GEOLOGICAL CIRCULAR 76 - 7

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ENVIRONMENTAL CONCERNS ARISING FROM THE PRODUCTION AND DISPOSAL OF GEOTHERMAL WATERS

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GEOTHERMAL RESOURCES OF THE TEXAS GULF COAST—ENVIRONMENTAL CONCERNS ARISING FROM THE PRODUCTION AND DISPOSAL OF GEOTHERMAL WATERS

by
Thomas C. Gustavson
Charles W. Kreitler

ABSTRACT

Disposal and temporary surface storage of spent geothermal fluids and surface subsidence and faulting are the major environmental problems that could arise from geopressured geothermal water production. Geopressured geothermal fluids are moderately to highly saline (8,000 to 72,000 parts per million total dissolved solids) and may contain significant amounts of boron (19 to 42 parts per million). Disposal of hot saline geothermal water in subsurface saline aquifers will present the least hazard to the environment. It is not known, however, whether the disposal of as much as 54,000 m^3 (310,000 barrels) of spent fluids per day into saline aquifers at the production site is technically or economically feasible. If saline aquifers adequate for fluid disposal cannot be found, geothermal fluids may have to be disposed of by open watercourses, canals, and pipelines to coastal bays on the Gulf of Mexico. Overland flow or temporary storage of geothermal fluids may cause negative environmental impacts.

As the result of production of large volumes of geothermal fluid, reservoir pressure declines may cause compaction of sediments within and adjacent to the reservoir. The amount of compaction depends on pressure decline, reservoir thickness, and reservoir compressibility. At present, these parameters can only be estimated. Reservoir compaction may be translated in part to surface subsidence. When differential compaction occurs across a subsurface fault, fault activation may occur and be manifested as differential subsidence across the surface trace of the fault or as an actual rupture of the land surface.

The magnitude of environmental impact of subsidence and fault activation varies with current land use; the greatest impact would occur in urban areas, whereas relatively minor impacts would occur in rural, undeveloped agricultural areas.

Geothermal resource production facilities on the Gulf Coast of Texas could be subject to a series of natural hazards: (1) hurricane- or storm-induced flooding, (2) winds from tropical storms, (3) coastal erosion, or (4) expansive soils. None of these hazards is generated by geothermal resource production, but each has potential for damaging geothermal production and disposal facilities that could, in turn, result in leakage of hot saline geothermal fluids.

INTRODUCTION

Data from oil and gas wells in the Cenozoic sediments of the Gulf Coast indicate that waters of abnormally high temperature occur below the top of the geopressured zone. This zone, one of abnormally high pore-fluid pressure, occurs at depths at which fluids contained within incompletely compacted and dewatered sediments support some of the weight of the rock overburden. In the Texas Gulf Coast, the depth of the geopressured zone increases with the age of the sediments. Geopressured Frio Formation sediments usually occur at depths of 2 km (6,600 ft) or more, whereas geopressured Pleistocene sediments on the Continental Shelf occur at depths of approximately 1 km (3,300 ft).

Dissipation of heat at the Earth's surface occurs at a mean rate of 1.5 microcalories per square centimeter per second (μ cal/cm^2/sec). Heat dissipation has resulted in a geothermal gradient in the Earth's surficial rocks such that mean rock temperature increases approximately 25°C (77°F) per kilometer of depth. Where the insulating properties of rocks at depth are high, the geothermal gradient increases markedly. The undercompacted or geopressured zones of the Gulf Coast apparently act as effective heat insulators slowing the dissipation of heat to the surface (Jones, 1969; Lewis and Rosi, 1969). As a result, rock and pore water below the top of the geopressured zone usually have high temperatures, locally exceeding 288°C (520°F).

The Frio Formation is the youngest of three formations on the Texas Gulf Coast—Wilcox, Vicksburg, and Frio—that are currently being investigated for geothermal energy. Bebout and others (1975a, 1975b) have identified several areas along the Gulf Coast where thick, laterally extensive sands containing water with temperatures of 149°C (300°F) or more occur within the geopressured zone of the Frio Formation (fig. 1). Hot water produced from these geothermal sources has considerable potential energy stored as heat, a portion of which could be converted to electrical energy.

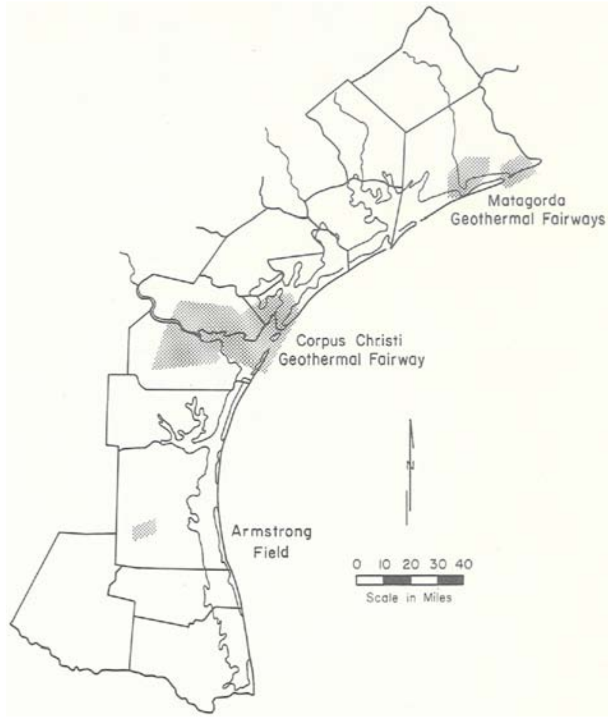

Fig. 1. Location of geothermal fairways along the southern Gulf Coast of Texas.

This report is an attempt to foresee general environmental concerns that will arise during exploration for and development of geopressured geothermal resources on the Texas Gulf Coast (fig. 1). Disposal of hot saline water and potential subsidence and faulting of the land surface that may result from geopressured geothermal water production are the principal concerns and have been recognized as such by others (Herrin and Goforth, 1975; Papadopulos, 1975; Moseley, 1975). This report provides a preliminary evaluation of these and other potential environmental effects and suggests studies to evaluate them.

GEOTHERMAL FLUID DISPOSAL

Selection of disposal sites and methods of disposal for the enormous volumes of hot saline water that will result from geothermal production are two of the most perplexing problems that have arisen in the planning for geothermal resource development. Commercially viable generating facilities will have to be supplied by 5 to 10 wells, each capable of producing 3.8 m^3 per minute (1,000 gallons) or about 5,500 m^3 (34,000 barrels (bbls)) per day (approximately 170,000 to 340,000 bbls per day for a single generating facility). Although geothermal waters may be used by other industries for other purposes after passing through the generating facility, the problem of disposal is not lessened. The responsibility for disposal is simply transferred to others.

Questions requiring immediate answers include: (1) What are the physiochemical characteristics of geopressured fluids? (2) What are the characteristics of the environment that will be in contact with geothermal fluids through their disposal, storage, or transportation? and (3) What is the regulatory framework in which disposal must be considered?

Physiochemical Characteristics of Geothermal Fluids

Water Chemistry.—Using interpretations of electrical logs, Dorfman and Kehle (1974) suggest that salinities of geothermal reservoirs are comparatively fresh (total dissolved solids (TDS) < 5,000 parts per million (ppm)) and could be used for irrigation and general use with minor desalination treatment. Dorfman and Kehle (1974) reasoned that diagenetic changes of montmorillonite to illite in deep Gulf Coast sediments allow as much as 15 percent of the water contained in the muds to be expelled as fresh water, thus decreasing the salinity of adjacent sandy aquifers.

More recently, analyses of water samples from below the top of the geopressured zone have become available for 9 wells throughout Aransas, Nueces, Refugio, and San Patricio Counties and for 15 wells in Kenedy County (Taylor, 1975). For the samples from Aransas, Nueces, Refugio, and San Patricio Counties, TDS range from a minimum of 8,000 ppm to a maximum of 72,000 ppm (fig. 2). Chloride concentration ranges from 3,500 to 46,000 ppm and sodium-plus-potassium concentration ranges from 2,000 to 20,000 ppm. For the samples from Kenedy County, TDS ranges from 18,000 to 40,000 ppm (fig. 3). For these same waters, the pH varies from 4.9 to 10. If these water samples, all taken within 1 km (3,500 ft) of the top of the geopressured zone (figs. 4 and 5), are representative of geothermal fluid salinities within the geopressured zone, then produced geothermal waters will vary from moderately saline waters to brines.

Water samples from two wells in the geopressured Chapman Ranch field, south of Corpus Christi, Texas, were analyzed for major and minor chemical constituents. Formation waters were sampled at a depth of 3,350 m (11,000 ft); pore pressures were 668 kg/cm^2 (9,500 psi). The samples are classified as NaCl waters with TDS of approximately 40,000 milligrams per liter (mg/l) (table 1). Semiquantitative spectrographic analyses of these geopressured waters show boron concentrations ranging from 19 to 42 mg/l. These concentrations are similar to those found by Collins (1975) for Tertiary Formation waters from Louisiana. If high boron concentrations are characteristic of geopressured waters throughout the Texas Coast, then this constituent alone will prevent their use in irrigation and may prevent their disposal into marine waters. Even the most boron-tolerant plants need irrigation waters with less than 3.8 mg/l boron (Richards, 1954).

Trace quantities of aluminum, beryllium, copper, and iron were found in the Chapman Ranch geopressured waters. Table 2 shows the elements analyzed and their individual detection limits. Detection limits have been derived by multiplying the percent of sensitivity in a sodium-potassium matrix times residual on evaporation (ROE) (Harvey, 1964, table 2, p. 58).

In Louisiana, geopressured waters of the Manchester field are moderately saline (16,000 to 26,000 mg/l TDS), but less saline than overlying normally pressured waters (600 to 180,000 mg/l TDS) (Schmidt, 1973). In Hidalgo County in South Texas, the average salinity for a geopressured reservoir is about 25,000 mg/l TDS (Papadopulos, 1975).

Geothermal Fluid Temperatures.—The temperature distribution of fluids within the geopressured zone is imprecisely known. Data are usually limited to a single bottom-hole temperature for each well. Isothermal maps of the middle and southern Gulf Coast (Bebout and others, 1975a, 1975b) are generally conservative because of the common practice of well-bore cooling, or even icing, prior to logging to protect temperature-sensitive electronic components of electrical logging sondes. Reported fluid temperatures in geothermal fairways, nevertheless, are locally in excess of 149°C (300°F). Maximum recorded bottom-hole temperatures of the Texas Gulf Coast exceed 288°C (520°F).

Geothermal fluids will probably lose only a moderate amount of heat energy while passing through the generating facility. They will probably retain temperatures of at least 100°C (212°F) when the process of wastewater disposal begins.

Physiochemical Properties of Surface Water

In the processes of developing geothermal resources, contamination of fresh water by hot saline geothermal fluids must be prevented. In order to recognize the distribution of fresh-water resources, maps of the distribution of surface water, lakes or ponds, sloughs, drainage or irrigation ditches or canals, and artificial reservoirs were compiled for the Armstrong field in Kenedy County and for the Matagorda County and Corpus Christi fairways (figs. 5, 6, and 7). The major fresh-water streams are the Nueces River, Oso Creek, and Chiltipin Creek in the Corpus Christi area and the Colorado River and Big Boggy Creek in Matagorda County. The lower reaches of these streams and other minor streams may be influ-

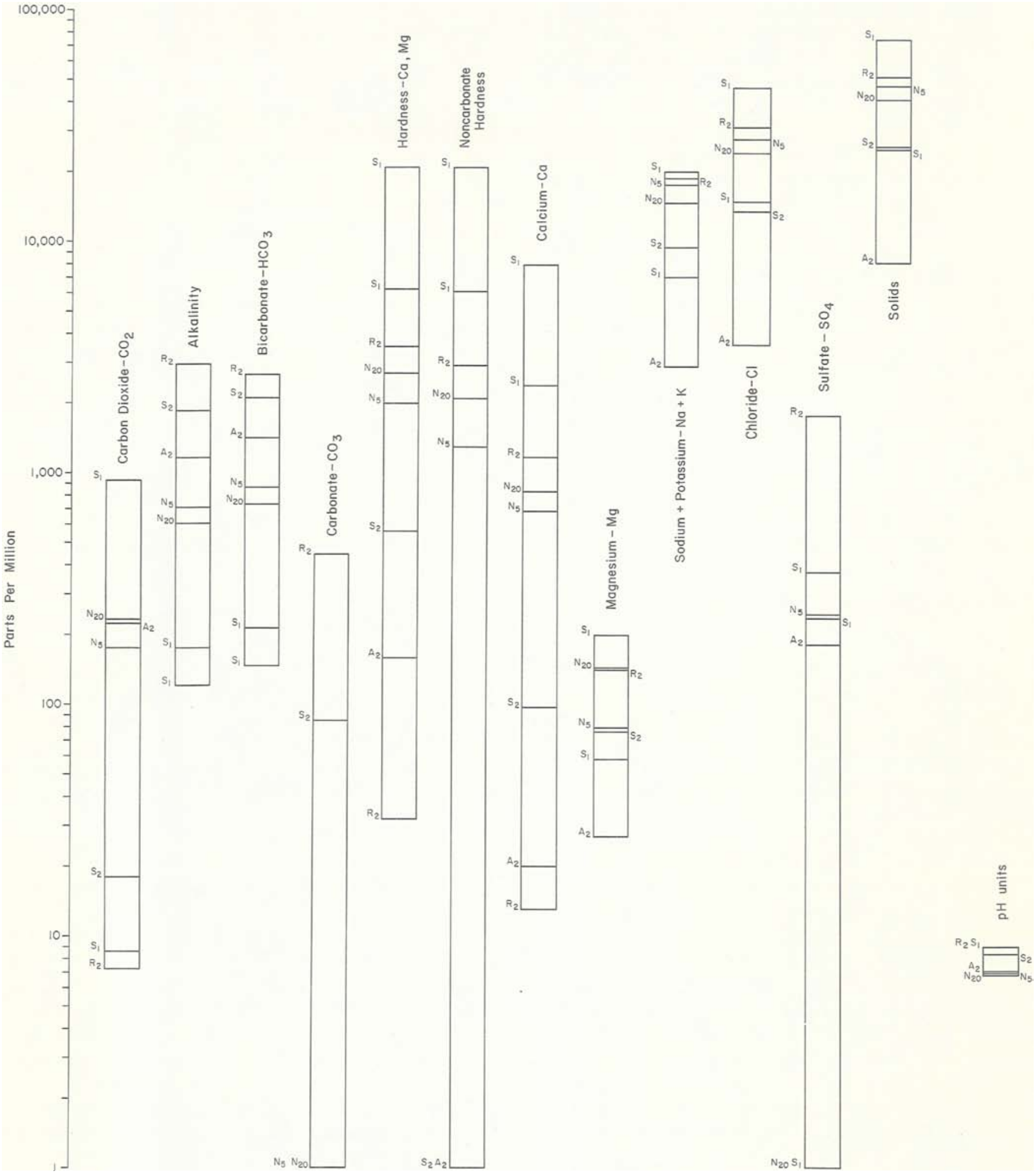

Fig. 2. Analyses of water from within the geopressured zone, Aransas (A), Nueces (N), Refugio (R), and San Patricio Counties (S) (Taylor, 1975). (See figure 4 for location.)

