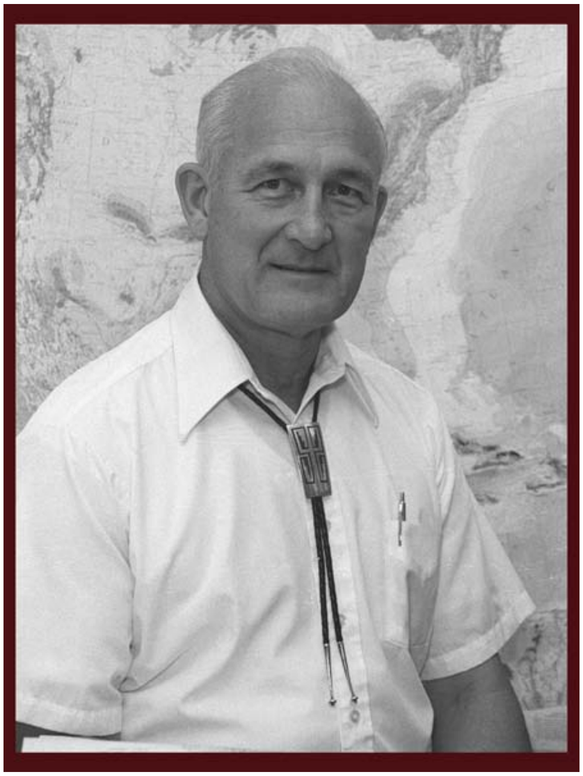
Jackson School of Geosciences
The University of Texas at Austin

FROM THE EARTH TO THE MOON

A RESEARCH SYMPOSIUM

Honoring the

Scientific Contributions
of
William R. Muehlberger



Patricia Wood Dickerson & Mark Cloos, Convenors

August 27 – 29, 2010

2010
Jackson School of Geosciences
The University of Texas at Austin
1 University Station, C1160
Austin, TX 78712-0254

DEDICATION: ***William R. Muehlberger***

Bill Muehlberger has never confined himself to one state, one country, one continent, or one celestial body. His professional preparation included a year studying civil engineering at the University of California at Berkeley, where he also reigned as Intramural Heavyweight Wrestling Champion. His geological schooling (B.S., 1949; M.S., 1949; Ph.D., 1954) was at Caltech, where he achieved distinction in both academic and athletic arenas: outstanding senior of his class, co-developer of the flush seismograph, and fullback of the football team. His collegiate career was punctuated by stints in the Marine Corps (1942-46, 1950-52) and culminated in doctoral work in Sierra Pelona and the Soledad Basin, California.

He then strode out of Southern California, Ph.D. in hand and bolo around his neck, to begin a 50-year affiliation with the University of Texas at Austin – as professor, chairman, and now professor emeritus in the Department of Geological Sciences. His research and that of his 84 M.A. and Ph.D. students have resulted in hundreds of publications, and his distinguished teaching has garnered eight awards and endowed professorships. Continent- and hemisphere-scale projects reflect the scope of his thinking – he directed production of the first *Basement Rock Map of the United States* (USGS, 1968). He compiled the most recent *Tectonic Map of North America,* grounded in plate tectonics concepts (AAPG, 1996), and for those efforts was given the Outstanding Paper Award (1998) of the GSA Structure and Tectonics Division.

Beyond the continents and hemispheres of Earth, others of Bill's students have conducted field studies on the Moon. Taos Plateau and the Rio Grande gorge provided excellent geological analogues to features near Apollo mission landing sites. Bill was principal investigator for geology for the Apollo 16 and 17 missions, and he continued to instruct astronauts in Earth observations from Skylab, Apollo-Soyuz, Space Shuttle, and the International Space Station. Two NASA medals attest to his contributions to astronaut and public instruction in geological and solar system exploration: the 1973 Medal for Exceptional Scientific Achievement and the 1999 Public Service Medal. His most recent NASA encomium (May, 2010) was a Team Innovation Award from Johnson Space Center.

Space explorers and schoolchildren, teachers and graduate students, retirement home residents and youth groups – legions of us throughout the world can state that Bill Muehlberger has changed the way in which we view our planet.

