Société d'Agriculture de Seine-et-Oise]: Versailles, Marlin, p. 109-120.

Margat, J., Pennequin, D., and Roux, J.-C., 2013, History of French Hydrogeology in Howden, N., and Mather, J., eds., AIH History of Hydrogeology, Boca Raton, CRC Press, p. 59-99.

Martel, E.A., 1894, *Les Abîmes*: Paris, Delagrave, 580 p.

Meinzer, O.E., 1927, Plants as Indicators of Ground Water, USGS Water Supply Paper 577: Washington D.C., US Government Printing Office, 95 p.

Meinzer, O.E., 1934, The history and development of ground-water hydrology: Journal of the Washington Academy of Sciences, Vol. 24, No. 1. p. 6-31.

Renard, Philippe, 2007, Stochastic hydrogeology: What professionals really need?: Ground Water vol. 45, no. 5, p 531-541.

Tixeront, J., 1956, *Note sur les roles respectifs de Darcy and Paramelle dans la fondation de l'hydrogéologie moderne*. Assoc. Inter. Hydrol. Scienc., Darcy Symposia, Dijon, Sept., Publ IAHS No. 41, T 11, p. 7-9.

# Appendices

## Appendix A. References cited in

## Paramelle's 1827 **Report to the Department of Lot**

Appendix A. Authors cited in Abbé Paramelle, 1827. *Mémoire hydrologique et géologique sur le département du Lot*, handwritten manuscript. Transcribed by J. Taisne and T. Pélissié, published by Spéléo-Club de Paris, 2010.

**References cited at end of text**


Buffon, 1749. *De la théorie de la terre*.

Depping, G.B., 1811. *Merveilles et beautés de la nature en France*

Desmarest, Nicolas. (1751-72) [contributor to *Encyclopédie*, (*Dictionnaire raisonné des sciences, des arts et des métiers*, edited by Diderot]

*Encyclopédie*, (1751-1772)

Garnier, F. 1822. *De l'Art du Fontenier Sondeur.*

Hale [Hall in original appears to be a typo –tr. note], 1764. *Le gentilhomme cultivateur*, *ou Corps complet d'agriculture*. [French translation of English book – tr. note]

Halley, E. 1687. *Philosophical Transactions* (*Review of the Royal Society of London*) No. 189.

Mariotte, E., 1686. *Traité du movement des eaux*

Nollet, abbé J.A., 1743. *Leçons de Physique expérimentale*

Pliny the Elder, (about 60 AD) *Histoire naturelle*

Pluche, abbé N.A., 1732. *Le Spectacle de la Nature, ou Entretiens sur les particularités de l'Histoire naturelle*

Plutarche, beginning of 2nd century AD. *Vie de Paul-Emile*

Seneca, about 50 AD. *Questions naturelles*

Valmont de Bomare, J.-C., 1764. *Dictionnaire raisonné universel d'Histoire naturelle*

Varenius, B., 1650. *Géographia generalis*

Vitruvius, (1st century BC). *De architectura*

Woodward, J., 1735. *Essay toward the natural History of the Earth* (1735)


**References cited in text**


Buffon. *Théorie de la terre, 2e Discours* (topic: depth to which water penetrates)

*Encyclopédie*, art. *Fontaine* (topic: water cycle) (topic: depth to which water penetrates)

Halley (*Trans. Phil. no 189*) (topic: evaporation)

Mariotte, *Traité du mouvement des eaux*. (topic: water cycle)

Nollet, *Physique expérimentale, XIIe leçon* (topic: water cycle)

Pliny, *Hist. Nat., Livre XXXI, chap XXX*

Pluche, *XXe and XXIe Entretiens*. (topic: water cycle)

Pluche, *Spect. de la Nat., Entr. XXI* . (topic: depth to which water penetrates)

Seneca, *Quest. Nat., livre III* (topic: depth to which water penetrates)

Varenius *Geog. lib 1 chap 16*) (topic: depth to which water penetrates)

**Authors sorted chronologically:**

**Ancients**

Vitruvius (80-70 BC – AD 15)

Seneca (4 BC – AD 65

Pliny the Elder (AD. 23 - 79)

Plutarch AD 46- 120)

**17th century**

Halley (1656-1742)

Marriotte (1620-1684)

Varenius (1622-1650)

**18th century**

Buffon (1707-1778)

Desmarest (1725-1815)

Hale (b?-d. 1759)

Nollet (1700-1770)

Pluche (1688-1761)

Valmont de Bomare (1731-1807)

Woodward (1665-1728)

*Encyclopédie* (1751-1772)

**19th century**

Depping (1784-1853)

Garnier

# Appendix B. References cited in

## Paramelle's ***The Art of Finding Springs*, 2nd edition, 1859.**

This appendix is a list of authors Paramelle cited in the text. He did not always cite authors' full names, publication names, or publication years. If he named the publication, he usually abbreviated it. Names highlighted with an asterisk are authors whose geology books Paramelle recommends to those who wish to study geology in more detail; these authors are listed in the Preface to *The Art of Finding Springs*, but Paramelle does not mention book titles or first names of these authors.

I have added comments and information about many references in square brackets, but I did not track down every reference. M. Bakalowicz and K. Taylor contributed substantially to this appendix. Dates in parentheses are the author's birth and death dates.


Arago, 1835, *Annuaire* (1786-1853). [Likely the annual publication of the Bureau des Longitudes]

Arago. *Notice sur les puits artésiens*. [May be a "notice" published in one of the annual publications of the Bureau des Longitudes]

Baudrimont, [Alexandre], [undated]. *Géol, notions génér*. [appears to be *Traité élémentaire de minérologie et de géologie*, Paris, H. Cousin. Title page undated.]

Baumgarten, *Annales des ponts et chaussées*, 2e series, t. XII.

Bélidor, 1737, *Architecture hydraulique*, Paris.