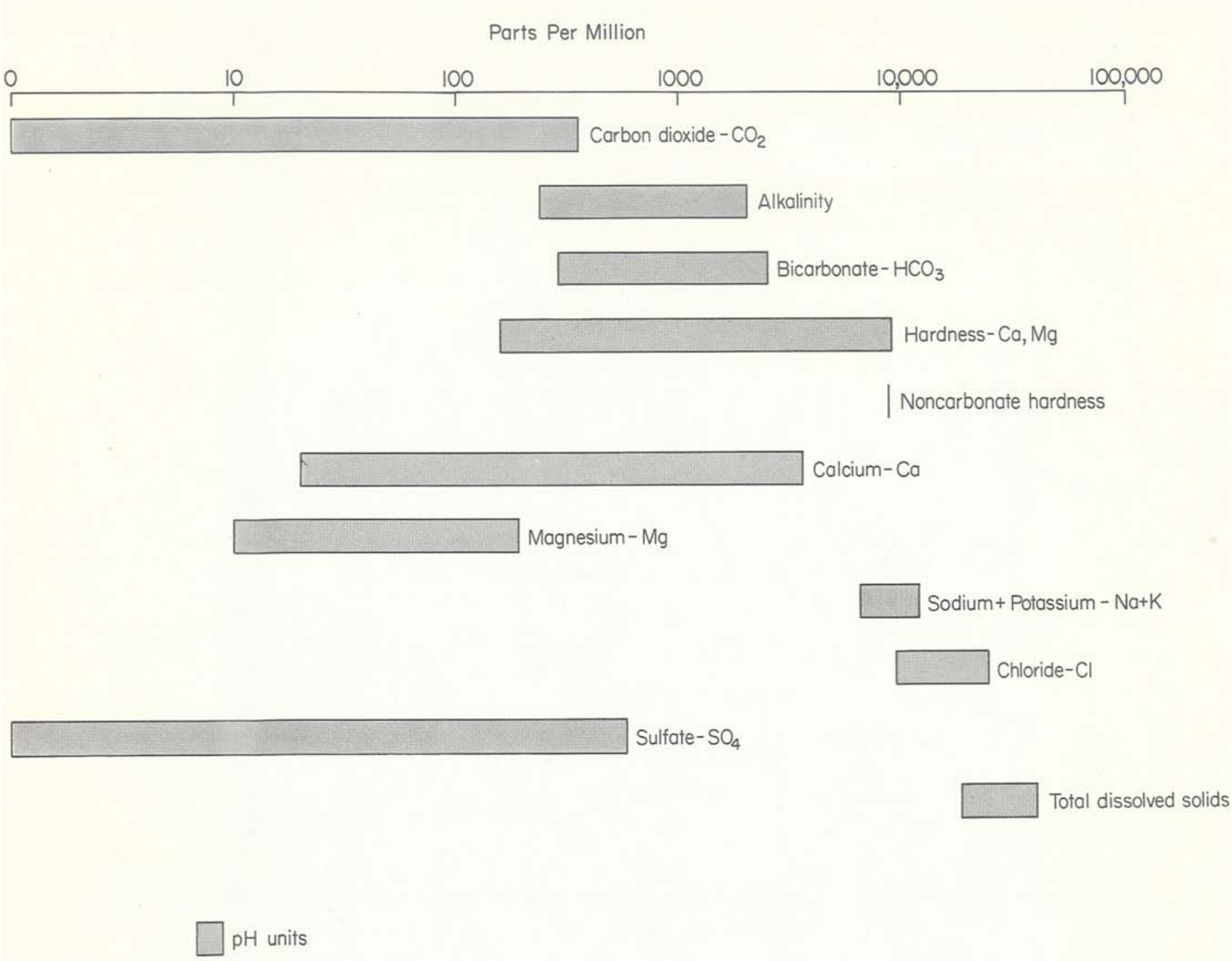

Fig. 3. Analyses of water from within the geopressured zone, Kenedy County (Taylor, 1975). (See figure 6 for location.)

enced by wind or astronomical tides resulting in fluctuations in salinity.

Water analyses and discharge rates from the Nueces River, Oso Creek, and the Colorado River (U. S. Geological Survey, 1974) indicate that these waters are usable for irrigation and that the water of the Nueces River is suitable for human consumption after treatment. Total dissolved solids are usually less than 500 ppm for the Nueces River and less than 300 ppm for the Colorado River.

Disposal of saline oil field waters has polluted surface waters in several areas of the Texas Coastal Zone. Chiltipin Creek lies east of the Nueces River and drains a small basin into Copano Bay (fig. 7). Creek waters contain high concentrations of calcium, magnesium, sodium, and chlorine ions, with TDS as high as 39,000 ppm (fig. 8). Salinities of the creek waters vary inversely with discharge and thus are high during periods of low discharge and low during periods of high discharge; rainwater dilutes the salt concentration of waters that are apparently percolating into the stream. The pollutants in Chiltipin Creek are attributed to salt-water disposal associated with petroleum production. Sulfate content is consistently low, whereas the chloride content fluctuates inversely

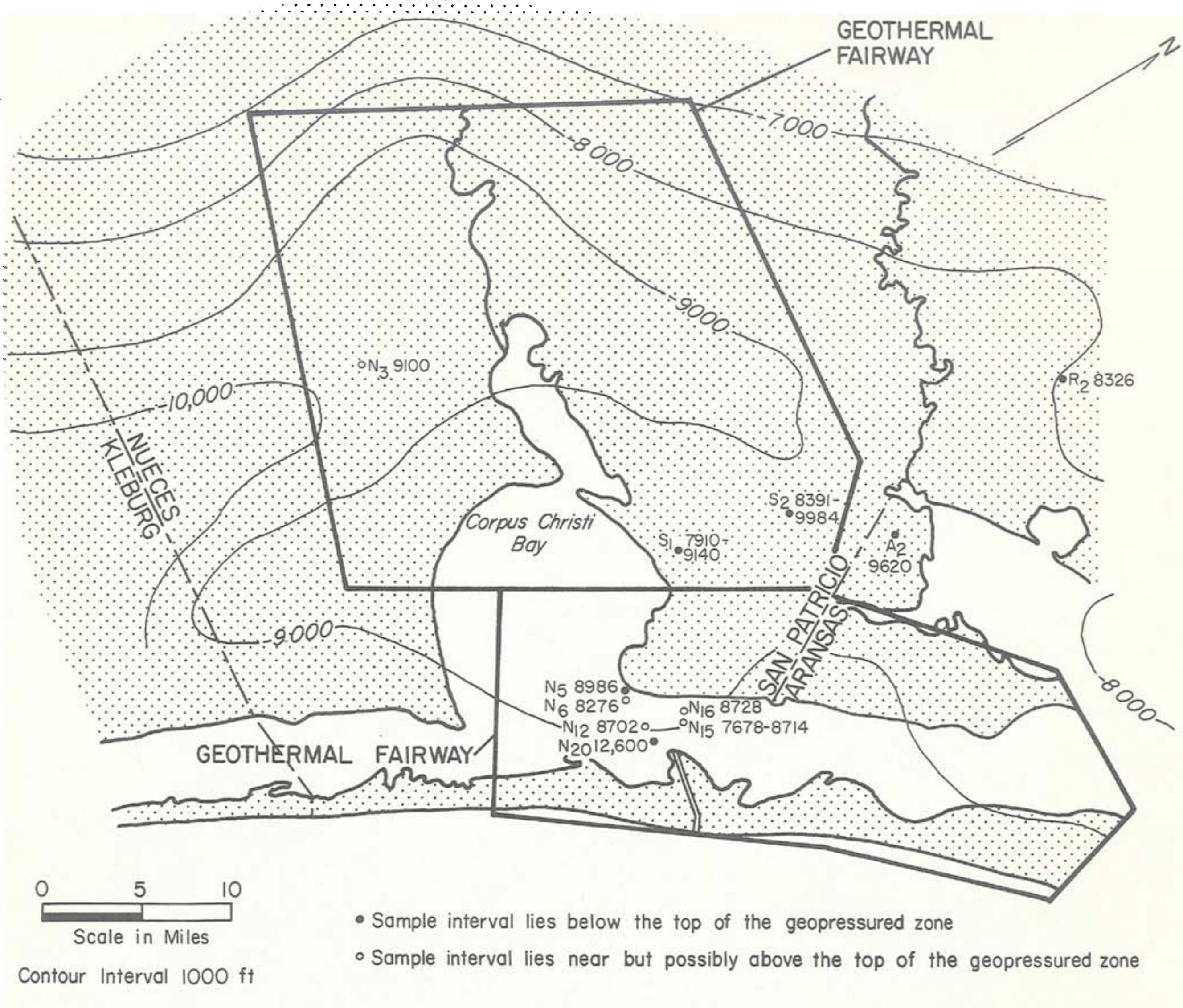

Fig. 4. Structure contour map of the top of the geopressured zone, Corpus Christi area, with locations and depths of water analyses (after Bebout and others, 1975a; 1975b).

with discharge, suggesting that the sulfate content is a natural product of the basin soils and that chloride content is a contaminant (Shafer, 1968). The only recognizable source of chloride ion is abandoned salt-water evaporation pits that lie in the Chiltipin Creek drainage basin. Although the use of evaporation pits to dispose of salt water has been disallowed by the Texas Water Quality Board since January 1, 1969, water pollution has continued for 6 years since the pits were abandoned.

Other incidences of pollution of shallow ground water and streams from salt-water evaporation pits have been observed in Matagorda County (Hammond, 1969) and in the Hamlin, Texas, area (William A. Trippet II, personal communication, 1975). The material lining these pits did not prevent percolation of large volumes of salt water into the substrate.

Disposal Areas

The Gulf of Mexico, coastal bays, estuaries or lagoons, and saline aquifers are potential sites for disposal of hot saline water. The major environmental concerns in these areas are the effects of temperature and salinity of produced waters on

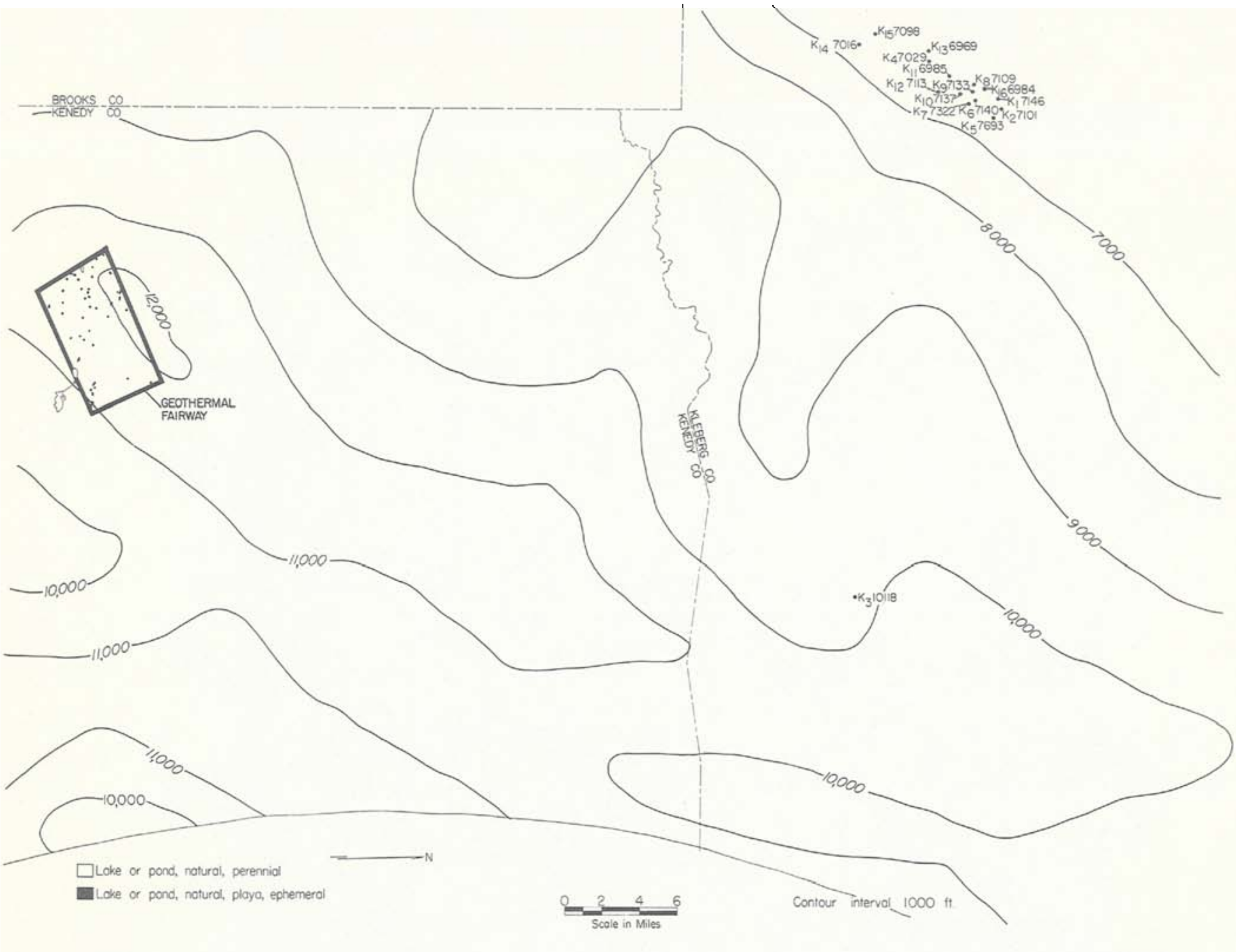

Fig. 5. Structure contour map of the top of the geopressured zone, natural water systems of the Armstrong fairway, and locations and depths of water analyses, Kenedy County (compiled from Bebout, 1975b, and Brown and other, in press).

surface-water bodies. The salinity of the geothermal waters will probably approach that of normal seawater, although it is possible that salinity will be substantially less.

Coastal Bays, Estuaries, and the Gulf of Mexico.—The salinity of produced geothermal waters does not preclude their disposal into marine waters of the Gulf of Mexico or into certain coastal waters. Coastal waters are characterized by highly variable salinities, ranging from fresh water to hypersaline (Parker, 1960; Brown and others, 1976; Brown and others, in press; McGowen and others, 1976). If saline fluids were adequately mixed in coastal water, they would have little effect on the overall salinity of the bays, lagoons, or estuaries because of the vastly greater volume of bay, lagoon, or estuarine water. Furthermore, periodic freshening of bays and estuaries by flood waters would not be significantly diminished by geothermal fluid disposal.

The temperature of geothermal waters will probably be greater than 95°C (200°F) when discharged from the generating facility. These waters will require extensive cooling if they are to be disposed of into coastal waters or the Gulf of Mexico (Texas Water Quality Board, 1975). If geothermal waters are cooled to temperatures such that the maximum temperatures and temperature differentials attributable to the heated effluent remain within the regulatory guidelines, then

Table 1. Chemical analyses of geopressured waters from Chapman Ranch field, Corpus Christi, Texas.

Major Constituent	Well: W. F. Lehman No. 1[a]	Well: Lehman Gas Unit No. 1[a]
	Concentration (mg/l)	
HCO_3^-	526	581
Cl^-	25,000	21,000
SO_4^{--}	30	30
Na^+	16,000	14,000
K^+	230	150
Ca^{++}	71	52
Mg^{++}	90	110
SiO^2	68	71
ROE[b]	42,000	38,000
epm[c] balance (cation)/(anion)	0.997	1.025
Temperature (°C)	43	29
pH	6.3	6.5

[a]Sample from portable separator at well head.

[b]Residual on evaporation.

[c]Equivalent parts per million.

environmental impact will be minimized. South Texas river, bay, estuarine, and Gulf waters are characteristically warm during the summer months. Surface-water temperatures can reach 43°C (111°F) in Laguna Madre and 35°C (95°F) in bays, lagoons, and estuaries (Parker, 1960). Natural temperatures of these waters equal or exceed the maximum ambient temperature, 32°C (90°F), suggested by the National Technical Advisory Committee for water-quality standards. Natural temperatures also equal or exceed the maximum ambient temperature, 35°C (95°F), suggested by the Texas Water Quality Board for tidal river reaches and bay and Gulf waters. High ambient air temperatures such as those occurring in the Corpus Christi fairway, which has a mean maximum July air temperature of 34.5°C (94°F) (Dallas Morning News, 1974), will increase the difficulty of cooling saline geothermal waters during summer months. High ambient temperatures for coastal waters, at times already exceeding maximum temperatures suggested by regulatory agencies, will make disposal of hot saline fluids into coastal waters difficult unless they have been cooled to 35°C (95°F) or less.

Saline Aquifers.—The Railroad Commission of Texas permits well operators to dispose of saline water by injection into formations that contain mineralized water unfit for agricultural or general use and that do not contain oil, gas, or geothermal resources. Injection of spent geothermal fluids into saline aquifers is, in theory, the ideal method of salt-water disposal. This method limits environmental hazards to the immediate areas of the geothermal wells, injection wells, and generating facility. As long as the geothermal fluids are

Table 2. Semiquantitative spectrophotometric analyses of evaporation residual.

Element	Concentration Range[a] (mg/l)		Lower Level of Detection (mg/l)	
	W. F. Lehman No. 1[c]	Lehman Gas Unit No. 1[c]	W. F. Lehman No. 1	Lehman Gas Unit No. 1
Beryllium	0.13 to 0.26	0.11 to 0.22	0.013	0.011
Bismuth	ND[d]	ND	.34	.30
Boron	25 to 42	19 to 38	1.3	1.1
Cadmium	ND	ND	21.0	19.0
Chromium	ND	ND	.021	.019
Cobalt	ND	ND	.13	.11
Copper	0.17 to 0.38	0.11 to 930	.034	.030
Gallium	ND	ND	.084	.076
Iron	8.4 to 16.8	2.7 to 3.8	.25	.23
Lead	ND	ND	.84	.76
Manganese	ND	ND	.63	.57
Molybdenum	ND	ND	.13	.11
Nickel	ND	ND	.13	.11
Silver	ND	ND	.042	.038
Strontium	126 to 252	38 to 72	.042	.038
Tin	ND	ND	.63	.57
Titanium	ND	ND	1.3	.1
Vanadium	ND	ND	.21	.19
Zirconium	ND	ND	.29	.27

[a]Concentration range calculated from weight percent of ROE.