— *Patricia Wood Dickerson*

William R. Muehlberger
Graduate Fellowship in Structural Geology/Tectonics

The idea of the WRM Fellowship began about three years ago when Pat Dickerson started kicking around the idea of a "Tech Fest" in honor of Bill Muehlberger. A major logistical problem was that Bill's students, friends, and family had scattered over the face the Earth (when they stayed on the planet) pursuing highly varied and successful careers. Pat persisted and about a year ago dragooned a very willing contingent of Bill's graduate students, his family, and the Jackson School into pulling this Research Symposium together.

We realized that we also wanted to create a permanent gift to the University of Texas at Austin in Bill's name. We discussed partially funding construction of the new student facilities at the Jackson School and purchasing equipment for the labs, but everyone we asked for ideas came back to how much Bill loved to teach. Bill had taught us for a half century and we wanted to assure that his love of learning would continue through the next half century. We initially decided on a Scholarship fund and then changed our minds after thinking about the individual we wanted to honor. Therefore, in keeping with the Bill Muehlberger tradition of encouraging us to do better than our best, to go farther than we thought possible, we raised our goal from a Scholarship to a Fellowship.

We founded the Endowment Charter for a Graduate Fellowship in Bill's name at the Jackson School of Geosciences on May 1, 2010 with the goal of raising a minimum of $250,000 over five years. The Jackson School – and in particular, Kimberly Rose – provided much of the day-to-day work of helping raise the required funds.

The function of the WRM Fellowship, as a permanent and evergreen fund, is to help attract the best graduate students in structural geology to the Jackson School and to defray their living expenses once they arrive, so that they might concentrate on their studies. When it came to defining the qualifications of a candidate graduate student, we asked Bill to write the requirements for the Fellowship. Bill's words and choices are included this paragraph extracted from the Endowment Charter:

"Said funds shall be used to establish the William R. Muehlberger Graduate Fellowship in Structural Geology/Tectonics as a permanent endowment for the benefit of the John A. and Katherine G. Jackson School of Geosciences. Funds distributed from the endowment shall be used to award a fellowship to a graduate student possessing the greatest breadth and depth of geologic knowledge and who is focused on a research project aimed at resolving an important structural geology or tectonic problem. An annual award is not required if no sufficiently qualified candidates can be found, and unused distributions should be reinvested back into the principal of the corpus. The award shall be awarded in consultation with the Chair of the Department of Geological Sciences or his/her designee."

Thanks to all of you who have donated so generously and who have made this Fellowship viable in a remarkably short time.

Thank you, Bill, for giving so much of yourself for such a long time.

— Lisa K. "Rusty" Goetz

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Research Symposium Honoring
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FRIDAY, AUGUST 27, 2010
6:00 – 9:00 p.m. OPENING RECEPTION
Sponsored by Jackson School of Geosciences
Welcome & Structure of Symposium — Patricia Dickerson & Mark Cloos, Convenors

SATURDAY, AUGUST 28, 2010
8:15 – 8:30 a.m. Opening remarks — Sharon Mosher, Dean, Jackson School of Geosciences

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Tim Denison, Convenor

8:30 Tim Denison
Buried Basement Rocks Uncovered, 1962-1964

8:45 Sharon Mosher
Advances in Understanding of Grenvillian Orogenesis in Texas

9:00 Robert Hatcher, Karl Karlstrom, Rodger Denison, Jason Saleeby, Zorca Saleeby, Randy Keller, Suzan van der Lee, W. R. Muehlberger
The Transcontinental (I-40) Geologic and Geophysical Cross Section: Technical and Non-Technical Versions, Inspired by Bill Muehberger and Marcus Milling

9:15 Mark Cloos
High-Level Nuclear Waste in Japan: The Problem and Plan

9:30 Ray Leonard
World Oil Reserves and Production: Past, Present and Future

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Thematic Global Maps and Basin Classifications POSTER
Or Wie Sag Ich Es Meinem Kinde?
Presentation to Muehlberger: *Atlas of Thematic Global Maps*

Bill St. John – Tectonics of the Western Indian Ocean POSTER
Poster on display. Abstract in this volume. Regrettably, no oral presentation.