*Beudant, [François Sulpice], *Phys., liv. III, 2e section, art. IV*. [Likely: *Traité de Physique*] (1787-1850)

Bordeu, *Eaux minérales du Béarn* [appears to be: Bordeu, A., 1750. *Diss. sur les eaux minérales du Béarn*, Paris, in 12., cited as reference in Merat, F.V. and De Lens, A.J, *Dictionnaire universel de matière médical et de thérapeutique générale, Tome premier*, Paris, Balliere, Mequignon-Marvie, Gabon, 1829.]

Boubée, *Abrégé de Géol*., Chaleur central. [Appears to be Boubée, Nérée, 1834. *Cours Abrégé de géologie où développement du tableau de l'état du globe à ses differens ages*, Paris, Au Bulletin d'histoire naturelle de France.

Boué, [Ami.], [1835], *Guide du géologue-voyageur*, 2 vol. in -12, Paris, F.W. Levrault. (1794-1881)

Boué, Chap IV, § 3 [this may refer to the *Guide* listed above or to the *Mém. géol*. below]

Boué, *Mém. géol*. p. 3. [likely Boué, Ami, 1832, *Mémoires géologiques et paléontologiques*, Paris, F.- G. Levrault.]

Bouillon-Lagrange, [Edmé-Jean-Baptiste] page 50 [no text cited] (1764-1844)

Brisson, [no date cited] *Physique* No. 1044, No. 1211 [probably Brisson, Mathurin Jacques. Perhaps: 1781-1800, *Dictionnaire raisonné de physique*. Paris, Thou.] (1723-1806)

*Brongniart, Alexandre, [1807, *Traité élémentaire de minéralogie, avec des applications aux arts: ouvrage destine à l'enseignement dans les lycées nationaux*, 2 vol.: Paris, Deterville] (1770-1847)

Buffon, [Georges Louis Leclerc Comte de], (addition to article on earthquakes) (1707-1788)

Buffon, *art. Génésie des Minéraux*

Buffon, *Min., argiles et glaises*.

Buffon, [1778], *Époques de la nature*, discours préliminaire.

Buffon, [1749], *[De la] théorie de la terre*, IIe discours

Buffon, Volume II, p. 44.

*Burat, [Amédée], *Géol. appliquée*, Ch II. [Probably: *Géologie appliquée* or *Traité de la recherché et de l'exploitation des minéraux utiles*, Paris, 1843.] (1809-1883)

Cardan, Jérôme. (1501-1576)

Carlet, [Joseph], [1851], *Traité élémentaire des roches*, introduction [*Traité élémentaire des roches*, Carilian-Geoury and Dalmont, Paris, 176 p.]

Cassiodorus, *Book III, letter LIII* (c. 485 – c 585)

Charnock

Cordier, [Pierre Louis Antoine], 1828, *Essai sur la température de la terre*. (1777-1861)

Cotte, Louis [?]

Couplet, [Claude Antoine], (1642-1722)

Cuvier, *Rech*. tome IV, p. 556. [perhaps: *Recherches sur les ossemens fossiles de quadrupeds, où l'on rétablit les caractères de plusieurs espèces d'animaux que les révolutions du globe paroissent avoir détruites* (4 volumes, 1812) or *Recherches sur les ossemens fossiles* (5 volumes, 1821-23)] (1769-1832)

*D'Aubuisson des Voisins, 1819, *Géognosie*, volume. I, pages 450, 453, 458; Volume 1, note 7 [probably: *Traité de Géognosie*] (1769-1841)

D'Obrzenski, 1657, *Traité de la nouvelle philosophie*, Ferrara.

*D'Omalius d'Halloy, *Géol,* Chap II. [perhaps: *Eléments de Géologie*, 1831] (1783-1875)

*D'Orbigny, Alcide Dessalines. *Géol*. Chap 1. [perhaps *Cours élémentaire de paléontologie et géologie stratigraphiques*, 1852] (1802-1857)

Dalton

Dausse, François-Benjamin 1842. *Annales des ponts et chaussées*, t. III, p. 201. [Maybe "De la pluie et de l'influence des forêts sur les cours d'eau" pp. 184-209, K. Taylor, personal communication]

Davity, Pierre, 1637, *Empire du monde*. (1573-1635)

De Gasparin, [Adrien], [1843-49]. *Cours d'agriculture*, t. 1., p. 485 (1783-1862) [Adrien Etienne Pierre de Gasparin, 1st ed., 5 vols. 1843-1850. Vol. 1, 1843. (K. Taylor, personal communication]

De Girardin, *Report to the Société d'agriculture et de commerce de Rouen*.

*De la Bèche, Henry, [1832]. *L'Art d'observer en géologie* [English title: *A Geological Manual*, Philadelphia, Carey & Lea] (1796-1855)

De La Métherie, [1795 1st ed, 1797 2nd ed], *Théorie de la terre*, sections 1275, 1246, 1233, 1218, 1423. (1743- 1817)

De Malbos. *Bulletin de la Société géologique*, t. X, page 354.

Degousée, [J.M.A.], [1847], *Guide du Sondeur*, 2 vol in 8°, Chap 1. Also p. 458. [Paris, Langlois and Leclercq.]

Delpon, *Statistique du department du Lot*, t. I, p. 117-121.

*Demerson, [J.L.]. *Géol*., p. 74. [perhaps: *La Géologie enseignée en vingt-deux lecons*, Paris, Audin, 1829]

Descartes, [R., 1644], *Principes de la philosophie* (1596 – 1650)

Demarest, [L'An III, roughly 1794], *Géographique physique*, art. *Sénèque, Encyclopédie Méthodique* (1725- 1815)

Dickinson

Dickson

*Dict. de l'Acad.*, [*Dictionnaire de l'Académie*] at the word "*source*." [See Translator's Notes in Chapter 2.]