[b]Lower level of detection calculated from percent sensitivity in sodium potassium matrix. (Harvey, 1964, table 2, p. 58) in ROE.

[c]Sample from portable separator at well head. Samples acidized with concentrated HNO_3.

[d]Not detectable.

adequately contained and insulated, hazards to plant and animal life would be minimal.

Although the geometry and occurrence of sand bodies in the relatively shallow subsurface of the Texas Coast is well known, their suitability as disposal sites for large volumes of spent geothermal fluids is not completely understood. Apparently the shallowest thick and laterally extensive sand that might be suitable to accept large volumes of spent geothermal fluids is the basal Miocene sand that lies above the Anahuac Shale. In the geothermal fairways the depth to this unit exceeds 5,000 ft. In the Coastal Zone, the depth to the base of fresh ($<$ 1000 ppm TDS) to slightly saline ($<$ 3000 ppm TDS) ground water is relatively shallow (figs. 9, 10, and 11). The interbedded sands and shales between the basal Miocene Sand and the base of the fresh to slightly saline ground-water zone are probably sufficiently thick to prevent contamination of shallow ground water by geothermal fluids.

In 1961, 93 percent or approximately 2,381,000 m^3 (15,000,000 bbls) of saline oil field waters produced in Matagorda County was

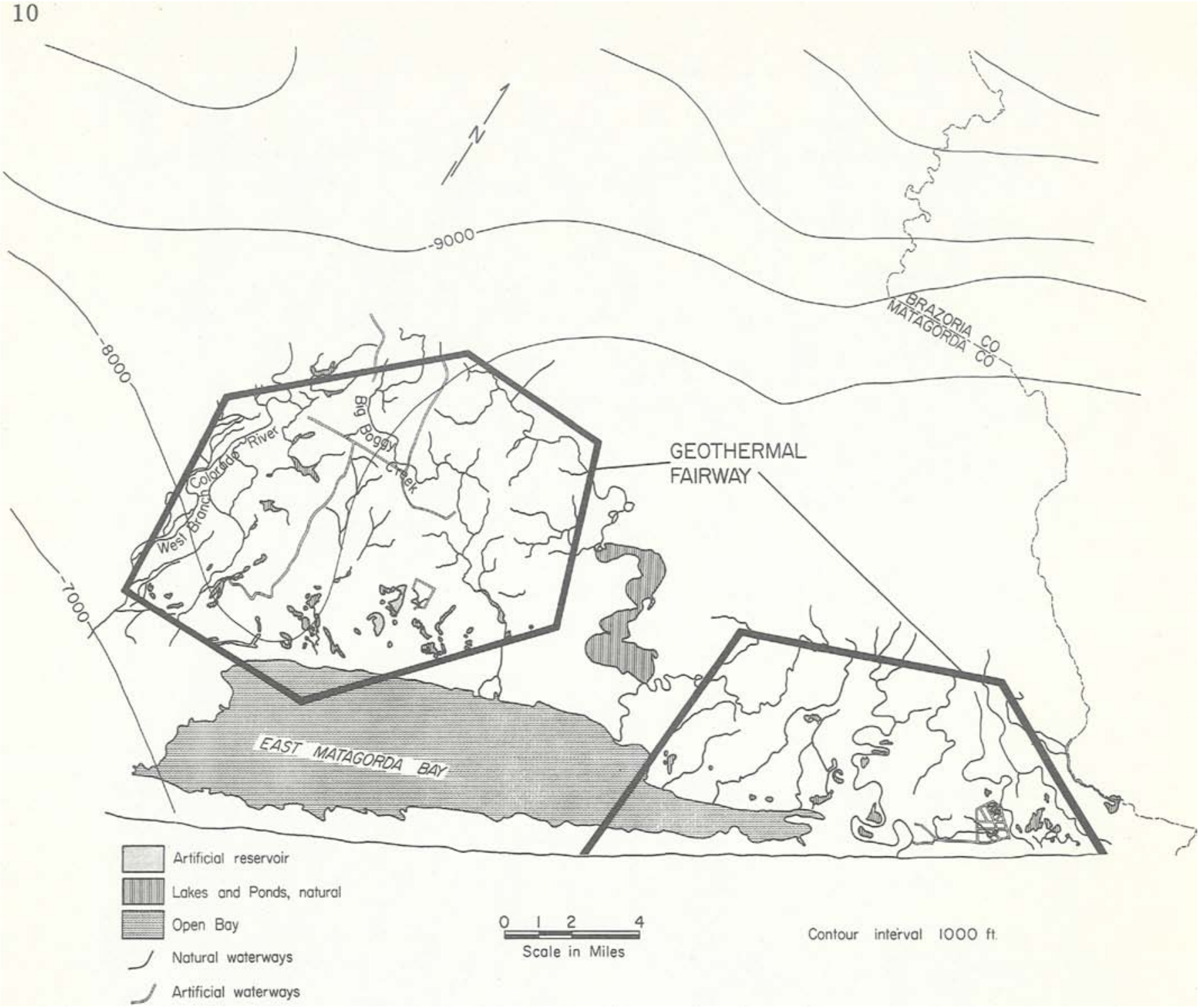

Fig. 6. Structure contour map of the top of the geopressured zone and surface-water systems, Matagorda County fairways (compiled from Bebout and others, 1975a, and McGowen and others, 1976).

disposed of by deep subsurface injection wells (Hammond, 1969). This is approximately the projected monthly production for a single geothermal electrical generating site. Injection zones for 43 wells in the county ranged from 451.2 m to 2,165.3 m (1,480 to 7,102 ft) below land surface with injection pressures ranging from 0 (gravity flow) to 70.4 kg/cm^2 (1,000 psi). Of these wells, only two have high rates of disposal: one at a rate of 952.4 m^3 (6,000 bbls) per day under a surface pressure of 56.3 kg/cm^2 (800 psi) and another at 1,587.3 m^3 (10,000 bbls) per day under a surface pressure of 21.1 kg/cm^2 (300 psi). Many of the injection wells require high surface pressures to dispose of relatively small volumes of water. For example, the no. 1 J. B. Beld injection well (Hammond, 1969) requires surface pressures of 56.3 kg/m^3 (800 psi) to dispose of only 23.8 m^3 (150 bbls) per day. The limited data that are available regarding rates of injection and the surface pressures required for injection suggest that the capacity of formations to take up disposed fluids is highly variable. Most disposal rates are usually less than 158.7 m^3 (1,000 bbls) per day even though surface pumping pressures range upward to 70.4 kg/cm^2 (1,000 psi). At disposal rates of 1,587.3 m^3 (10,000 bbls) per day, the highest reported disposal rate, 20 to 40 disposal wells per generating site will be needed.

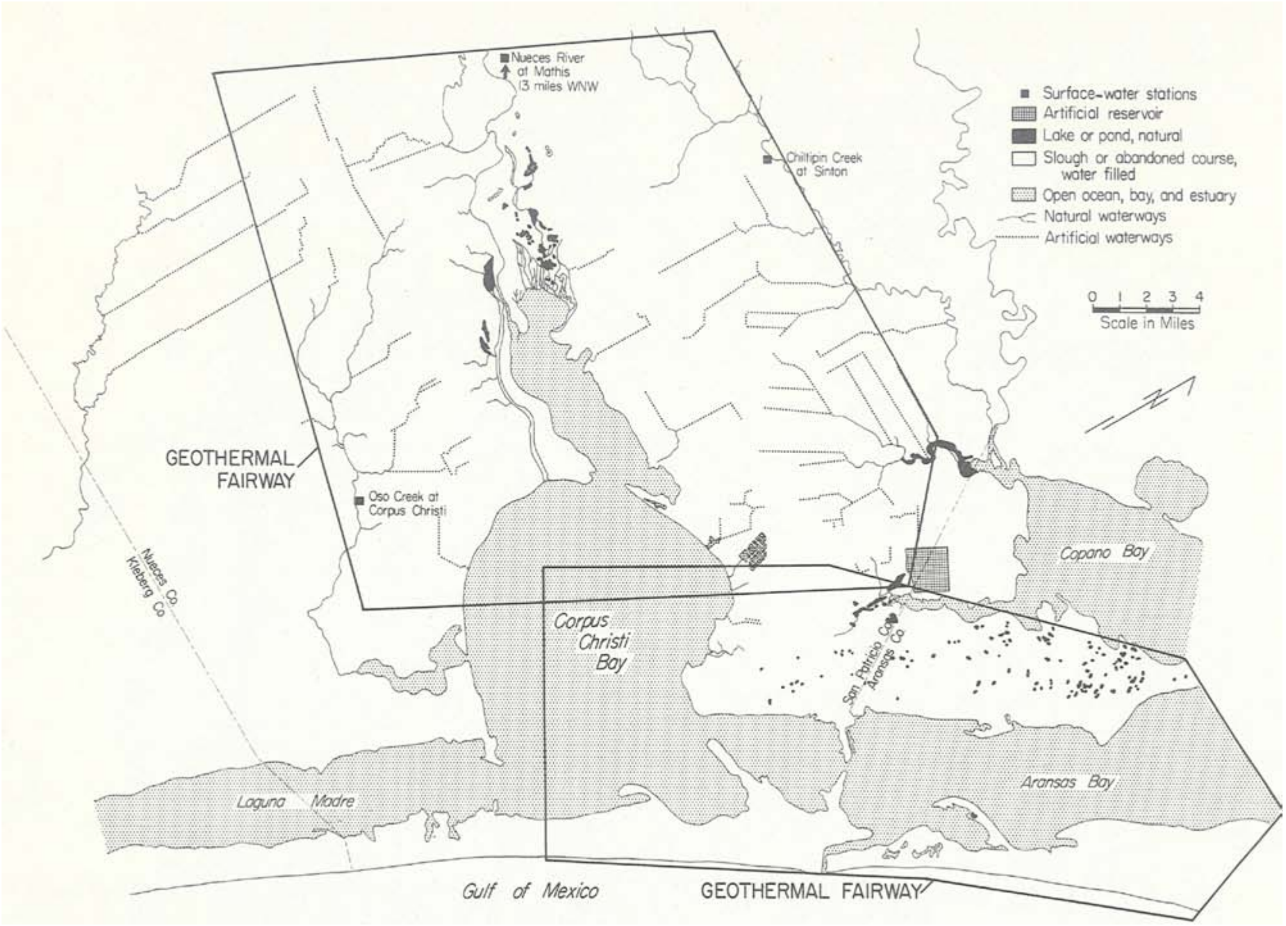

Fig. 7. Surface-water systems (compiled from Brown and others, 1976) and surface-water sample stations.

Fluid Transport Mechanisms—Surface Storage

The production of large volumes of hot saline fluids requires transportation and storage prior to disposal. Pipelines, open canals, or natural watercourses could be used to transport fluids to disposal sites. (See Railroad Commission of Texas rule 8C1c.) If fluids are reinjected, piping to the disposal wells from the generating facility will minimize environmental impact.

Transport in canals, pipelines, or natural watercourses (figs. 5 and 7) may be desirable if fluids are to be disposed of offshore or in bays, lagoons, or estuaries. Mechanisms that will enhance natural cooling can be built into the channel system, such as systems of baffles or devices to increase turbulence and mixing. Open-channel flow, however, increases markedly the possibility of environmental problems. Channels, whether they are canals or natural watercourses, will have to be lined and sealed with impervious material to prevent leakage of saline water into the surface sands and alluvium that are recharge areas for shallow aquifers (figs. 12, 13, and 14).[1] For the same reason, temporary storage pits and pits to retain accidental spills in the production and generating areas must also be lined and sealed with impervious material. The effectiveness of seals used in the past is questionable. Ground water, apparently contaminated by salts derived from old evaporation pits, is still draining into Chiltipin Creek 6 years after salt-water evaporation pits were abandoned.

[1]The simplified environmental maps in figures 12, 13, and 14 are derived from the Environmental Geologic Atlas of the Texas Coastal Zone. These regional maps are designed to show broad areas where environmental impacts from geothermal resource development could occur:

1. Pollution of fresh surface-water and ground-water resources could occur in units designated as fresh-water bodies, recharge areas, and dunes or eolian material.
2. Unique environments such as marshes, swamps, grassflats, and oyster reefs could be destroyed or damaged by an influx of geothermal fluids.

Damage or destruction of biota and soils could occur anywhere in the area as a result of contact with geopressured geothermal fluids.

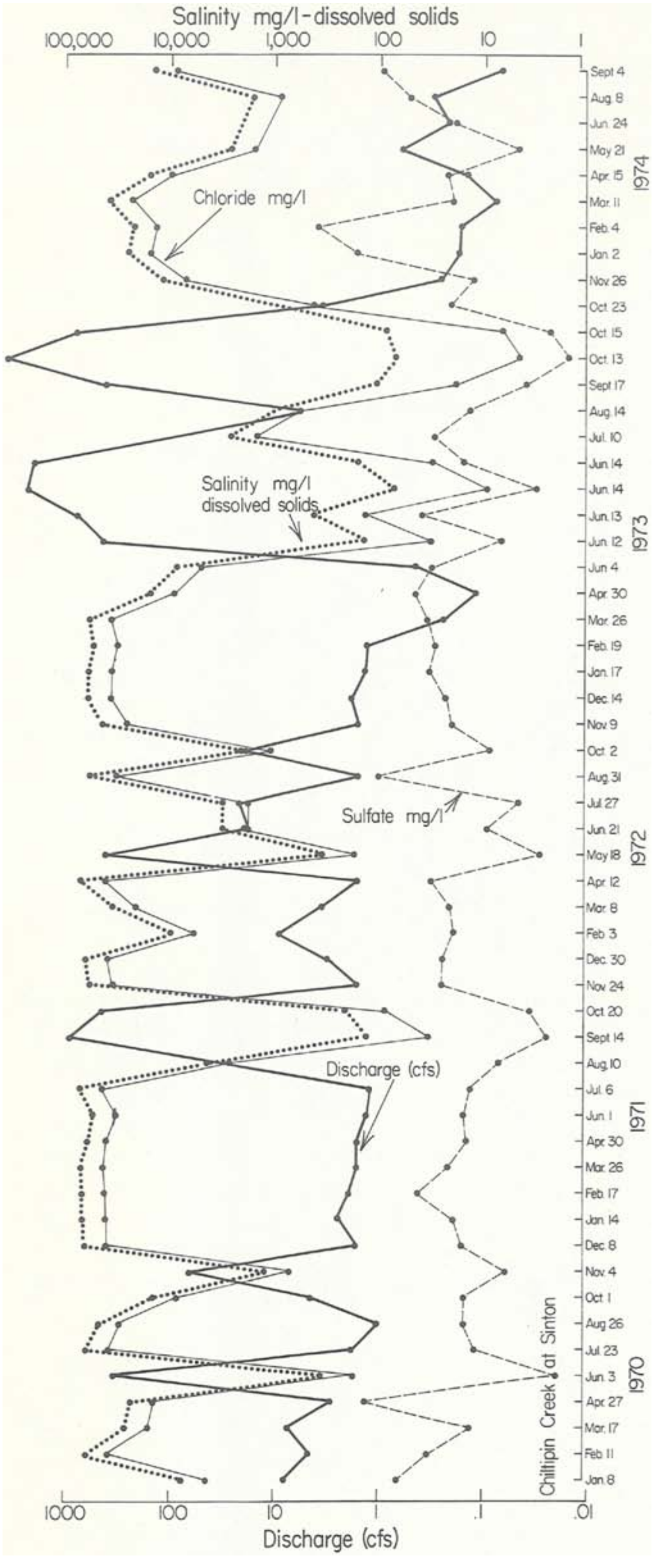

Fig. 8. Total dissolved solids, chloride, sulfate, and discharge curves for Chiltipin Creek at Sinton, Texas, from January 1970 to September 1974 (U. S. Geol. Survey, 1970b, 1971, 1972, 1973, 1974).

Additional problems that will arise from the use of an open channel to transport geothermal fluids are the effects on wildlife and plants. Plant and animal life that cannot tolerate salt water will probably die out in the immediate vicinity of channels. They could be replaced by salt-tolerant species, perhaps some of the same species that presently occur along tidal channels or marshes of the Texas Coast. Because of the high temperature of the fluids, watercourses transporting geothermal fluids would probably contain neither plant nor animal life, with the possible exception of salt- and temperature-tolerant algae. The channels will be relatively narrow, but they will form an effective barrier to wildlife. Wildlife, especially smaller species, will probably not attempt to cross through the hot water carried in the open channels. If geothermal fluids are put into natural streams they will be diluted, but their environmental impact may not be diminished.