10:00 – 10:15 Break, refreshments
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10:15 a.m. – 2:45 p.m.
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David Dunn, Convenor

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10:30 Ian Norton
Continental Crust Spreading: a Process for Synextensional Creation of Continental Crust Inferred from Analysis of the Evolution of Death Valley

10:45 C. M. Woodruff, Jr.
Engineering Geologic Problems near the Mt. Bonnell Fault – Homage to W.R. Muehlberger and Richard H. Jahns

11:00 Eric Muehlberger
A Muehlberger-Trained Geologist

NEW MEXICO
11:15 Paul Bauer
Bill Muehlberger: Honorary New Mexico Field Geologist

11:30 William R. Muehlberger
Rio Grande Rift of Northern New Mexico – Geological and Geophysical Training Ground for Astronauts from Apollo Missions to the Present

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WEST TEXAS
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Hell's Half Acre Thrust, Marathon Basin, Texas: History of Understanding Out-of-Sequence Thrusting

1:15 Patricia Dickerson, Richard Hanson, Jonathon Roberts and Mark Fanning
Magmatism in the Western Ouachita-Cuyania Basin – Evolution of the South-Central Laurentian Margin

1:30 Richard Erdlac
Structure and Tectonics of the Permian Basin and Trans-Pecos Texas – A Review of Published and Unpublished Oddities

1:45 Patricia W. Dickerson, Edward W. Collins, and William R. Muehlberger
Big Bend of the Rio Grande: Geologic Mapping by the Muehlberger Cohort and Research Prospects POSTER

2:00 Michael Wiley
Gravity and Magnetometer Survey, Culberson and Hudspeth Counties, Trans-Pecos Texas: from Texas Lineament to Rio Grande Rift

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Breaks sponsored by Lisa K. Goetz

2:30 – 5:15 p.m.
Theme: Lunar Geology & Human Exploration of Space
Jim Head, Convenor

2:30 Jim Head
Basin Formation on the Moon: New Insights since Apollo

2:45 Charles Duke
Exploring the Descartes Highlands of the Moon

3:00 William Ambrose
Origin, Distribution, and Chronostratigraphy of Asymmetric Secondary Craters and Ejecta Complexes in the Crisium Basin POSTER

3:15 Harrison "Jack" Schmitt
Apollo 17 Lunar Exploration and Its Implications

3:30 Cliff Frohlich, Yosio Nakamura and Jennifer Glidewell
Possible Extra-Solar-System Cause for Certain Lunar Seismic Events

3:45 Yosio Nakamura
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A New Lunar Roadmap for a New Era of Exploration: Building upon the Past for a Productive Future

4:15 Joe Reese
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4:30 Alexander Ritchie
Geologic Observations from Skylab, America's First Space Station, 1973-1974

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Sponsored by Marathon Oil

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Presentation to Muehlberger – Duane Ross (NASA-JSC) and Patricia Dickerson
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SUNDAY, AUGUST 29, 2010

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8:45 Ricardo Padilla y Sánchez
Tectonics of Eastern Mexico, 1980-2010: What We Knew Then, What We Know Now

9:00 Peter Hennings
Geometry of Thrusts and Folds in the Chihuahua Tectonic Belt

9:15 Mark B. Gordon, Cecilia Pall-Gordon, Ann E. Blythe, Peter Copeland, Raymond Donelick, Benoît Deffontaines and Jacques Angelier
Tectonic Evolution of the Chortís Block: Age Constraints

9:30 Peter A. Emmet
Structure and Stratigraphy: A Comparison of Onshore and Offshore Honduras

9:45 Paul Mann
Why Geologic Field Work Is Still Important in the Caribbean and Other Areas

10:00 Rob Rogers, Chris Hammond and Kait Barber
Basal Stratigraphy of a NW-Trending Jurassic Rift in Honduras (Chortis Block)

10:15 – 10:45 Round Table Discussion: Reminiscences of the Early Years in Honduras and Guatemala (John Everett, Ric Finch, Zan Ritchie, Bill Dupre, et al.)