*Dict. de Trévoux*, at the word "source" [*Dictionnaire de Trévoux*] [See Translator's Notes in Chapter 2.]

*Dict. de M. Landais*, at the word "source" [*Dictionnaire of Mr. Landais*] [See Translator's Notes in Chapter 2.]

Duhamel, [J. B.], 1660, *Livre des météores*, Paris. [perhaps: *De Meteoris et fossilibus*, Paris 1659] (1624-1706)

Dupasquier, [Alphonse], [1840], *Des Eaux de source et des eaux de rivière*, Chap VI. [probably: *Des eaux de source et des eaux de rivière: comparées sous le double rapport hygiénique et industriel, et specialement des eaux de source de la rive gauche de la Saône, près Lyon, étudiées dans leur composition et leurs propriétés, comparativement à l'eau du Rhône:* Lyon, Perrin in-8°, 41 pp.]

Dupleix

*Encyclopédie*, art. *Fontaine* [See Translator's Notes in Chapter 2.]

*Encyclopédie*, article *Abreuver* [See Translator's Notes in Chapter 2.]

*Encyclopédie moderne*, article *Eau*. [See Translator's Notes in Chapter 2.]

Epicurus, *Letter to Pytoclus* (341-270 BC)

Fabricius, [Jean Albert], 1743, *Théologie de l'eau*, 1 vol in 8°. [Paris, Chaubert Durand. Original German published in 1734]

Fourier, [J., 1827, *Mémoire sur les températures du globe terrestre et des espaces planétaires, Mémoires de l'Académie royale des sciences de l'Institut de France*, vol. 7, p. 569-604.

Fourier, [J., 1833, *Mémoire d'analyse sur le mouvement de la chaleur dans les fluides, Mémoires de l'Académie royale des sciences de l'Institut de France*, vol 12, p. 507-530]

Garnier, [F., 1822], *De l'Art du Fontainier-Sondeur*, 1 vol in 4°. [Paris, Huzard.143 pp.]

*Gasc, [either Jean Pierre or Jean Charles?]

Gassendi [Pierre], [1649] *Commentaire sur Diogene de Laerce* [*Commentary on Diogenes Laërtius*] (1592-1655)

Gensanne, [Antoine de, 1776, *Histoire naturelle de la province de Languedoc*, http://www.geolales.net/Gensanne.html]

Halès, [Stephen] (1677-1761)

Hallé [medical doctor], *Dictionnaire de médicine*. [probably: Hallé, Guilbert et Nysten, *Dictionnaire des sciences medicales*. Paris. 1812]

Halley, [Edmund, 1687, *An account of the evaporation of water. Philosophical Transactions (Review of the Royal Society of London*, no. 189] (1656-1742)

Héricart de Thury, [Louis-Etienne], *Consid géol*. [likely: *Considérations géologiques et physiques,* 1829, Bachelier, Paris.] Sections 191, 199, 206, 231, 232, 233, 234, 330, 343, 344. (1776-1854)

Héricart de Thury, [Louis-Etienne], *3e Notice* (1776-1854)

Hippocrates. *De aere, aquis et locis* [*Air, water, and places*], (460-370 BC)

Humboldt [on Earth's internal temperature] (1769-1859)

*Huot, J.-J. N., 1836, *Report to Société d'Agriculture de Seine-et-Oise; Géol*, chap VIII.

*Huot, J.-J. N., *Encyclopédie moderne*, article on *versants*. (1790-1845)

Kircher, [Athanasius]. 1678, *Mundus subterraneus*, 2 vol. in-fol° (1601-1860)

Kulm, 1741. *Indications sur l'origine des fontaines et l'eau des puits*, Bordeaux

Lahire, [probably Philippe de La Hire], 1689, *L'école des arpenteurs* (1640-1718)

Le Beau

Le P. [P. = Père] François, [François, Jean], [1655]. *La Science des Eaux* (1582-1668)

*Lecocq, [Henri ?], (1802-1871)

Londe [medical doctor], *Dictionnaire de médicine*. [probably: *Dictionnaire de médecine et de chirurgie pratiques*. Paris, 1829]

Lydiat, [Thomas], 1605. (1752-1646)

*Lyell, Charles (1797-1875)

Malès, a customer of Paramelle's, commune de Chasteaux, Corrèze .

Mariotte, [E.], 1686, [*Traité du mouvement des eaux*] (1620-1684)

Marsigly [maybe Marsili, Luigi Ferdinando], (1658-1730)

Mentelle, [E.], and Malte-Brun, [C.], *Géogr*., livre VI [probably *Géographie mathématique, physique, et politique de toutes les parties du monde* (6 vols, published between 1803 and 1812). [Mentelle, Edmé (1730-1816); Malte-Brun, Conrad (1775-1826)]

Minard, [Charles-Joseph], *Cours de construction*, p. 317 [Probably: *Cours de construction des ouvrages hydauliques des ports de mer*. Paris Carilian-Goeury et Dalmont, 1846] (1781-1870)

Monestier-Savignat, [A]. *Traité des inondations*, p. 42. [probably: *Etude sur les phenomènes, l'aménagement et la législation des eaux au point de vue des inondations, avec application au basin de l'Allier, rivière à regime torrential, affluent de la Loire*. 1858, V. Dalmont Paris]

Muncke

Muschenbroek, [Pierre], [1751], *Ess. de Phys*., section 1455, [*Essai de Physique*. Leyden, Samuel Luchtmans. (translation from Dutch)] (1692-1761)

Nollet, Abbé J.-A., 1743, *Phys*., 7th lesson, also *Physique expérimentale* 12th lesson. [Probably: *Leçons de Physique expérimentale*. Paris, Frères Guerin] (1700 – 1770)

*Nouveau Dict. d'Histoire naturelle*., art. *Source*; art. *Eau* [See Translator's Notes, Chapter 2]