Regulations Governing the Production and Disposal of Saline and/or Geothermal Fluids

Several State and Federal agencies, including the Railroad Commission of Texas, the Texas Water Quality Board, the Texas Air Control Board, the Texas Water Development Board, and the Environmental Protection Agency, have regulatory responsibilities that will directly or indirectly influence development of both a geothermal test well and, subsequently, a geothermal energy production/generation facility. Only those regulations that affect the production and disposal of saline water will be considered here. The Texas Air Control Board is charged under the amended Texas Clean Air Act of 1967 with safeguarding the "air resources of the State from pollution by controlling or abating air pollution and emissions of contaminants . . ." (Texas Legislature, 1967). At this time, it is not known if geothermal fluids will contain potential air pollutants. The two most likely air pollutants will be volatile carbon compounds and hydrogen sulphide resulting from the production of gas that is expected to occur with geothermal fluids.

The primary environmental concern of the Railroad Commission and the Texas Water Quality Board with respect to geothermal development is the impact of the disposal of hot saline geothermal fluids. The Railroad Commission of Texas (1975)

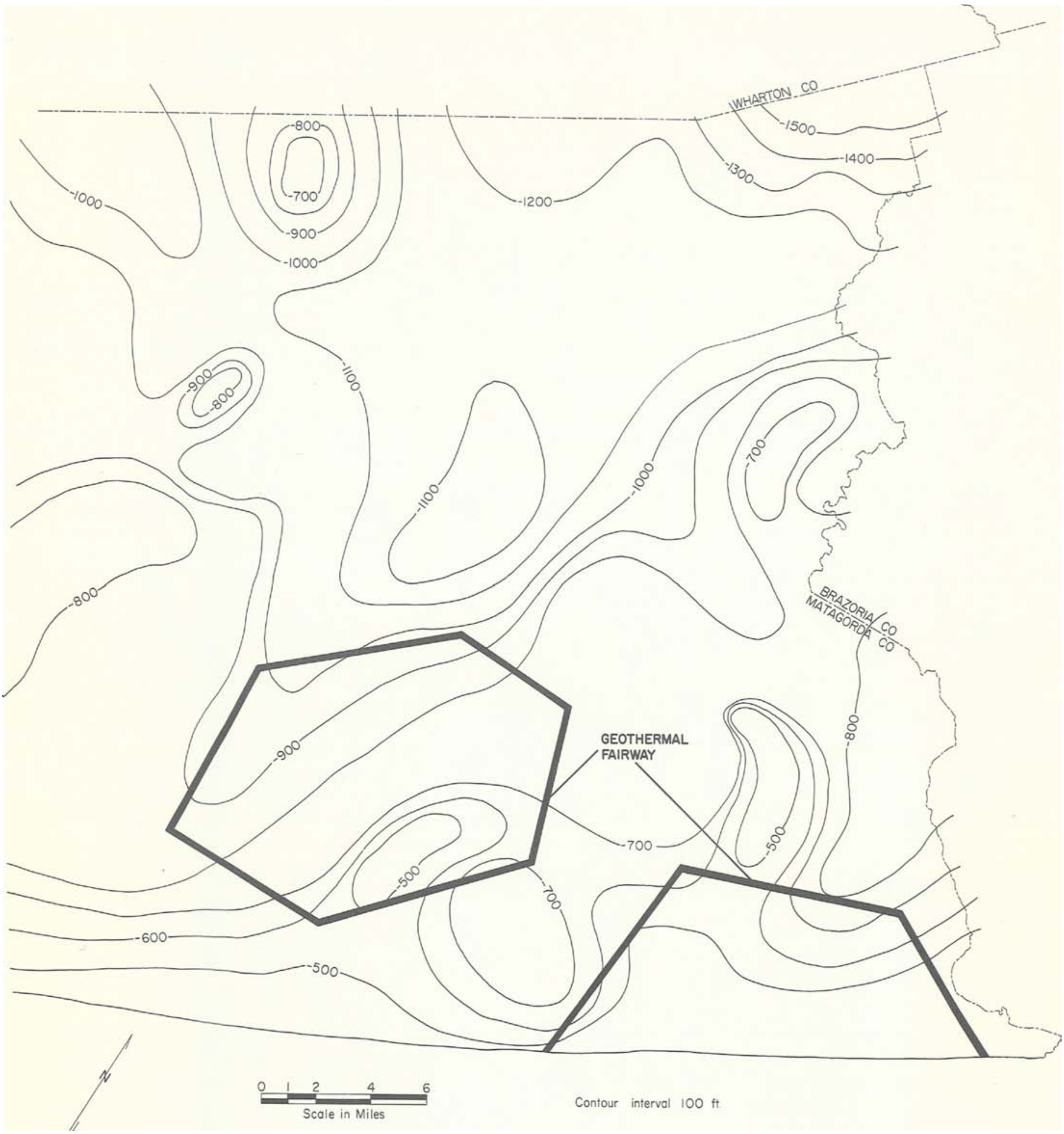

Fig. 9. Structure contour map of the base of fresh water (< 1,000 ppm TDS) (compiled from Hammond, 1969).

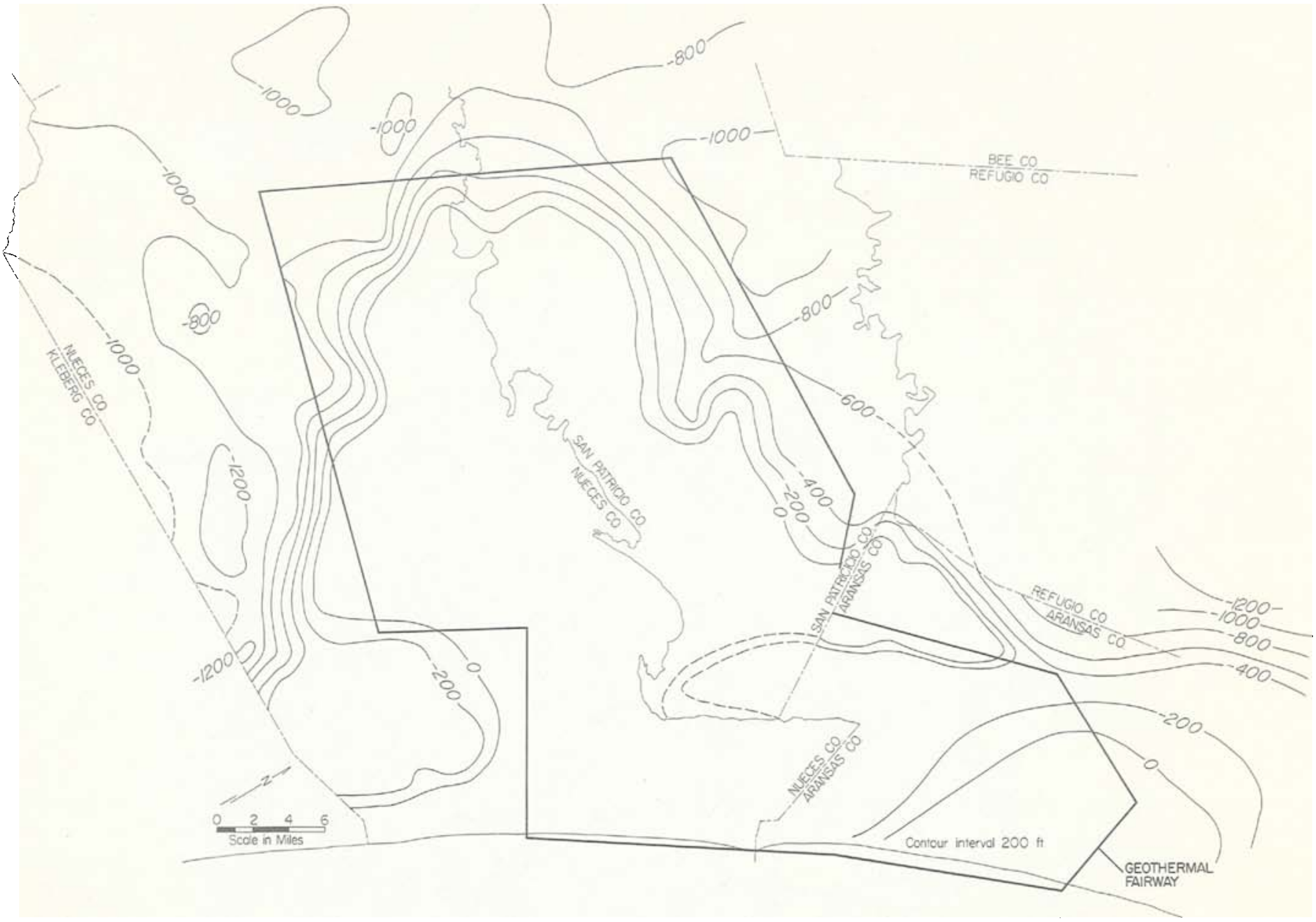

Fig. 10. Structure contour map of the base of slightly saline water (< 3,000 ppm TDS) (compiled from Shafer, 1968 and Wood and others, 1963).

will regulate the drilling and operation of geothermal resource wells and the disposal of fluids from geothermal resource wells under rule 8 as follows.

(A) Fresh water, whether above or below the surface, shall be protected from pollution . . . .

(B) . . . [The operation of] geothermal well or wells drilled for exploratory purposes . . . shall be carried on so that no pollution of any stream or watercourse of this State, or any subsurface waters, will occur as the result of the escape or release or injection of geothermal resource or other mineralized waters from any well.

(C1) . . . [All operators conducting] geothermal resource development and production are prohibited from using salt-water disposal pits for storage and evaporation of . . . geothermal resource waters . . . .

(C1b) Impervious collecting pits may be approved for use in conjunction with approved salt-water disposal operations . . . .

(C1c) Dishcarge of . . . geothermal resource waters into a surface drainage watercourse, whether it be a dry creek, a flowing creek, or a river, except when permitted by the Commission is not an acceptable disposal operation and is prohibited.

(D1) The [well] operator shall not pollute the waters of the Texas offshore and adjacent estuarine zones (salt-water-bearing bays, inlets, and estuaries) or damage the aquatic life therein.

(D2) . . . Geothermal resource well drilling and producing operations shall be con-

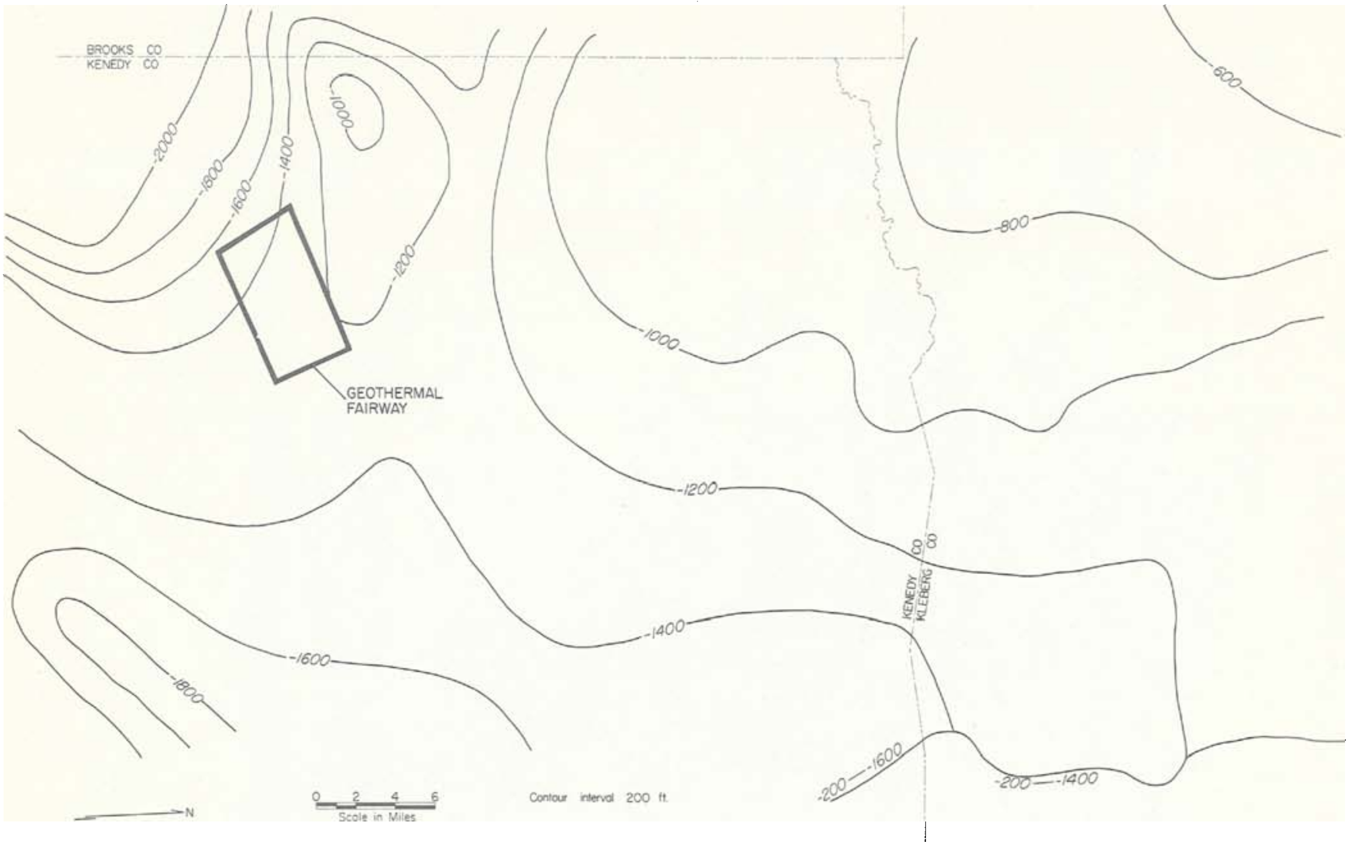

Fig. 11. Structure contour map of the base of slightly saline water (< 3,000 ppm TDS) (compiled from Wood and others, 1963).

ducted in such a manner to preclude the pollution of the waters of the Texas offshore and adjacent estuarine zones.

(D2a) The disposal of liquid waste material into the Texas offshore or adjacent estuarine zones shall be limited to salt water and other materials which have been treated, when necessary, for the removal of constituents which may be harmful to aquatic life or injurious to life or property.

The Railroad Commission of Texas (1975) also regulates the injection of saline water under rule 9 as follows.

(A) Salt water . . . unfit for domestic, stock, irrigation, or other general use may be disposed of . . . by injection into the following formations: [rules listed].

(A1) All nonproducing zones of oil, gas, or geothermal resources bearing formations that contain water mineralized by processes of nature to such a degree that the water is unfit for domestic, stock, irrigation, or other general use.

Water-quality standards developed by the Texas Water Quality Board were approved by the Environmental Protection Agency in October 1973 and were amended in 1975 (Texas Water Quality Board, 1975). These standards are in compliance with the Federal Water Pollution Control Act Amendments of 1972 (U. S. Congress, 1973). Under these standards, "it is the policy of the State . . . to maintain the quality of water in the State consistent with the public health and enjoyment, the propagation and protection of aquatic life, the operation of existing industries, and the economic development of the State . . . ." Furthermore, " . . . no waste discharges may be made which will result in the lowering of the quality of these waters unless and until it has been demonstrated to the Texas Water Quality Board that the change is justifiable as a result of desirable social or economic development" (Texas Water Quality Board, 1975, p. 1).