10:45 - 11:00 Break, refreshments
Breaks sponsored by Lisa K. Goetz

11:00 – 12:00 POSTER SESSION – authors present

12:30 CLOSING LUNCHEON
Sponsored by ConocoPhillips

Speaker: William R. Muehlberger
"Let Me Tell You How It Really Happened"

Presentation to Muehlberger – Sharon Mosher
W. R. Muehlberger Graduate Fellowship in Structural Geology & Tectonics

Abstracts

(alphabetical order by first author)

Origin, Distribution, and Chronostratigraphy of Asymmetric Secondary Craters and Ejecta Complexes in the Crisium Basin

William A. Ambrose
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The Crisium Basin is an asymmetric, multi-ring basin of Nectarian age. It is ~740 km in diameter, although there is evidence for a discontinuous 1,000-km-diameter outer ring. The basin contains several radially distributed, asymmetric secondary craters and genetically associated scours and crater chains. These asymmetric secondary craters have polygonal outlines and narrow rims, range in diameter from 10 to 30 km, and are shallow floored (commonly <1.5 km deep). Many are teardrop shaped, reflecting low-angle impacts. Similar morphologies for low-angle impacts have been demonstrated experimentally. The trajectory and source area of these types of secondary craters can be inferred from the orientation of their teardrop-shaped rims, which point away from impact sites. Asymmetric secondary craters in the Crisium Basin are part of a morphological continuum of ejecta features including teardrop-shaped craters, elongate craters, crater chains, and shallow-floored valleys, all present on the southeast margin of the basin. Asymmetric secondary craters in the Crisium Basin are differentiated from morphologically similar, primary craters by shallow floors; lack of slumps that produce asymmetry in small, complex, main-sequence craters; moderate to high levels of degradation owing to Nectarian age; long axis orientation radially from the basin center; and association with scours and crater chains. Other Crisium ejecta features are present to the north and northwest. The overall distribution of ejecta reflects an oblique impact from the west, resulting in a downrange butterfly-wing ejecta pattern consistent with ejecta patterns observed in experimental studies of oblique impacts, remote sensing, and modeling. Asymmetric secondaries associated with lunar basins are unique morphological features that can be used to constrain estimated ages of overlapped, extrabasinal landforms such as other craters, scarps, and ejecta from other basins. For example, the crater chain that includes Cartan (formerly Apollonius D) was previously interpreted to be Lower Imbrian in age. Based on its morphology, orientation, and association with other ejecta features, Cartan is interpreted to be Nectarian owing to its origin as Crisium ejecta. The number and degree of preservation of asymmetric secondary craters and scour features in the Crisium Basin is comparable to that of the Nectaris Basin. Asymmetry in the distribution of ejecta in the Humorum Basin is also attributed to postimpact lava flooding rather than the result of an oblique impact. The low density of well-preserved asymmetric secondary craters in the Humorum Basin relative to those of the Crisium and Nectaris Basins suggests that the Humorum impact event is older than either the Crisium or Nectaris impact events. However, this must be confirmed by acquiring radiometric age data from ejecta fields in these basins to establish a robust relationship between impact basin age and density of well-preserved ejecta features.

Thematic Global Maps and Basin Classifications

Albert W. Bally, Professor Emeritus
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This set of simplified , thematic global maps was designed to enhance the dialogue between specialized earth scientists, students and professors, explorationists and management etc . The maps aim to support basin classifications that serve as background analogues for hydrocarbon volume forecasts ranging from basin-wide to prospect scale. Except for polar maps all maps are on the same Mercator projection Most sedimentary basins have a polyphase evolution that varies widely among basins of different classes and also between basins of a single class .

A consensus on the best criteria for a commonly accepted basin classification has yet to be reached . Academic concepts and numerical models tend to assume a given basin origin subsequentiy evolving in a " canonical order " and following a trend that is compatible with the popular "Wilson Cycle ". Alas , in reality this cycle , like so many other tectonic "cycles " rarely , if ever , returns to the same 3- dimensional starting position. Instead , we see recurring themes and many variations thereof repeating themselves in different places and during different times .The purpose of this map series is to show the global distribution of key attributes of selected tectonic themes and their relation to other geologic themes. Given time, the number of tectonic themes to be shown on additional maps could expand greatly.