Nysten. *Dictionnaire de médecine*. [probably: Hallé, Guilbert et Nysten, *Dictionnaire des sciences médicales*. Paris. 1812]

Palissy, B., 1580, *de la Nature des Eaux et des Fontaines*. [probably: *Discours admirables de la Nature des Eaux et des Fontaines*, Paris, 1580] (1510-1589)

Palladius, [full name: Paladius Rutilius Taurus Emilianus, 5th century CE, Libri de re rustica https://fr.wikipedia.org/wiki/De_re_rustica

Papin, Nicolas, 1647, *Origine des sources*, printed in Blois. [probably: *Raisonnemens philosophiques touchant la salure, flux et reflux de la Mer et l'origines des sources, tant des fleuves que des fontaines*, Blois, François de la Saugère, 1647]

Paulian [likely Aimé-Henri Paulian, 1761, *Dictionnaire de Physique*

Perrault, Pierre, [1674], page 167. [Likely: *De l'origine des fontaines*, Paris, Pierre le Petit] (1611-1680)

Plato, Phaedo. (425-347 BC)

Pliny, *Histoire naturelle*, Book XXXI, Ch. XXI, XXII and XXVIII; Book XXVI. Ch. 3 [1833 Translation of M. Ajasson de Grandsagne. Paris, chez Panckoucke] (23-79 AD)

Pluche, [Abbé N.-A., 1732.] *Spect de la nat*., Entr XX; Entretiens XX and XXI [Probably: *Le spectacle de la Nature: ou Entretiens sur les particularités de l'Histoire naturelle*]

Poléni [likely Giovanni Poleni (1683-1761)

Reboul, [Henri], *Géolog*., chap XV (1763-1839)

Richard, [Jérôme], [1770-71]. *Hist. nat. de l'air*, VIIIe discours section 5, section XX [*Histoire naturelle de l'air et des météores*, Saillant & Nyon, Paris];

*Rivière, Alphonse-Auguste, *Géol*, chap III. [perhaps: *Eléments de géologie pure et appliquée*, 1839, Méquignon-Marvis, Paris] (1805-1877),

Robertum, 1696, *De origine fontium*, Oxonii. 1 Vol in-8° (1640-1696)

Rohault, 1676, *Traité de physique*, Paris. 2 vol in-12.

Rostan (doctor), *Dictionnaire de medicine*. [perhaps: *Dictionnaire de médecine*, 1824, Paris Chez Bechet Jeune.]

*Rozet, [Claude Antoine, perhaps: *Cours élémentaire de géognosie*, 1830, Paris, F.G. Levrault] (1798-1858)

Saintignon, [Joseph de]. *Phys*., 3e part., sect 2, chap 1. [perhaps: *Traité abrégé de physiques à l'usage des colleges*, Durand, 1763]

Saussure, [Horace-Benedict], 1796. *Voyages dans les Alpes, Agenda*; Chapter 15, section 281. [Neuchatel, Fauche] (1740-1799)

Scaliger, Joseph-Jules [or Joseph Juste] (1540-1609)

Sédilau

Seneca, *Quest nat*., Book III (4 BC- 65 AD)

Thales (c. 624 BC – c. 546 BC)

Tissot, [S.A.D., 1795], *De la Santé des gens de lettres*, [Grasset, Lausanne. 274 p.]

Tristan, Jules Marie Claude Marquis de Tristan, [1776-1861]

Troïl, [perhaps Uno von Troil]. [perhaps 1777] *Lettres sur l'Islande*, translated from Swedish, p. 304. (1746-1803)

Vallisneri, [probably: Vallisneri, Antonio], *Annot*. (1661-1730)

Valmont de Bomare, art. *Fontaine*. [See Translator's Notes in Chapter 2.] (1731-1807)

Van-Helmont, Jean Baptiste, *Principes inouîs de physique* (1580-1644)

Varenius, [Bernhardus]. [1650] *Géog*., lib 1, chap 16 [probably: *Geographia Generalis*, 1712, Imprensis Cornelii Crownfield] (1622-1650)

Vitruvius, [probably written between 30 and 15 BC] *Architecture* (81 BC – 15 AD)

Vood-Vard [may be WOODWARD, J. 1735, *Essay toward the natural History of the Earth*]

Wallerius, [Johan Gottschalle], (1709-1785)

Weyman, 1841, *Société géologique* [Trieste?] (Bulletin t. XII, p. 265)

## Appendix C. Authors who cite Paramelle

This is a work-in-progress bibliography of scientific authors who refer to Paramelle. Michel Bakalowicz contributed greatly to this list; he points out that Paramelle was unknown to the English-speaking scientific community because his book was not translated into English.


Adams, U. von, Gert M., 1987, *Der Wassersicjer Abbé Paramelle* (1790-1875) *Hexer oder Heiliger?* [Water seeker Abbé Paramelle. Sorcerer or Saint?]. Brunnerbau. Bau von Wasserwerken, Rohrleitungsbau, no.4, p 149-158.

Alfaro, C. and Wallace M., 1994, Origin and classification of springs. *Environmental Geology* (1994) 24:112 124.

Auscher, E.S., 1948, *L'art de découvrir les sources et de les capter*, Bailliere et Fils, Paris, 352 p.

Ausset, 1916, *Notes du curé de Saint-Céré*. [Discussion of Paramelle's accomplishments, unpublished.]

Barraqué, B., Chery, L., Margat, J., de Marsily, G., and Rieu, T. (undated) *Ground Water in the Southern Member States of the European Union: an assessment of current knowledge and future prospects. Country Report for France. European Academies Science Advisory Council.*

Brébisson, Alphonse de, 1836, *De la théorie de M. Paramelle pour la découverte des sources*. Lisieux: Impr. Durand et Cie.

Briffaut, Abbé, 1860, *Histoire de la ville de Fayl-Billot*, Besançon

Chalon P.F., 1913, *Les eaux souterraines. Recherche, captage et purification*. Ch Béranger, Paris, 470 p.