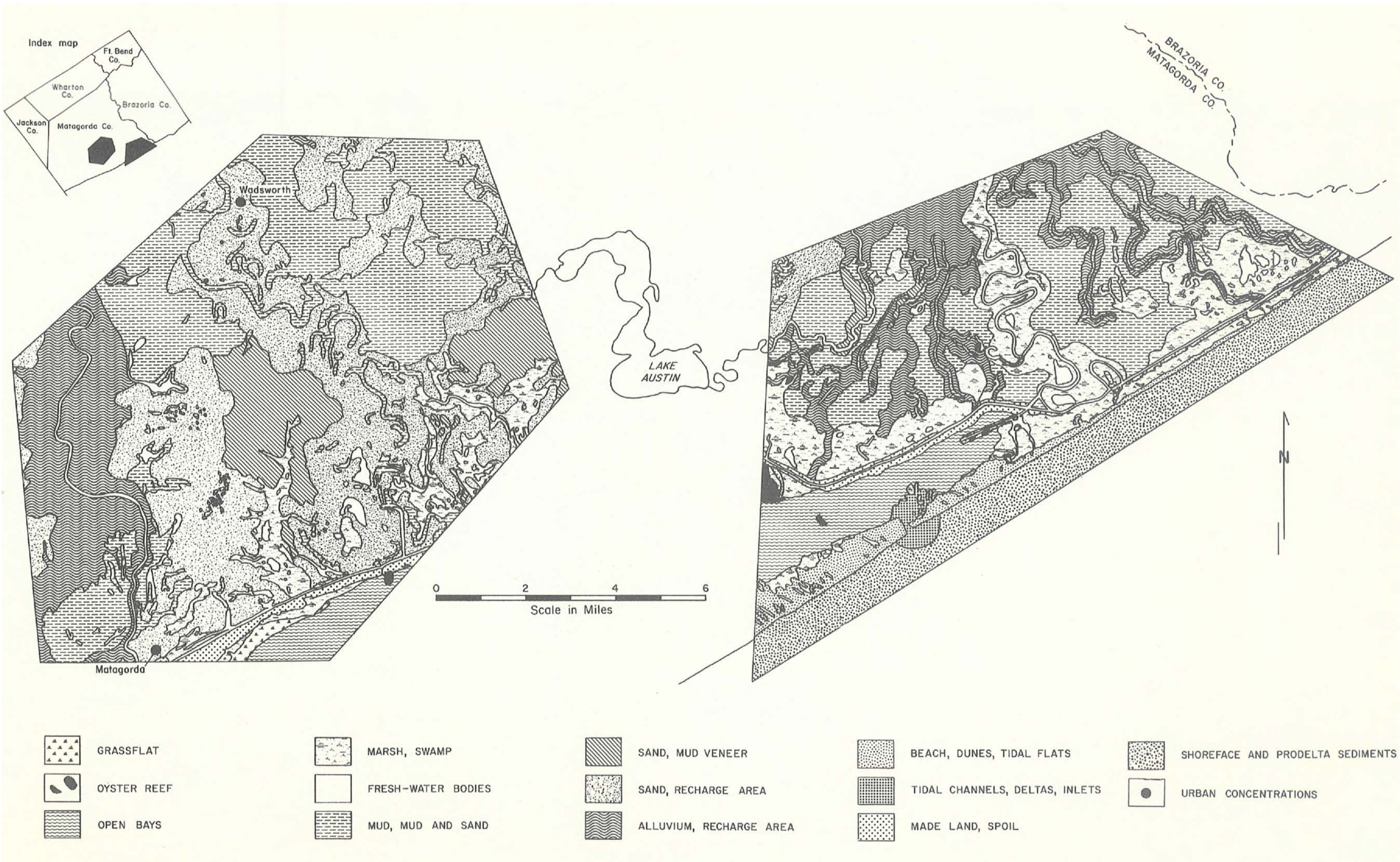

Fig. 12. Map of environmental biologic, geologic, and process units (compiled from McGowen and others, 1976).

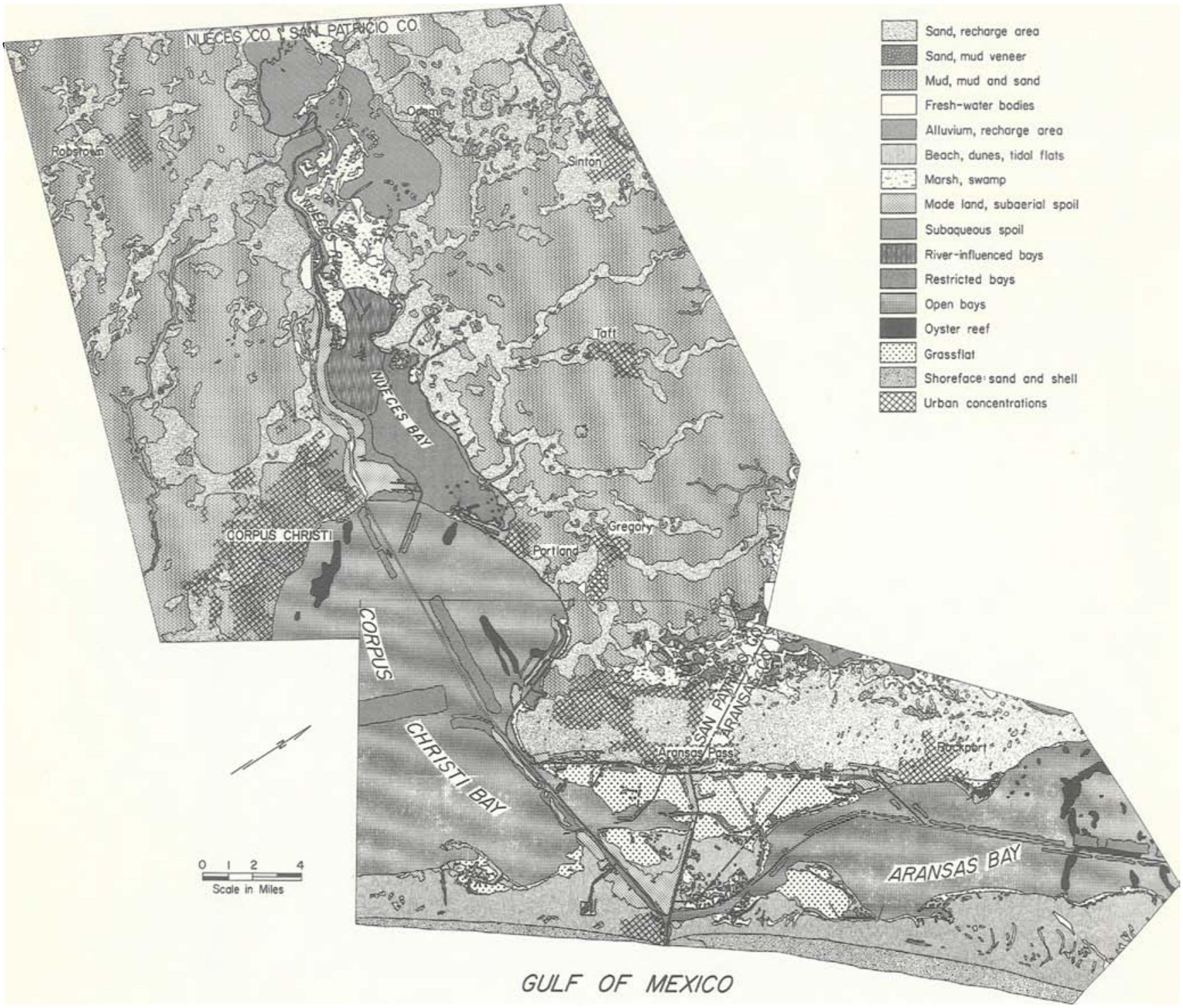

Fig. 13. Map of environmental biologic, geologic, and process units (compiled from Kier and others, 1974).

The following suggested limitations to thermal pollution as outlined in the Texas Water Quality Standards (Texas Water Quality Board, 1975) are of interest:

1. 2.75°C (5°F) rise over ambient temperature for fresh-water streams
2. 1.65°C (3°F) rise over ambient temperature for fresh-water impoundment
3. 2.2°C (4°F) rise or a maximum temperature of 52.5°C (95°F) in fall, spring, and winter, and 0.85°C (1.5°F) rise or a maximum temperature of 52.5°C (95°F) in summer for tidal reaches of rivers and bay and Gulf waters.

The Texas Water Quality Board recognizes that salinities of estuaries are highly variable and that the dominant factor affecting salinity variations is the weather. Salinity standards are now incompletely defined but are under study.

The preceding review of the regulations and policies of Texas agencies that apply to the disposal of salt water indicates that:

1. Temporary salt-water collecting or storing is permitted.
2. Salt water treated (including cooling) to remove harmful constituents may be released into bays, estuaries, and the Gulf of Mexico.

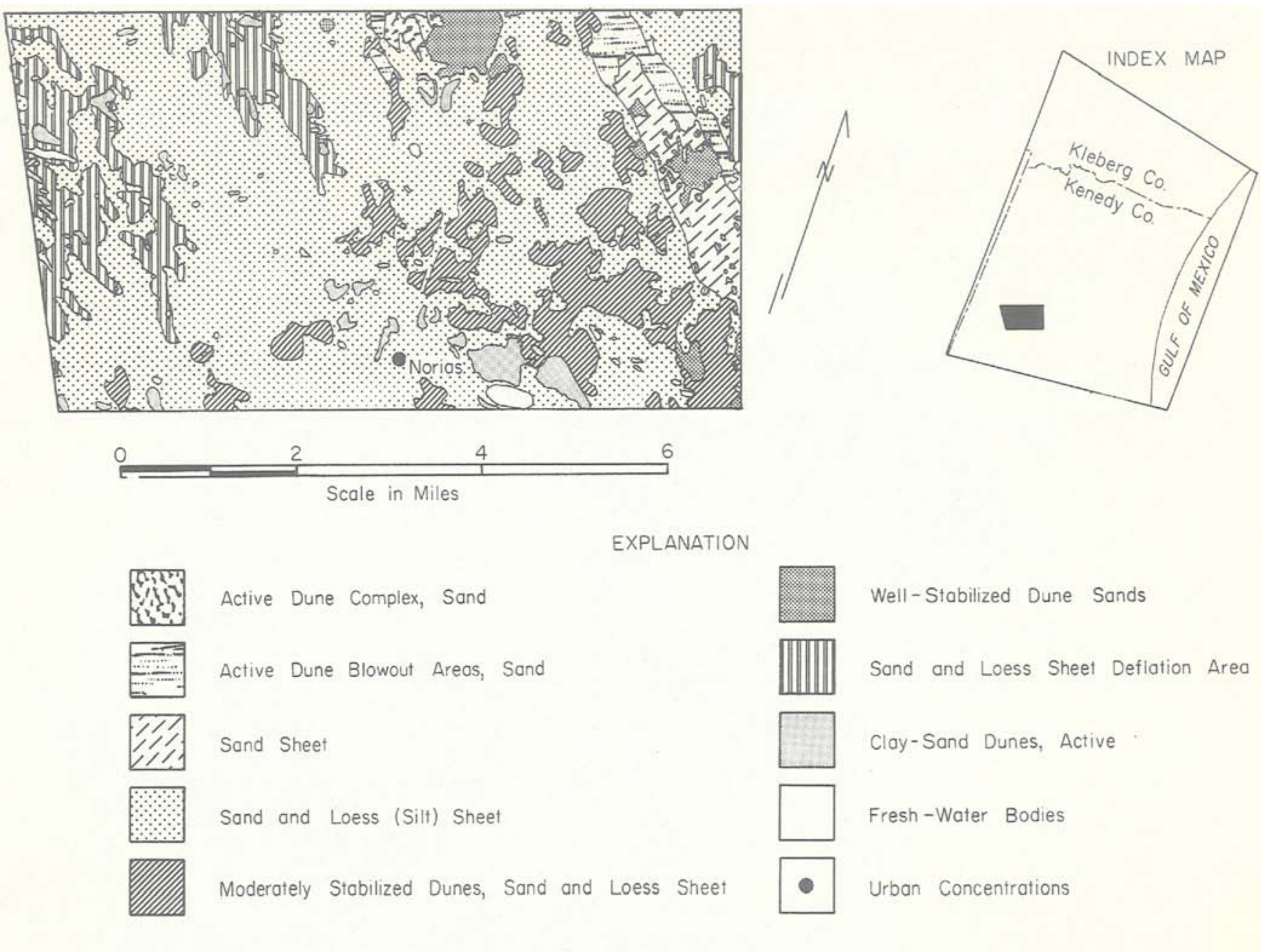

Fig. 14. Map of environmental geologic and process units (compiled from Brown and others, in press).

3. Under certain circumstances, the discharge of salt water into natural watercourses is permitted.
4. The reinjection of salt water into saline aquifers is permitted.
5. The lowering of standards for certain water bodies is permitted if sufficient need for economic development can be demonstrated.

POTENTIAL SUBSIDENCE AND FAULT ACTIVATION

Production of geothermal water from geopressured zones in Tertiary Gulf Coast sediments has potential for causing land subsidence and for activating surface faults. Estimates of potential faulting and land subsidence can be made from simple mathematical models and by drawing analogies with subsidence and faulting attributed to production of oil, gas, and shallow ground water elsewhere in the Gulf Coast.

The environmental impact of geopressured geothermal production depends on the geographic location of the reservoir as well as the hydraulic and geologic characteristics of the reservoir.

Faulting and subsidence in urbanized areas close to sea level will have a more adverse impact than faulting and subsidence in rural inland areas.

Geopressured Sediments and Reservoir Compaction

Geothermal waters of the Gulf Coast will be produced from sediments of the geopressured zone where pore-water pressures are abnormally high in comparison to pore-water pressures in other sediments that occur at equal depths. Rapid deposition and burial of sands and muds have prevented complete compaction and dewatering of the sediments. Under normal conditions, muds or mudstones undergo a decrease in porosity from greater than 50 percent at deposition to as little as 4 percent following burial, dewatering, and compaction. Porosity decreases logarithmically with depth under normal hydrostatic conditions (fig. 15). Partly compacted and dewatered muds and mudstones may retain porosities as high as 15 to 30 percent at depths greater than 3,600 m along the Gulf Coast (Dickinson, 1953; Rubey and Hubbert, 1959; Bredehoeft and Hanshaw, 1968; Dickey and others 1968; Chapman, 1972; Rieke and Chilingarian, 1974; Magara, 1975).

The high porosity of geopressured mudstones creates the potential for surface subsidence. Production of large quantities of water from geopressured sandstones may permit depressuring of intercalated or surrounding geopressured mudstones and a subsequent decrease in mudstone porosity. If depressuring occurs, the reservoir will undergo some compaction. Some of this compaction may be translated to land subsidence.

The lateral extent of reservoir compaction and land subsidence needs to be considered. Where there are no lateral barriers to a geothermal reservoir, ground-water production may lead to

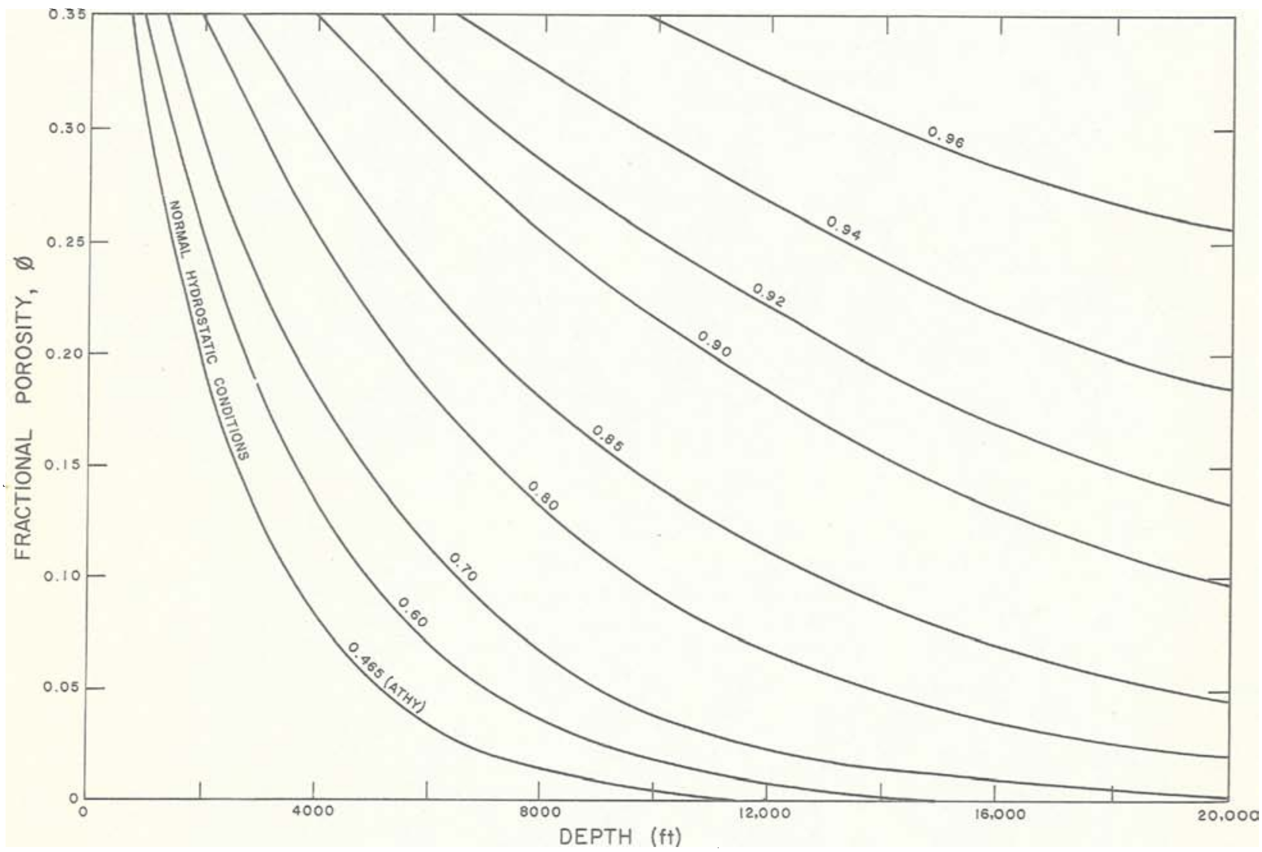

Fig.15. Relationship between porosity and depth of burial for various values of λ (fluid-pressure/overburden-pressure ratio) for an average shale or mudstone. Athy's curve (λ = 0.465) is assumed to represent "compaction equilibrium" condition. (After Rubey and Hubbert, 1959, fig. 4, p. 178, Courtesy of the Geological Society of America Bulletin.)

reservoir compaction and subsequent land subsidence over an extensive area. Most geothermal reservoirs, however, will probably be located between major growth faults that may act as lateral permeability barriers. Ground-water production and subsequent pressure declines may be confined to reservoirs within fault blocks. Differential compaction of sediments within a fault block may then cause fault movement and differential subsidence at land surface.

In considering the environmental impact of land subsidence and fault activation from geothermal production, four questions need to be addressed: (1) How much compaction of the reservoir will occur? (2) How much of the reservoir compaction will be translated to the land surface in the form of land subsidence? (3) What is the potential for fault activation? and (4) What will be the impact on present and future land use of the area being affected?

Potential for Reservoir Compaction.—The potential for reservoir compaction has been evaluated using two different approaches. The first method estimates the probable compaction of reservoir mudstones ($\triangle m$) using equation 1 (modified from Domenico, 1972, p. 234). For the potential geothermal reservoir in the Armstrong field, probable mudstone compactions are calculated as the products of the estimated specific storage (S'_s), the known mudstone thickness (m), and various assigned pressure declines ($\triangle h$) (table 3).

$$\triangle m = S'_s \triangle h \, m \quad (1)$$

where m = clay thickness
$\triangle m$ = change in clay thickness
S'_s = specific storage, $3.3 \times 10^{-4} m^{-1}$ (Papadopulos and others, 1975)
$\triangle h$ = pressure decline

The potential compaction ($\triangle m$) has been estimated for the Armstrong field, a geothermal fairway in Kenedy County (table 3).

The specific storage was assumed to be $3.3 \times 10^{-4} m^{-1}$ (from Papadopulos and others, 1975). Compaction values are also based on the assumption that pore pressures in the mudstone will reach equilibrium with the sandstone; diffusivity, therefore, has not been considered. Similarly, compressibility of water and the producing sandstones has been ignored although recent studies of sandstones from the geopressured zone indicate that compaction may occur through failure of the cementing material (Lindquist, 1976).

The net thickness of mudstone in tables 3, 4, 5, and 6 is from the area of maximum sand in the Armstrong Reservoir. Maximum reservoir thickness is 370 m. Pressure losses have been varied from 70 m of hydraulic head (100 psi) to 705 m of hydraulic head (1,000 psi). Papadopulos (1975) predicted an average pressure loss of 640 m for a hypothetical geothermal field that has had 20 years of production. From table 3, 1.6 to 31 m of compaction might be expected from these pore-pressure losses. With greater pressure declines and increased thickness of mudstone, there will be an increase in reservoir compaction.

The second approach in estimating potential compaction of geopressured mudstone is to multiply the thickness of mudstone in a reservoir by the long-term decrease in porosity caused by a decline of pore pressures (equation 2).

$$\triangle m = \triangle \phi \, m \quad (2)$$

where m = clay thickness
$\triangle m$ = change in clay thickness
$\triangle \phi$ = change in porosity

Table 3. Potential reservoir compaction in Armstrong field.

Armstrong Field Well No.	Net Thickness of Clay (m)	Compaction Resulting from Reservoir Pressure Decline			
		Pressure Decline, m(psi)			
		70 (100)	352 (500)	640 (908)	705 (1000)
		Compaction (m)			
5	70	1.6	8.1	14.7	16.0
7	113	2.6	13.0	23.9	26.0
22	146	3.4	17.0	30.8	34.0

Table 4. Potential reservoir compaction in Armstrong field.

Armstrong Field Well No.	Net Thickness of Clay (m)	Compaction Resulting from Reservoir Pressure Decline		
		Pressure Decline, m(psi)		
		70 (100)	500 (352)	705 (1000)
		Porosity Change (%)		
		1	2	5
		Compaction (m)		
5	70	0.7	1.4	3.5
7	113	1.1	2.2	5.7
22	146	1.5	3.0	7.3

Table 5. Potential land subsidence over Armstrong field.

Armstrong Field Well No.	Net Thickness of Clay (m)	Subsidence Resulting from Reservoir Pressure Decline			
		Pressure Decline, m(psi)			
		70 (100)	352 (500)	640 (908)	705 (1000)
		Subsidence (m)			
5	70	0.6	3.0	5.4	5.9
7	113	1.0	4.8	8.8	9.6
22	146	1.3	6.3	11.4	12.6

At depths greater than 3,600 m (12,000 ft) within the Armstrong field, the fluid-pressure/overburden-pressure ratio (λ) is 0.85. For pressure reductions of 100 psi (70 m), 500 psi (352 m), and 1,000 psi (705 m), λ would be reduced to 0.84, 0.83, and 0.77, respectively. From figure 15, porosities would be reduced from 13 to 12 percent ($\Delta \phi = 1$ percent), from 13 to 11 percent ($\Delta \phi = 2$ percent), and from 13 to 8 percent ($\Delta \phi = 5$ percent), respectively. Using these porosity decreases, the mudstone thickness for the Armstrong wells, and equation 2, the calculated vertical compaction for the mudstone in the Armstrong Reservoir varies from 0.7 to 7 m (table 4).

Geothermal ground-water production will probably cause mudstone compaction within geopressured reservoirs. The first and second approaches predict significantly different amounts of compaction because of differences in the initial assumptions used in the calculations. Papadopulos (1975) estimated the compaction of a geopressured reservoir to be approximately 1 m by determining sandstone compressibility and mudstone compaction. Mudstone compaction was based on

Table 6. Potential land subsidence over Armstrong field.

Armstrong Field Well No.	Net Thickness of Clay (m)	Subsidence Resulting from Reservoir Pressure Decline		
		Pressure Decline, m(psi)		
		70 (100)	352 (500)	705 (10000)
		Subsidence (m)		
5	70	0.3	0.5	1.3
7	113	0.4	0.8	2.1
22	146	0.6	1.1	2.7

Hantush's (1960) leaky-aquifer theory. This theory provides a third, different estimate of reservoir compaction. A more accurate estimate for reservoir compaction will be known only when mudstone compressibilities can be determined experimentally with actual core material from a geopressured geothermal reservoir. The different approaches, however, suggest that some mudstone compaction should be expected when pore pressures are lowered significantly within the reservoir.

Potential for Surface Subsidence.—The methods for estimating potential reservoir compaction are not directly applicable for estimating land subsidence because the translation of compactional strain at depth to land subsidence has not been considered. The resultant strain from reservoir compaction may be partially absorbed by overlying sediments. Geertsma (1973) and Finol and Farouq Ali (1975) have shown that for equal amounts of reservoir compaction, land subsidence will diminish as reservoir depths increase and as lateral dimensions of the reservoir decrease. Although they are deep, geothermal reservoirs are expected to have extensive lateral dimensions. The potential for land subsidence, therefore, needs to be considered.

Geertsma (1966, 1973) quantified the interaction of an isolated shrinking inclusion, the reservoir, and the overlying sediments. With Geertsma's (1966) theory of poroelasticity and Geertsma's (1973) tables, approximate values for land subsidence as a result of reservoir compaction can be calculated (tables 5 and 6). For the Armstrong field, assumed to be a disk-shaped reservoir with a radius of 4.8 km, approximately 37 percent of the compaction at the center of the reservoir could be translated into subsidence. The potential land subsidence (tables 5 and 6) can be evaluated by multiplying the reservoir compaction (first and second approaches) by this translation percentage. Land subsidence could vary from 0.3 m to more than 10 m.

One location where surface subsidence has been associated with oil and gas production from geopressured sediments is the Chocolate Bayou field on the Gulf Coast (fig. 16). There has been more than 0.3 m of subsidence in the Chocolate Bayou oil and gas field, where production is at depths of -2,438 to -3,962 m. Oil production has been from normally pressured horizons, whereas gas production has been from the geopressured zone. Periods of maximum rates of annual subsidence do not coincide with periods of maximum oil production but rather with periods of maximum gas production from geopressured horizons (fig. 17). If subsidence results from oil production, then there is a lag period during which strain is transmitted from the producing horizon (-2,438 to -3,962 m) to the surface. On the other hand, subsidence over the Wilmington oil field in California occurred concomitantly with oil production with no apparent lag period (Mayuga and Allen, 1969). Sediment compaction from gas production from the geopressured horizons appears to be a more logical cause of the land subsidence. Land subsidence over the Chocolate Bayou oil and gas reservoir further suggests that the possibility of subsidence from geopressured geothermal groundwater production should be given serious consideration.

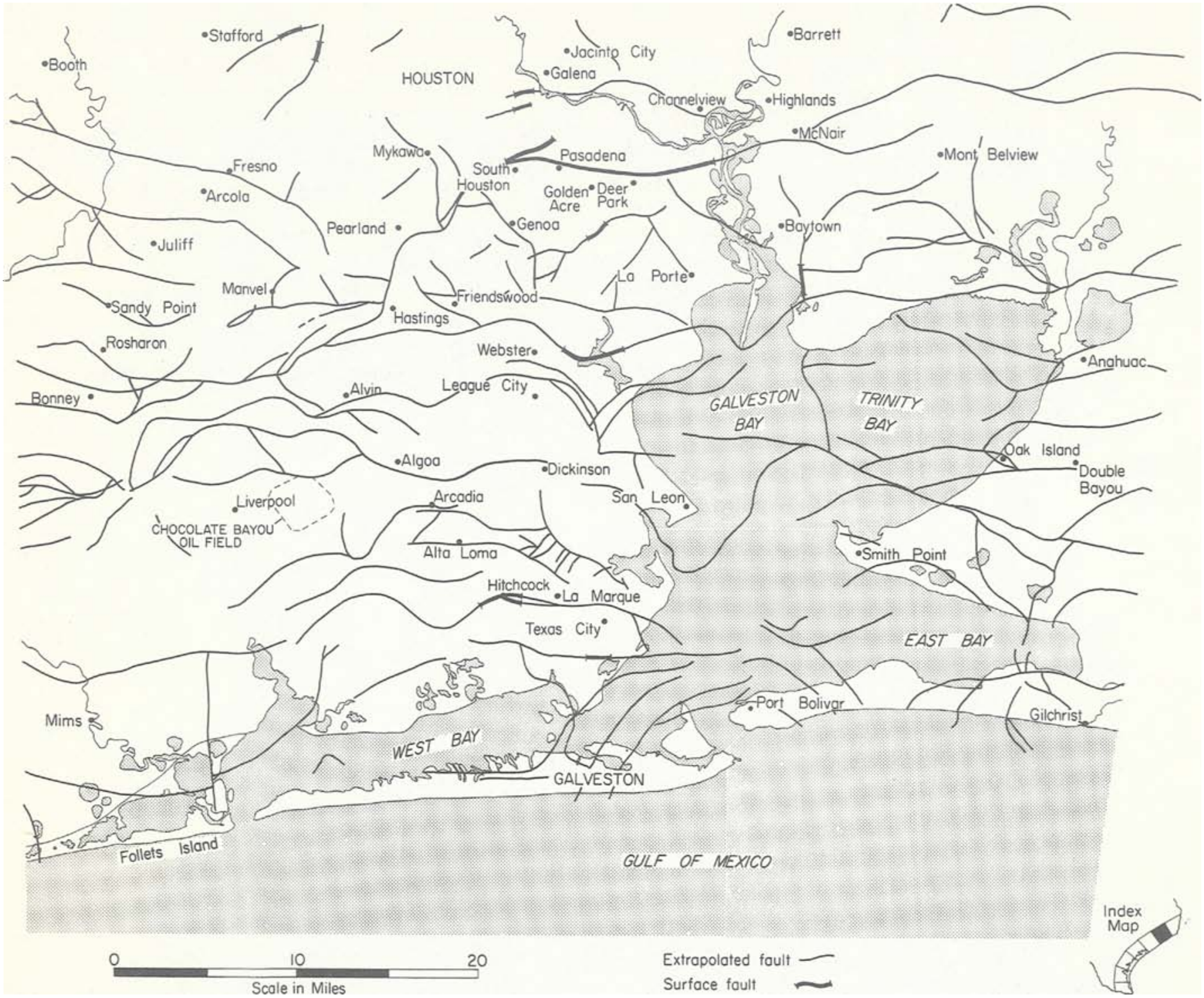

Fig. 16. Coincidence of active surface faults with surface traces of extrapolated subsurface faults, Houston-Galveston area. Note location of Chocolate Bayou oil and gas field.

Potential for Fault Activation.—Teritary and Quaternary sediments of the Gulf Coast are extensively faulted. Extensive ground-water production from geothermal reservoirs may activate the growth faults that intersect the geothermal horizons.

Subsurface faults do not die out in the upper Cenozoic sediments but in many cases extend to the land surface. Their natural rate of movement, however, is so slow that their surficial expression is evident only through subtle geomorphic features such as lineations and rectilinear stream-drainage networks (Kreitler, 1976). Structural control of stream drainage is particularly evident in the Houston-Galveston area. Active faults appear to control sections of Buffalo Bayou, Clear Creek, Highland Bayou, and Cypress Creek.

The Houston area has more than 240 km of active faults, making it the most active area for faulting in the Coastal Zone. The surface traces of most faults extrapolated from the subsurface are commonly coincident with active surface faults (fig. 16). Active surface faults, therefore, are not strictly surface or near-surface phenomena but are

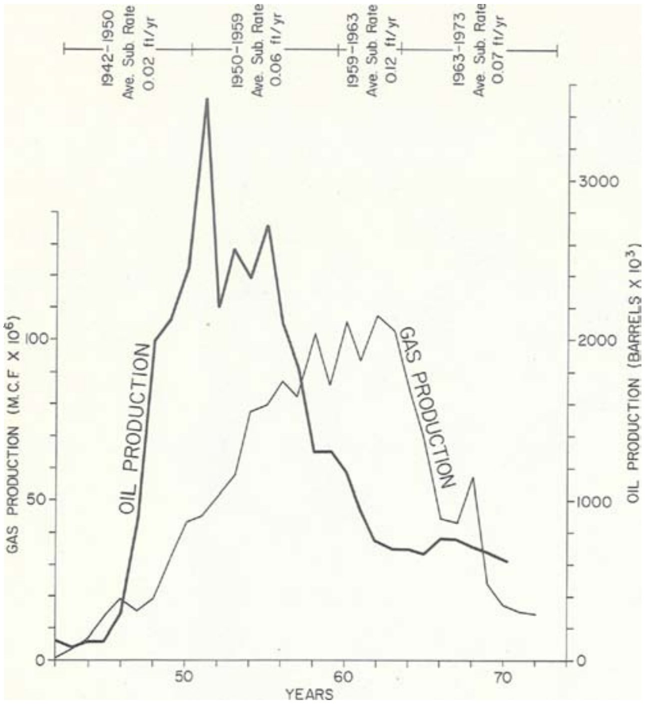

Fig. 17. Comparison of rates of subsidence to oil and natural gas production from Chocolate Bayou oil field between the years 1942 and 1973. Production rates of oil and gas from the Railroad Commission of Texas.

probably related to subsurface faults occurring in older Gulf Coast sediments. Van Siclen (1967) has documented this relationship in detail for the extension of subsurface faulting in the Addicks oil field to the Addicks fault, an active surface fault. Woodward-Lundgren and Associates (1974) has established, through seismic profiling, the surface extension of a subsurface fault in the Pasadena, Texas, area. Several fault extrapolations are also coincident with rectilinear stream drainage networks where no apparent fault escarpment exists (for example, sections of Buffalo Bayou and Cedar Bayou).

Faults appear to act as complete or partial barriers to fluid migration. When production is only on one side of a fault, pore pressure declines, and sediment compaction is greater on the producing side of the fault than on the other side. This subsurface differential compaction is manifested at the surface as fault movement or differential subsidence across the surface trace of the fault.

Tilt meters across the Eureka Heights fault and the Long Point fault in western Houston show excellent correlation between fault movement and the decline of the piezometric surface (water level) in the shallow artesian Chicot aquifer (fig. 18). As the piezometric surface declines, the downthrown side of the Eureka Heights fault drops, but as the piezometric surface rises, there is a slight rebound of the downthrown side.

In the Saxet field west of Corpus Christi, a 6-foot scarp has appeared along a segment of the surface extrapolation of a regional growth fault. The active segment of this fault lies almost exclusively within the Saxet oil and gas field (fig. 19); fault movement has occurred since the onset of production (W. A. Price, personal communication, 1975). Leveling profiles across the Saxet field show rapid increases in subsidence at the fault (fig. 20). Subsidence rates from 1950 to 1959, 7 cm per year (0.22 ft per year), are approximately twice the rates from 1942-1950, 4 cm per year (0.14 ft per year). A rapid increase in gas production from shallow sands occurred from 1950 to 1959 (table 7). Oil production, however, decreased during this period. It appears that the production of high-pressured gas may have led to the compaction of the shallow gas sands on the downthrown side of the Saxet fault. This differential compaction is evident at the surface as differential land subsidence and fault activation.