Darcy, H., 1856, *Les Fontaines publiques de la ville de Dijon* :Paris, Dalmont, 647 p.

De Marsily, G., 2003, About Darcy's Law. *GSA Abstracts with Programs* (Annual Meeting), v. 35, p. 448.

Ellis, A.J., 1917, *The Divining Rod: A History of Water Witching*, USGS Water Supply Paper 416. US Government Printing Office, Washington DC

Gèze, B., 1958, *Sur quelques caractères fondamentaux des circulations karstiques*, *Actes IIe Congr. Intern. de Spéléologie*, Bari 1958, p. 3-22.

Gèze, B., 1947, *L'origine des eaux souterraines*. *Annales de Spéléologie*, II:3-10.

Grimaud de Caux, 1863, *Des eaux publiques et de leur application aux besoins de grandes villes*, Dezobry, Fd Tardou et Cie, Paris.

Jones, P.B., Walker, G.D., Harden, R.W. and McDaniels, L.L.,1963, The Development of the Science of Hydrology, *Texas Water Commission Circular 63-03*.

Huot, 1836. *Memoires de la société d'agriculture de Seine et Oise*, Versailles, Marline, Imprimeur de la Société.

Margat, J., Pennequin, D., and Roux, J-C., 2013, History of French Hydrogeology, in Howden and Mather, eds., 2013*, AIH History of Hydrogeology*, p. 63.

Martel, E.A., 1890, *Les Cévennes*, Delagrave, Paris.

Martel, E.A., 1894, *Les Abîmes*. Delagrave, Paris.

Martel, E.A., 1919, *L'Evolution souterraine*. Flammarion, Paris, 323 p.

Martel, E.A., 1921, *Nouveau traité des eaux souterraines*, Paris, Librairie Octave Doin, 838 p.

Meinzer, O.E., 1923, *The Occurrence of Ground Water in the United States, USGS Water Supply Paper 489*, US Government Printing Office, Washington, DC.

Meinzer, O.E., 1927, *Plants as Indicators of Ground Water, USGS Water Supply Paper 577*, US Government Printing Office, Washington DC.

Meinzer, O.E., 1934, The history and development of ground-water hydrology. *Journal of the Washington Academy of Sciences*, Vol. 24, No. 1.

Meinzer, O.E. ed., 1942*, Physics of the Earth IX. Hydrology*. McGraw Hill Book Company, 712p.

Nace, Raymond, 1978, Hydrology: a science 5,000 years in the making, in *The Unesco Courrier*, February 1978.

Pali, A., 1932, *La recherche des eaux souterraines. La science des eaux ou hydrologie souterraine et l'art de faire sourcer les eaux*. *Actualités scientifiques et industrielles*. Bailliere et Fils, Paris, 189 p.

Renard, Philippe, 2007, Stochastic hydrogeology: What professionals need? Ground Water vol. 45, no. 5, p. 531-541.

Rohrbacher, R.F., 1887, *Histoire universelle de l'église catholique*, vol. 13, pages 637-638.

Roques, H., 1956, *Etudes Régionales: A propos de l'hydrogéologie de la bordure nord-est du causse de Gramat (Lot). Annales de Spéléologie*, 10-11. 1955-56.

Roux, J-C., Margat, J, 2013, *Histoire l'Hydrogéologie français*, BRGM.

Simmons, C., 2007, Henry Darcy (1803-1858): Immortalized by his scientific legacy, in *Aquifer Systems Management: Darcy's Legacy in a World of Impending Water Shortage*, ed. by Chery, L., and de Marsily, G. International Association of Hydrogeologists selected papers. Taylor and Francis, London.

Taisne, J. and Choppy, J., 1987, *Un des premiers hydrogéologues du karst: L'Abbé Paramelle*, "*Hydroscope*". *Karstologia* No. 9, 1987.

Taisne, J., 1986. *L'Abbé Paramelle. Petite histoire d'une statue*: *Grottes et Gouffres* no. 101, September, 1986.

Teissier-Rolland, J., 1842, *De l'Abbé Paramelle et de divers moyen d'amener des eaux à Nismes:* Nimes, Balivet et Fabre, 176p.

Tixeront*,* J., 1956, *Note sure les roles respectifs de Darcy and Paramelle dans la fondation de l'hydrogéologie moderne*. *Assoc. Inter. Hydrol. Scient., Darcy Symposia*, Dijon, Sept., Publ IAHS No. 41, T 11, p. 7-9.

Trombe, F., 1950. *Les eaux souterraines*, PUF, Que Sais-je? No. 455.

## Appendix D. Archival research conducted for this project

In 2014 and 2015, I visited the Departmental Archives in all departments where Paramelle worked. In The table below shows 39 instead of the 40 departments attributed to Paramelle because it lists only Savoie and not Haute Savoie. Paramelle worked in Savoie before 1860, when it was annexed to France as two departments, Savoie and Haute Savoie. The map in Taisne and Choppy (1987) shows the departments of Savoie and Haute Savoie as departments where Paramelle worked. Counting both of them brings the total to 40. I did not visit the Departmental Archives of Haute Savoie; it is my impression that all the documents about Paramelle's work in the entire Savoie are housed in the archives in Chambéry, the traditional capital prior to its annexation.

In 2013, I visited the Bibliothèque Nationale in Paris to look for copies of the newspapers Paramelle cited in *The Art of Finding Springs.*

As a result of my research, I met two individuals who have identified water systems that still exist that were constructed as a result of Paramelle's discoveries. Both are in the Department of Côte-d'Or and are listed below in that department.

The table below is a chronological list of departments Paramelle visited, according to Chapter XXX of *The Art of Finding Springs*. Dates of Paramelle's visits are based on documents found in archives and newspaper accounts; I have not yet found dates for all of Paramelle's visits.