Differential subsidence, though not accompanied by fault activation, is also evident from deeper oil and gas production in the Chocolate Bayou field. A lineation shown on the west side of the subsidence profile (fig. 21, near benchmark P53) is coincident with the zone of rapid increase in subsidence. An extrapolated fault shown on the east side of the field, between benchmarks N691 and M691, is coincident with a sharp increase in subsidence. No obvious escarpment exists at this locality, but with continued differential subsidence, an active fault would be expected to develop.

In the Cholocate Bayou field, the translation of strain from regions of differential reservoir compaction at depth to the land surface apparently follows the dip of a subsurface fault; it does not occur directly upward. The coincidence of the zone of differential subsidence and the surface trace of the fault is approximately 2.4 km (1.5 miles) northeast of the subsurface location of the fault at depth of 2.4 km (8,000 ft). The areas of potential subsidence resulting from geothermal exploitation may be limited to areas bounded by

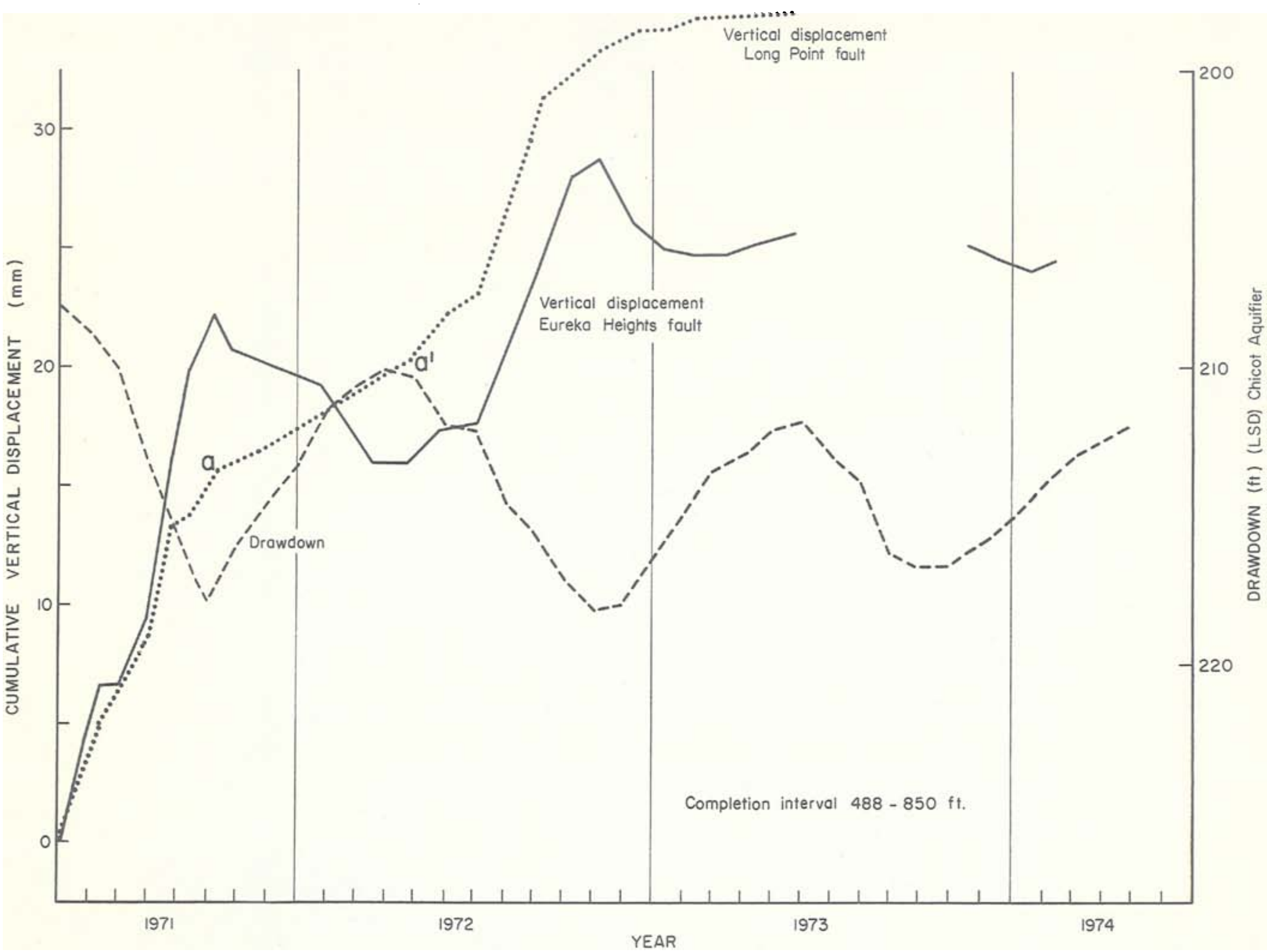

Fig. 18. Cumulative vertical displacement on Long Point and Eureka Heights faults in western part of Houston compared to drawdown of piezometric surface of Chicot aquifer. Displacement data for April 1971 to April 1972 from Reid (1973); displacement data for May 1972 to January 1974 and drawdown data for Federal observation well L-J-65-13-408 (from R. Gabrysch, personal communication, 1974).

the surface traces of growth faults that confine the geothermal reservoir. If fault activation occurs as a result of differential compaction of geopressured reservoirs, normally pressured oil and gas reservoirs or shallow artesian aquifers, then fault movement can be expected to occur along the surface traces of fault extrapolations.

Fault extrapolations are made from subsurface structure maps using one or two datum surfaces in the Frio Formation. Where two surfaces are available, the angle of the fault extrapolation is based on the dip of the faults between these two surfaces. Where only one subsurface datum is available, then the dip of the fault extrapolation is assumed to be 45 degrees. Figures 19, 22, and 23 show the location of four geothermal fairways, the Armstrong field, the Corpus Christi fairway, and two fairways in southeastern Matagorda County, in relationship to the surface traces of the extrapolated faults. If fault activation does result from production of these geopressured geothermal reservoirs, then the active faults should be coincident with the surface traces of extrapolated faults.

Environmental Impact of Subsidence and Fault Activation

The geographic location of the geopressured geothermal reservoir controls the magni-

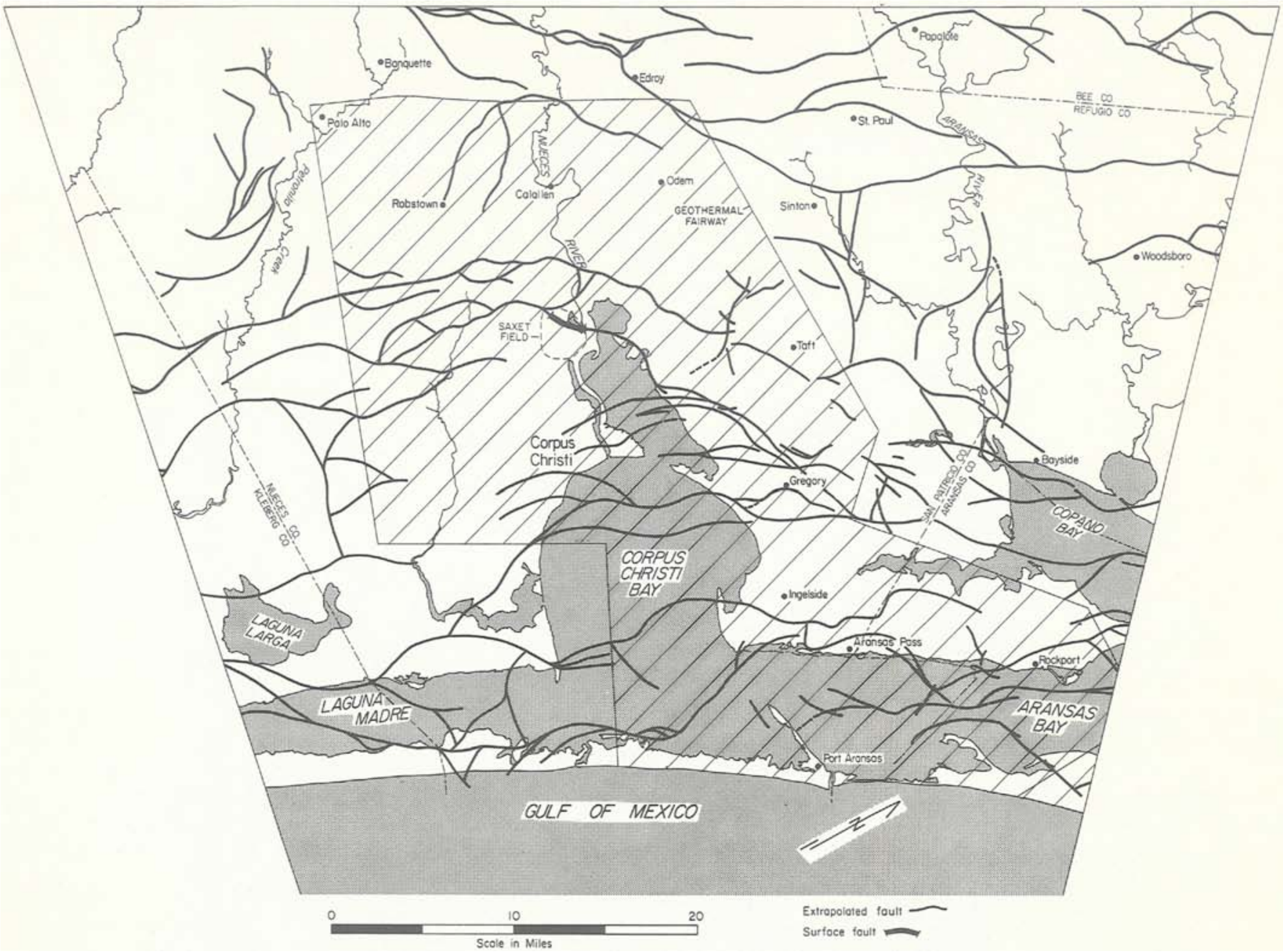

Fig. 19. Location of Corpus Christi geothermal fairway in relationship to surface traces of extrapolated subsurface faults. Note location of active fault in Saxet oil and gas field. Base map from Environmental Geologic Atlas of the Texas Coastal Zone—Corpus Christi Area.

tude of certain aspects of the environmental impact of geothermal energy development. Subsidence and fault activation are not critical problems until they adversely affect the quality of the present or future land use of a particular area. For example, in Harris and Galveston Counties, fluid production has caused extensive land subsidence and has activated several surface faults. These faults intersect two airports, interstate highways at 11 different locations, railroad tracks at 28 locations, and pass through 11 communities in which more than 200 houses evidence fault damage. Land subsidence in Harris and Galveston Counties has greatly increased the area that may be affected by future hurricane flooding. In the Galveston Bay area of these counties the flood surge from Hurricane Carla (1961) inundated 314 km^2 (123 square miles). With the subsidence that has occurred since Hurricane Carla, an additional 64 km^2 (25 square miles) of land can be expected to be flooded (an increase in the flooding area of about 20 percent) in a hurricane of the same magnitude and characteristics of Carla. The environmental impact of faulting and subsidence in Harris and Galveston Counties is high because of their population density, low elevation, and proximity to the Gulf of Mexico.

The Armstrong field, the Corpus Christi fairway, and two fairways in Matagorda County are being considered as potential reservoirs (fig. 1). In the event of geothermal fluid production from any

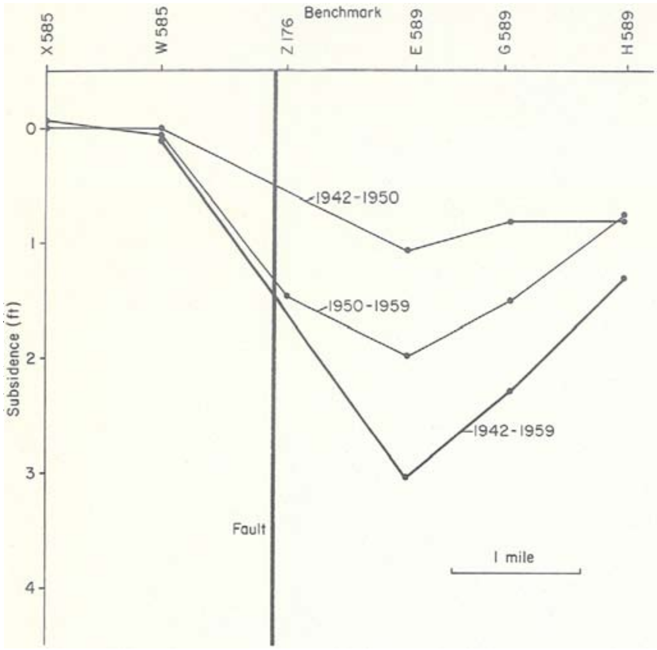

Fig. 20. Land subsidence over Saxet oil and gas field, Corpus Christi, Texas. Benchmark 589 over the center of the field. Note fault control of subsidence (between benchmarks W585 and Z176). (See figure 19 for field location.)

of the fairways, a certain amount of subsidence and fault activation could occur. Under these circumstances, predictions of the relative intensities of certain environmental effects can be made.

The primary land use for the Armstrong field is unimproved rangeland (Brown and others, in press). The elevation of the land is approximately 9.1 m (30 ft), and the area is 24 km (15 miles) from the coast. Fault activation in the vicinity of this field could rupture a major gas-transmission line. Land subsidence would not increase the area affected by hurricane salt-water flooding. The Armstrong area, however, was inundated by fresh-water flooding during Hurricane Beulah (U. S. Army Corps of Engineers, 1968), and land subsidence would probably increase the depth and extent of fresh-water flooding.

The Corpus Christi geothermal fairway underlies Corpus Christi Bay and the greater Corpus Christi area. Major land uses in the area include agriculture, suburban, urban, and industrial development (Brown and others, 1976). The area includes Corpus Christi Bay and a portion of the

Table 7. Subsidence versus oil and gas production in Saxet field.

		Date (yr)		
		1942 to 1950	1951 to 1959	1960 to 1974
Gas production M cf[a] x 10^6/yr	Upper sand (300 to 900m)	7.7	19.1	5.2
	Middle sand (900 to 1,524m)	12.8	7.0	3.4
	Lower sand (1,524 to 2,440m)	5.3	1.5	3.3
	Total	26.1	27.6	11.8
Oil production (bbls/yr)		2,086,672	765,541	576,891
Annual subsidence rate		4cm/yr (0.138ft/yr)	7cm/yr (0.22ft/yr)	———

[a]Thousand cubic feet

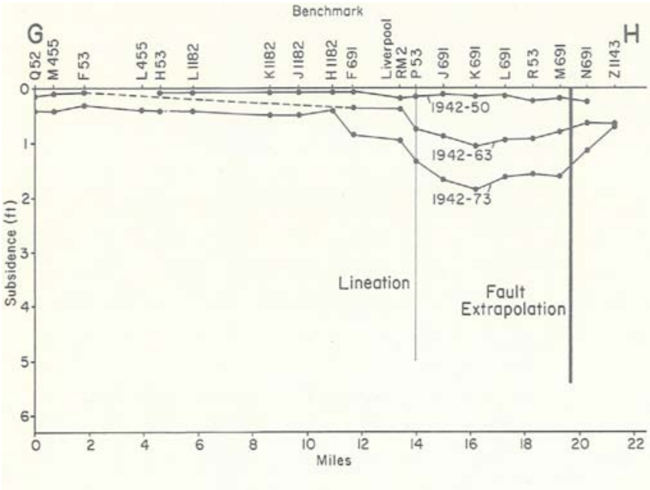

Fig. 21. Land subsidence over Chocolate Bayou oil and gas field. Note coincidence of differential subsidence with lineation and surface trace of extrapolated subsurface fault. (See figure 16 for field location.)

Gulf coastline. The elevation for most of downtown Corpus Christi is above 7.6 m (25 ft); flooding in that area would probably be minimal. Much of the residential area southeast of Corpus Christi, however, is below the 7.6 m (25 ft) elevation. Subsidence in this area could increase the area affected by hurricane flooding. Similarly, industrial development along Nueces Bay could be affected by land subsidence. Fault activation would probably cause significant structural damage regardless of where it occurred in the greater Corpus Christi area. Land subsidence and surface faulting induced by geothermal water production could have a major negative environmental impact on the Corpus Christi area.

Geothermal fairways in Matagorda County underlie rangeland and cropland. The fairways are relatively close to the coast; therefore, subsidence could increase the area of potential salt-water flooding induced by hurricane surges.