P's order: Chronological order of Paramelle's visits
Chef-lieu: Department's administrative center
Dept. No: Official French department number
Number of images: documents photographed

| P's Order | Department | Chef-lieu | Year of P's Visit | Dept No. | Date of My Visit | Archives visited **in addition to** Departmental Archives | No. of images |
|---|---|---|---|---|---|---|---|
| 1 | Lot | Cahors | 1818 -1832 | 46 | 6/27/2013<br>6/24/2014 | Bibliothèque municipale de Cahors,<br>Société des Etudes du Lot,<br>Catholic Diocese | Bib: 3<br><br>Soc:22<br>Dioc: 0 |
| 2 | Corrèze | Tulle | 1831 | 19 | 6/23/2015 | | 7 |
| 3 | Aveyron | Rodez | ? | 12 | 6/25/2015 | | 4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | Dordogne | Perigueux | 1834 | 24 | 6/22/2015 | Office de Tourisme Vallée de la Dordogne Rocamadour Padirac; Bibliothèque Municipale | 90+ |
| 5 | Charente | Angoulême | 1834 | 16 | 7/28/2015 | | 0 |
| 6 | Lot-et-Garonne | Agen | ? | 47 | 6/26/2015 | | 3 |
| 7 | Cantal | Aurillac | 1835 | 15 | 6/24/2015 | | 10 |
| 8 | Vienne | Poitiers | 8/1835 | 86 | 7/29/2015 | | 150? |
| 9 | Gironde | Bordeaux | 1836 | 33 | 7/27/2015 | | 0 |
| 10 | Savoie | Chambéry | May 1836 | 73 | 8/7-8/2014<br>6/2-3/2015 | | 200+ |
| 11 | Seine-Inferieure[1] | Rouen | Aug 1836 | 76 | 7/8/2015 | | 420+ |
| 12 | Cher | Bourges | 1836 or after | 18 | 7/16/2015 | | 27 |
| 13 | Loir-et-Cher | Blois | 1837? | 41 | 7/10/2015 | Fonds anciens de la Bibliothèque Abbé Grégoire | 70+ |
| 14 | Charente Inférieure | La Rochelle | 1836 | 17 | 7/30/2015 | | 12 |
| 15 | Basses Alpes | Digne-les-Bains | 1836-37 | 4 | 5/21/2015 | | 3 |
| 16 | Gers | Auch | ? | 32 | 7/4/2014 | | 48 |
| 17 | Bouches du Rhone | Marseille | 1838/1840 | 13 | 6/12/2014 | | 52 |
| 18 | Var | Draguignan | 18? | 83 | 5/29/2015 | | 10 |
| 19 | Hautes Alpes | Gap | year? | 5 | 5/20/2015 | | 1 |
| 20 | Hérault | Montpellier | 1841, May | 34 | 6/20-22/13<br>6/17/2014<br>7/7-8/2014<br>3/1/2015<br>6/28/2015<br>9/30/2016 | | 0 |
| 21 | Gard | Nimes | 1841/1842 | 30 | 6/16/2014 | | 175 (book) |
| 22 | Vaucluse | Avignon | 1842 | 84 | 6/18-20/13<br>7/9/2014 | Médiatheque Ceccano | 16 |
| 23 | Drôme | Valence | 1842 Nov | 26 | 5/18/2015 | | 18 |
| 24 | Loire | St. Etienne | 1843 ? | 42 | 7/10/2014 | | 108 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 25 | Ardèche | Privas | 1843 | 7 | 5/2015 | Archivist found www.memoireet actualité.org Lists 90 newspapers that mention P. | |
| 26 | Doubs | Besancon | 1844 | 25 | 8/4/2014 | | 19 |
| 27 | Jura | Lons le Saunier | 11/1844, 4/1845 | 39 | 6/5/2015 | | 0 |
| 28 | Haute Saône | Vesoul | 1846 May | 70 | 8/5/2014 | | 72 |
| 29 | Saône-et-Loire | Mâcon | 1846/47? | 71 | 6/10/2014 | | 17 |
| 30 | Vosges | Epinal | May 1847 | 88 | 8/2014 | | |
| 31 | Meurthe[2] | Nancy | 1847 | 54 | 7/21/2015 | | 90 |
| 32 | Côte-d'Or | Dijon | April 1849 | 21 | 7/24/2013 | Archives municipales<br>Bibliothèque municipale<br>Bibliothèque d'études<br>Moloy: Daniel Clement (2013)<br>Gevrey-Chambertin: Gerald Naigeon (2016) | 32 |
| 33 | Haute Marne | Chaumont | May 1849 | 52 | 7/23/2015 | Los Silos (former granary, now public library - 16 photos) | 430 +16 |
| 34 | Moselle | Metz | 1848? | 57 | 7/21/2015 | Two sites, one was AD, other? | 36 + 19 |
| 35 | Meuse | Bar le Duc | | 55 | 7/31/2014 | | 0 |
| 36 | Haut Rhin | Colmar | end Sept 1850? | 67 | 7/21-22/15 | Bibliothèque municipale, pole culturel | 9 |
| 37 | Aude | Carcassone | 1850 or later | 11 | 7/1/2015 | | 2 |
| 38 | Haute Garonne | Toulouse | 1852 | 31 | 7/4/2014 | | 4 |
| 39 | Ariège | Foix | 1853? | 9 | 7/3/2014 | | 6 |

Notes:

1. Seine-Inférieure is now Seine-Maritime
2. Meurthe later merged with Moselle

Reference:

Taisne, J., and Choppy, J., 1987, *Un des premiers hydrogéologues du karst: L'Abbé Paramelle, "Hydroscope"* in Karstologia No. 9, 1987, p. 53-58.

# References

Chapter 1

Clement, D., 2014, "*Il était une fois*" (personal communication)

Darcy, H., 1856, The Public Fountains of the City of Dijon [Translated from *Les Fontaines publiques de la ville de Dijon*: Paris, Dalmont, 647 p.

*Journal de l'Ain*, 7 May 1841.

Naigeon, G., 2016, *C'était Hier N° 4, Sur les Traces du Passé* (personal communication)

Taisne, J., 1986, *L'Abbé Paramelle. Petite histoire d'une statue: Grottes et Gouffres*, Bulletin of the Spéléo-Club de Paris, No. 101, September 1986, p. 25-26.

Taisne, J., and Choppy, J., 1987, *Un des premiers hydrogéologues du karst: L'Abbé Paramelle, "Hydroscope*"in Karstologia No. 9, 1987, p. 53-58.

Chapter 2: References for Translator's Notes

Ellenberger, F., 1999, History of Geology Volume 2, The Great Awakening and its First Fruits – 1660-1810: Balkema/Rotterdam/Brookfield, 404 p.

Gaffiot, F., 1934, *Dictionnaire latin-français*: Paris, Hachette: www.lexilogos.com/latin/gaffiot.php (Accessed April 2017)

Grand Robert & Collins French-English Dictionary, 2008: Paris, Le Robert, electronic dictionary.

Kalmar, J. and Dovacs-Palffy, P., 2008, Geochemical Study of Leptinites from Stejera (Romania): Carpathian Journal of Earth and Environmental Sciences, Vol. 3, No. 1, pp 49-64.

La Fontaine, Jean de, 1967. *Fables Tome Premier Livres I à VI*: Bordas.

Larousse, 1992. *Dictionnaire de la langue française*, LEXIS 2nd edition. Paris, Larousse, 2109 p.

Laudan, R., 1987, *From Mineralogy to Geology*: Chicago, University of Chicago Press, 278 p.

Levallois, J.J., 1988, *Mesurer La Terre: 300 ans de géodesie francaise*: Paris, Presses de l'Ecole Nationale des Ponts et Chaussées, 389 p.

Littré, Emile, 1873-74, *Dictionnaire de la langue française*: Paris, L. Hachette. http://www.littré.org

Michel, J-P, Carpenter, M.S.N., Fairbridge, R.W., 2004, *Dictionnaire des sciences de la terre* [Dictionary of Earth Sciences], 4th edition: Paris, Dunod, 496 p.

Moureau, M. and Brace, G., 2000, *Dictionnaire des sciences de la terre* [Dictionary of Earth Sciences]: Paris, Editions TECHNIP, 1096 p.

Neuendorf, K., Mehl Jr., J., and Jackson, J.A., 2005, *Glossary of Geology*, 5th Edition: Alexandria, Virginia, American Geological Institute, 779 p.

Rudwick, M.J.S., 2008. Worlds Before Adam, University of Chicago Press, 614 p.

Schneer, C.J., 1969, Toward a History of Geology: Cambridge, Massachusetts, M.I.T Press, 469 p.

Taylor, K.L., 2013, A Peculiarly Personal Encyclopedia: What Desmarest's Geographie-Physique tells us about his life and work: Earth Sciences History, vol. 32, no.1, pp. 39-54.

Webster's Revised Unabridged Dictionary, 1913: Springfield, Massachusetts, G. & C. Merriam Company.

Webster's New Collegiate Dictionary, 1981: Springfield, Massachusetts, G. & C. Merriam Company.

## Chapter 3

Chalikakis, M.K., 2006, *Application des méthodes géophysiques pour la reconnaissance et la protection de ressources en eau dans les milieux karstiques* [Geophysical methods applied to water exploration and protection in karst environments] [PhD thesis]: Paris, Université Paris 6., 217 p.

Darcy, H., 1856, The Public Fountains of the City of Dijon [Translated from *Les Fontaines publiques de la ville de Dijon*: Paris, Dalmont, 647 p.

Gèze, B., 1969, *Le Spéléologue Robert de Joly (1887-1968) et son apport à la science des Cavernes*: *Annales de Spéléologie*, Vol. 24, No. 4, p. 619-638.

Huot, J.-J.-N., 1836, *Memoires de la Société d'agriculture de Seine et Oise* [Report to Société d'Agriculture de Seine-et-Oise]: Versailles, Marlin, p. 109-120.

Mangin, A., 1969, *Etude Hydraulique du Mécanisme d'Intermittence de Fontestorbes*: *Annales de Spéléologie*, Vol. 24, no. 2, p. 253-299.

Martel, E.A., 1894, *Les Abîmes*: Paris, Delagrave, 580 p.

Meinzer, O.E., 1927, Plants as Indicators of Ground Water, USGS Water Supply Paper 577: Washington D.C., US Government Printing Office, 95 p.

Mentelle, [E.], and Malte-Brun, [C.], 1803-1812, *Géogr.*, livre VI [probably *Géographie mathématique, physique, et politique de toutes les parties du monde* [Mathematical, physical, and political geography for all parts of the world: Paris, Tardieu and Laporte.

Paramelle, J-P, 1827, *Mémoire hydrologique et géologique sur le département du Lot* [Hydrologic and geologic report on the Department of Lot], handwritten manuscript submitted to the Conseil General of the Department of Lot, transcribed by J. Taisne and T. Pélissié, published by Spéléo-Club de Paris, 2010.

Paramelle, J.-P., 1859, *L'Art de découvrir les sources* [The Art of Finding Springs], 2nd Edition: Paris, Dalmont et Dunod. 428 p.

Peck, R.B, 1969, Advantages and limitations of the Observational Method in Applied Soil Mechanics: Géotechnique 19, No. 2, 171-187. Reprinted in Institute of Civil Engineers, 1996, The Observational method in geotechnical engineering: London, Thomas Telford Publishing, 223 p.