A nuclear powerplant (South Texas Project) is located on the edge of one of the two Matagorda fairways. Land subsidence could cause fresh-water flooding problems from the Colorado River at the plant site. Fault activation at the plant site could cause structural damage to the nuclear powerplant. Further evaluation of specific areas for a geothermal reservoir in Matagorda County may indicate that the potential field is not near the proposed nuclear powerplant site and that the potential for flooding and faulting at the plant site will not be increased. Until that question is resolved, the potential impact of subsidence and faulting on the nuclear powerplant must be considered.

Of the three geothermal fairways briefly discussed, the potential environmental impact in the Armstrong area would be far less than the potential impact of faulting and flooding in the Corpus Christi and Matagorda County areas.

NATURAL HAZARDS OF THE GEOTHERMAL FAIRWAYS

Several natural hazards exist for the geothermal fairways including shoreline erosion, stream flooding, hurricane flooding and winds, and expansive soils. Hazards and mitigations are discussed in detail by Brown and others (1974) and Gustavson (1975). None of these hazards results from the production of geothermal fluids. They are hazards that must be considered in the design and construction of geothermal production facilities.

The major streams within the fairways are the Nueces and Colorado Rivers. The Colorado River has completely covered its floodplain 9 times since 1913, about once every 9 years, whereas the Nueces River has completely covered its floodplain 13 times in the past 56 years, approximately once every 4.25 years (Patterson, 1965; U. S. Geological Survey, 1970a, 1975a, 1975b). Many of these floods result from the passage of tropical cyclones across the Gulf Coastal Plain. Since 1912, 12 storms with hurricane-force winds, 119.4 km/h (74 mph or greater), have made landfall in the vicinity of the Armstrong field and the Corpus Christi and Matagorda fairways. Hurricane Carla (1961) brought 241.9 km/h (150 mph) winds to portions of these fairways, and Celia (1970) brought 282.3 km/h (175 mph) winds when it made landfall in the Corpus Christi area and caused extensive wind damage. Hurricane Beulah (1967) produced 141 tornadoes including 11 within the vicinity of the Corpus Christi fairway (Novlan and Gray, 1974). Fresh water from the heavy rains of Hurricane Beulah flooded much of the Armstrong field area.

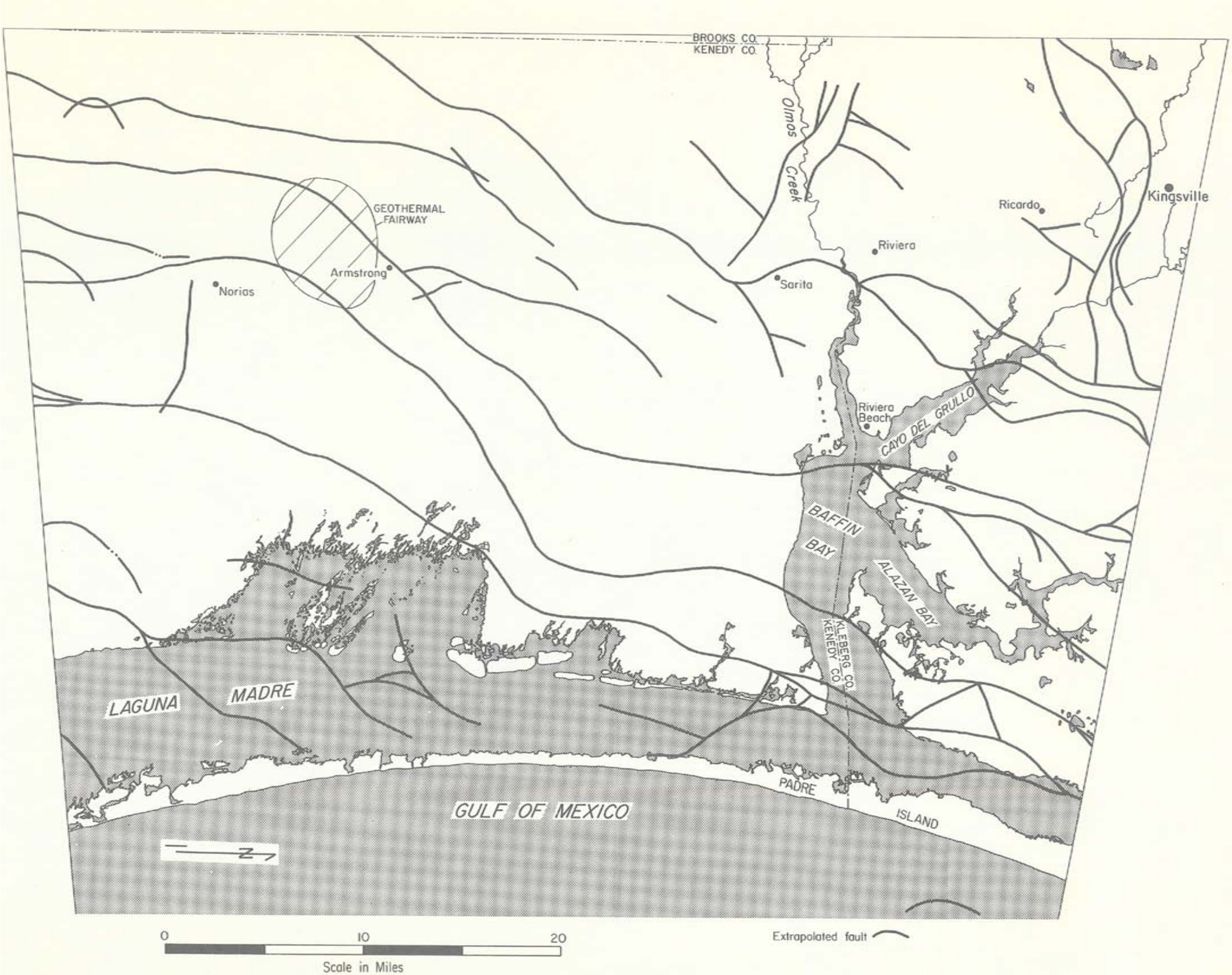

Fig. 22. Location of Armstrong geothermal fairway in relationship to surface traces of extrapolated subsurface faults. Base map from Environmental Geologic Atlas of the Texas Coastal Zone—Kingsville Area.

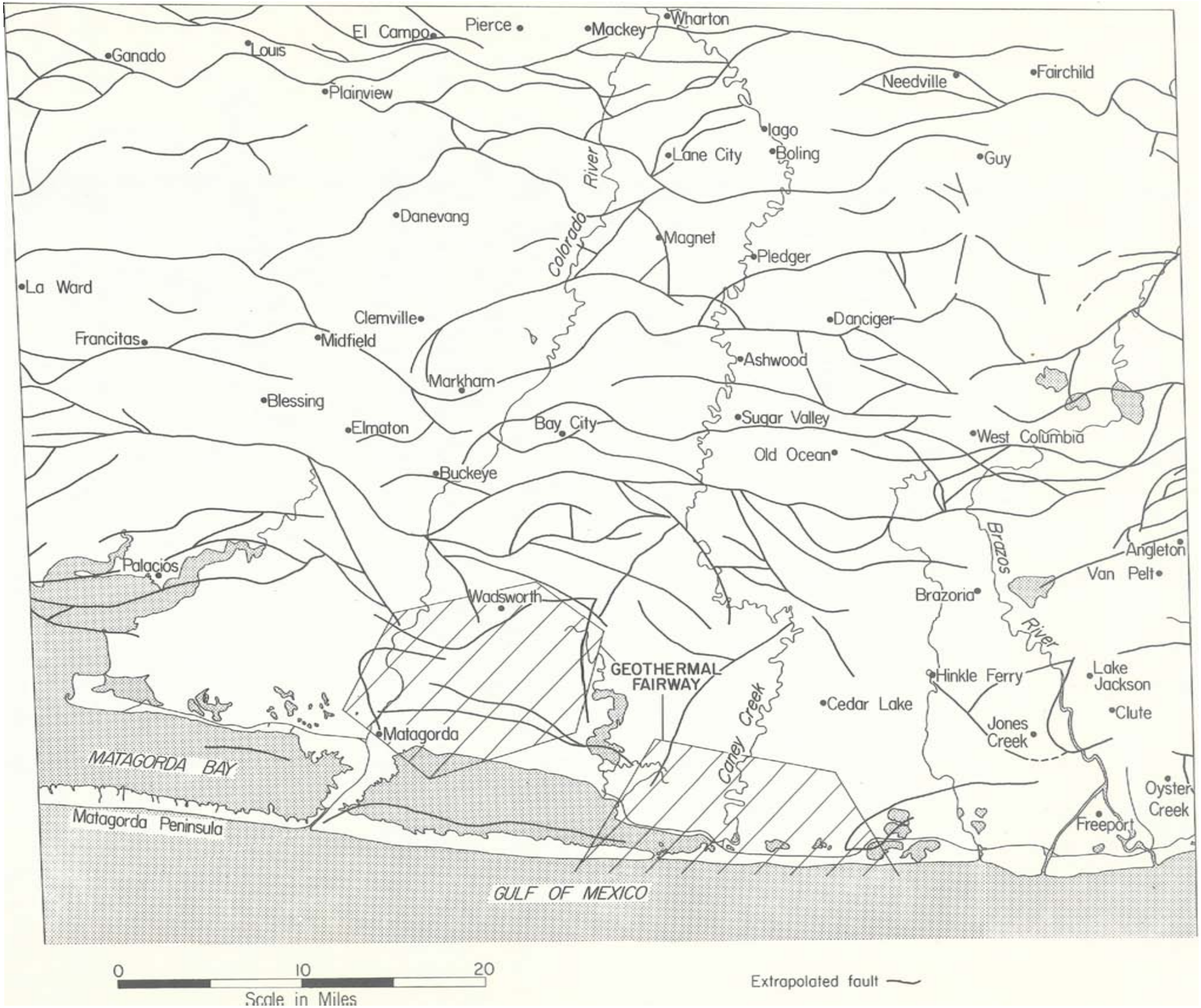

Fig. 23. Location of geothermal fairways in Matagorda County in relationship to surface traces of extrapolated subsurface faults. Base map from Environmental Geologic Atlas of the Texas Coastal Zone–Bay City-Freeport Area.

Storm surge as high as 6.7 m (22 ft) was created when Carla struck Matagorda Bay, causing extensive salt-water flooding. The environmental geologic maps (figs. 12, 13, and 14) illustrate those areas that are flood prone—areas of recent alluvium, marsh, swamp, and, in the Armstrong field, portions of active dune blowout areas, sand sheets, and sand and loess sheets. Hurricane-aftermath flooding resulting from heavy rainfalls is also a serious problem; approximately 76.8 cm (30 inches) of rain accompanied Hurricane Beulah.

Coastal erosion is a continuing problem along the Texas Gulf Coast. Approximately 55 percent of the coast, including coastal areas of both the Matagorda and Corpus Christi fairways, is presently undergoing erosion. Erosion rates exceed 3 m per year (10 ft per year) locally.

Sediments of the Texas Coastal Plain with high clay content develop expansive clay loam soils. The dominant clay mineral of coastal plain sediments is montmorillonite which has the capacity of adsorbing water and expanding when water is available. Conversely, montmorillonite contracts when it dries out. When clays and muds adsorb water and expand, they can develop pressures exceeding 142 metric tons per square meter on buried foundation members (Mielenz and King, 1955). This process results in moderate to severe limitations to construction in areas of predominantly mud or interbedded mud and sand (figs. 12 and 13). Engineering and construction techniques are available for at least partial mitigation of stresses resulting from expansive clay soils (Gustavson, 1975).

SUMMARY

The major environmental problems that could arise from geopressured geothermal water production will result from the disposal or temporary surface storage of spent geothermal fluids and from surface subsidence and faulting.

Water chemistry data for geopressured geothermal fluids indicate that they are moderately to highly saline (8,000 to 72,000 ppm TDS) and that they may contain significant amounts of boron (19 to 42 ppm). Disposal of hot saline geothermal water in subsurface saline aquifers will present the least hazard to the environment. It is not known, however, whether the disposal of as much as 54,000 m^3 (310,000 bbls) of spent fluids per day into saline aquifers at the production site is technically or economically feasible. An alternative method of disposal is to move geothermal fluids from the generating site by open watercourses, canals, or pipelines for disposal into coastal bays or the Gulf of Mexico. This method must be considered if saline aquifers adequate for fluid disposal cannot be found. Overland transport of geothermal fluids or temporary surface storage may cause the following environmental impacts:

1. Salts may accumulate in the sediments underlying geothermal watercourses or storage ponds.
2. Shallow ground-water-recharge areas may be contaminated by salt water.
3. Vegetation and animal life adjacent to geothermal watercourses or storage ponds that are not salt, boron, or temperature tolerant may decline or die.
4. Accidental spills, discharges, or flooding could damage agricultural lands adjacent to geothermal fluid watercourses, pipelines, or storage ponds.
5. Animal life will not be able to cross hot saline watercourses.
6. The ecological balance of portions of bays or estuaries or the Gulf of Mexico could be upset.
7. Air pollution could occur from toxic gases or carbon compounds if they are present within geopressured geothermal fluids.

Geothermal resource production facilities on the Gulf Coast of Texas could be subject to a series of natural hazards: (1) hurricane- or storm-induced flooding, (2) winds from tropical storms, (3) coastal erosion, or (4) expansive soils. None of these hazards is generated by geothermal resource production, but each has potential for damaging geothermal production and disposal facilities that could, in turn, result in leakage of hot saline geothermal fluids.

Production of fluids from geopressured geothermal reservoirs will result in reservoir pressure declines and subsequently in compaction of sediments within and adjacent to the reservoir. The amount of compaction depends on pressure decline, reservoir thickness, and reservoir compressibility. At present these parameters can only be estimated. Reservoir compaction may be translated in part to surface subsidence. When differential compaction occurs across a fault, fault activation may occur and be manifested as differential subsidence across the surface trace of the fault or as an actual rupture of the land surface.

The magnitude of environmental impact of subsidence and fault activation varies with current land use; the greatest impact would occur in urban areas, whereas relatively minor impacts would occur in rural, undeveloped agricultural areas.

RECOMMENDATIONS

Baseline environmental studies of the test well site, production, generating, and disposal areas, and areas of potential subsidence and faulting must be initiated and should be completed prior to initiation of a test well or construction of production/generating facilities. Baseline studies are needed to determine the condition of the environment prior to testing and development. Such studies are necessary for recognition of any environmental changes that may result from the activities of geothermal resource exploration and exploitation. Predictions of the impacts of geothermal resource development on land use may then be made. Certain studies should continue to monitor environmental characteristics throughout the life of the test well or production/generating facility. Recommended environmental studies should include the following.

1. Precise large-scale mapping of the affected areas. Detailed mapping is needed to aid in predicting possible effects to aspects of the environment resulting from geothermal resource development. Mapping should include: (1) environmental geology, (2) climate and air quality, (3) active geologic processes and natural hazards, (4) slope or topography, (5) biotope, (6) current land use, and (7) materials and soils.
2. Precise leveling surveys of production sites. Leveling surveys should be continued to determine if or at what rate subsidence is occurring.
3. Seismic monitoring surveys of production sites. Seismic surveys should be continued throughout the duration of production to determine if or at what rate or intensity seismic events occur.
4. Strain-gauge observations that will indicate, instantaneously, minute movements (subsidence) of the test or development area.
5. Modification of existing computer models developed by the Texas Water Development Board for water circulation in coastal bays and lagoons to indicate dispersion rates and paths for point sources of both chemical and thermal pollution.
6. Sampling of surface watercourses within the area of interest for chemical analysis, temperature, suspended material, and discharge. Sampling and analyses should be continued throughout the duration of production to detect if or to what extent surface water contamination has occurred.
7. Sampling of shallow ground water within the areas of interest for water chemistry, temperature, and regional ground-water movement. Sampling and analysis should be continued throughout the duration of production to detect if or to what extent groundwater contamination has occurred.
8. Precise three-dimensional mapping of subsurface structural elements from the base of geothermal production horizons to the surface. Predictions of the location, potential for, and degree of surface faulting within production areas can be made using these data.
9. Determination of the coefficients of compressibility for mudstones from presently available cores taken within the geopressured zone and from cores from the geothermal test well or geothermal development wells should be made. Using these data, predictions of reservoir compaction can be made.
10. Ground-water monitoring. If natural watercourses, canals, or storage pits are used to transport or contain spent geothermal fluids, a system of ground-water monitoring wells

must be employed to determine the extent or rate of infiltration of the fluid.

11. Biological surveys, including species distribution and analyses of critical and endangered species. If spent geothermal waters are introduced into surface waters, then repeated biological surveys must be made to determine if or to what extent the endemic biota have been affected.

12. Air-quality surveys. During the processes of producing, using, or disposing of geothermal waters, air-quality surveys must be made to determine if or to what extent air pollution is occurring.

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