Pluche, abbé N.A., 1732, *Le Spectacle de la Nature, ou Entretiens sur les particularités de l'Histoire naturelle* [The Spectacle of Nature, or Conversations on the particularities of Natural History]*, Entr.* [Discourse] XXI: Paris, Frères Etienne (1764 edition).

Taisne, J., 1986, *L'Abbé Paramelle. Petite histoire d'une statue*: *Grottes et Gouffres*, Bulletin of the Spéléo-Club de Paris, No. 101, September 1986, p. 25-26.

Taisne, J., and Choppy, J., 1987, *Un des premiers hydrogéologues du karst: L'Abbé Paramelle, "Hydroscope"*in Karstologia No. 9, 1987, p. 53-58.

## Chapter 4

Brune, G., 1981, Springs of Texas, Volume 1, 2nd edition: College Station, Texas A&M University Press.

Bureau of Economic Geology Geologic Atlas of Texas Del Rio Sheet, 1977

Collins, E., 2000, Geologic Map of the New Braunfels, Texas, 30 x 60 minute Quadrangle: Bureau of Economic Geology Miscellaneous Map No. 39, Scale 1:100,000, 1 sheet, 28 pages text.

Freeman, V., 1968. Geology of the Comstock-Indian Wells Area Val Verde, Terrell, and Brewster Counties, Texas, USGS Professional Paper 594-K: Washington, D.C., United States Government Printing Office, 26 p.

Hauwert, N.M., 2009, Groundwater Flow and Recharge within the Barton Springs Segment of the Edward Aquifer, Southern Travis and Northern Hays Counties, Texas. [PhD. Thesis] Austin, University of Texas, 328 p.

Kastning, E.H., 1987, Solution-subsidence-collapse in central Texas: Ordovician to Quaternary *in* Barry F. Beck and William L. Wilson, eds., Karst hydrogeology: engineering and environmental applications: Boston, A.A. Balkema, p. 41-45.

Lattman, L.H., and Parizek, R.R., 1964, Relationship between Fracture Traces and the Occurrence of Ground Water in Carbonate Rocks: Journal of Hydrology Vol. 2, No. 2, 1964, p. 73-91.

Paramelle, J.-B., 1856. *L'Art de découvrir les sources* [*The Art of Finding Springs*]: Paris, Victor Dalmont, 376 p.

Texas Natural Resource Information Service (http://tnris.org/data-download/#!/statewide)

Texas Parks and Wildlife Department Springs Database. Lynne Hamlin, personal communication, February 2017.

Texas Water Development Board (www.twdb.texas.gov/groundwater/data/drillsdb.asp)

Texas Water Operators (http://texaswateroperators.com.)

Thomas, R.G., 1972, The geomorphic evolution of the Pecos River system: Baylor Geological Studies Bulletin, No. 22: Waco, Texas, Baylor University, 40 p.

Veni, G., 1991. Draft report: Evolution of the Stockton Plateau, prepared for Intera, Austin, Texas.

White, W.B., 1988, Geomorphology and hydrology of karst terrains: New York, Oxford University Press, 464 p.

Wong, C.M., Williams, C.E., Pittock, J., Collier, U. and Schelle, P., 2007, World's top 10 rivers at risk: Gland Switzerland, WWF International. (wwf.panda.org/about_our_earth/about_freshwater/freshwater_problems/river_decline/10_rivers_risk)

## Chapter 5

Barraqué, B., Chery, L., Margat, J., de Marsily, G., and Rieu, T., (undated), Ground Water in the Southern Member States of the European Union: an assessment of current knowledge and future prospects, Country Report for France, European Academies Science Advisory Council (EASAC).

*Courrier du Gard*, reprinted in the *Journal de l'Ain*, May 7, 1841.

De Marsily, G., 2003, About Darcy's Law: Geological Society of America Abstracts with Programs (Annual Meeting), v. 35, p. 448.

Huot, J.-J.-N., 1836, *Memoires de la Société d'agriculture de Seine et Oise* [Report to Société d'Agriculture de Seine-et-Oise]: Versailles, Marlin, p. 109-120.

Margat, J., Pennequin, D., and Roux, J.-C., 2013, History of French Hydrogeology in Howden, N., and Mather, J., eds., AIH History of Hydrogeology, Boca Raton, CRC Press, p. 59-99.

Martel, E.A., 1894, *Les Abîmes*: Paris, Delagrave, 580 p.

Meinzer, O.E., 1927, Plants as Indicators of Ground Water, USGS Water Supply Paper 577: Washington D.C., US Government Printing Office, 95 p.

Meinzer, O.E., 1934, The history and development of ground-water hydrology: Journal of the Washington Academy of Sciences, Vol. 24, No. 1. p. 6-31.

Renard, Philippe, 2007, Stochastic hydrogeology: What professionals really need?: Ground Water vol. 45, no. 5, p 531-541.

Tixeront, 1956. *Note sur les roles respectifs de Darcy and Paramelle dans la fondation de l'hydrogéologie moderne*. Assoc. Inter. Hydrol. Scienc., Darcy Symposia, Dijon, Sept., Publ IAHS No. 41, T 11, p. 7-9.

# Vita

Patricia Bobeck is a geologist and linguist who holds degrees in French (B.A), Linguistics (M.A.), and Geology, (M.A. and PhD). Her career accomplishments include a master's thesis on Nine Point Mesa, Brewster County, Texas, and fifteen years as a soil and groundwater remediation specialist with Texas environmental agencies. An experienced translator and geologist, she translated French engineer Henry Darcy's 1856 *Public Fountains of the City of Dijon*, for which she won the American Translators Association's 2004 Berger Prize for Excellence in Scientific and Technical Translation. Darcy inspired her to return to the University of Texas at Austin to study hydrogeology and to conduct this study of geologist/hydrogeologist Jean-Baptiste Paramelle, who published his *Art of Finding Springs* in 1856.

Email: pbobeck@gmail.com

This dissertation was typed by the author.