Hydrocarbons systems evolve through times. Explorationists typically deal with the presently completed evolution of a basin, basin -separating arcs or else other long - wavelength uplifts. Thus tectonic processes, that are remote from the original cause and area of the early inception of the basin , often overwhelm the original basin-forming themes.

The tectonic evolution of sedimentary basins is best summarized in terms of Tectono-Stratigraphic (TS) megasequences that correspond to tectonic themes . Regional and sub-regional unconformities separating TS megasequences are best recognized on long regional reflection seismic transects . TS megasequences also correspond to all tectonic themes displayed today on global maps digital elevation maps in various stages of their evolution.

Bill Muehlberger: Honorary New Mexican Field Geologist

Paul Bauer
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Typing "Muehlberger" into the New Mexico Geologic Bibliography Database returns 47 hits. If not a spectacular number, then close to it, especially when we bear in mind that most of his professional life was spent working elsewhere. Moreover, the list contains: very few abstracts; two of the state's most popular geologic tour books; a handful of highly significant and often-referenced papers; and a series of trailblazing geologic maps that cover ~1000 square miles of geologically complex territory. What is truly remarkable is that Bill's publications span 50 years, from 1955 to 2005, and represent an amazing cross section of topics, from Precambrian petrology to the Quaternary evolution of the Rio Grande gorge.

His 1955 GSA Bulletin publication is titled *Relative age of Folsom Man and the Capulin Mountain eruption, Colfax and Union Counties, New Mexico*. The Folsom site is famous and enormously significant because projectile points were found with extinct bison bones, indicating that humans occupied the area much earlier than had been thought. Bill applied principles of stratigraphic correlation in an attempt to bracket the times of the bison hunt and the lava flows. The impact of this paper was felt well beyond the field of geology, and continues to be cited in even the most recent archeological papers on the site.

His 2005 New Mexico Bureau of Geology publication, *High Plains of northeastern New Mexico: Guide to geology and culture*, was a collaborative effort with Sally and a substantial reworking of his classic 1961 scenic trip to the High Plains. How many authors publish major book revisions 44 years later? We are grateful that Bill did, as this is one of our best-selling books, and a winner of the New Mexico Book Award.

Bill's career in New Mexico can be rather nicely divided into four phases of research. The preamble to these phases began when, as an undergrad at Cal Tech, he signed on as field assistant to Prof. Dick Jahns to work in the Ojo Caliente pegmatite district of north-central New Mexico in August of 1947, work that ultimately led to Jahns' 1953 opus on the origin of pegmatites. Upon finishing his PhD in 1954 and landing a faculty job at UT Austin, Bill straightaway plunged back into northern NM, enticed by summer support from the NM Bureau of Geology, a mutually rewarding relationship that has lasted for 55 years.

<u>Phase 1</u>: Northeastern NM (1954-1957). Bill mapped the Des Moines 15' quadrangle in cooperation with Brewster Baldwin, who was preparing a bulletin on the geology of Union County. Bill's field area covered a complicated inverted volcanic stratigraphy, the captivating Folsom Man site, and Capulin Mountain National Monument, the easternmost Cenozoic volcano in the US. The geologic map they constructed is still the definitive work. Our aquifer mapping program has just begun a hydrogeologic study of Union County in which their geologic map is the cornerstone. Bill assigned two graduate students to work in northeastern NM, one of whom was Charlie Mankin (PhD, 1958) who went on to become the

state geologist of Oklahoma and was pivotal in masterminding the STATEMAP geologic mapping program in the early 1990s.

<u>Phase 2</u>: Chama country (1957-1970). It took Bill ten years to orchestrate his return to Dick Jahns' high country. Bill was clearly in his element, as he and his nine graduate students dissected the geology of the region in a spectacularly productive manner. The students were devoted to pure field studies with titles such as *Geology of the Chama Area*. Bill and students put out a number of influential papers on the structure and tectonics of the Brazos uplift and Precambrian of the Tusas Mountains. Bill completed the Ojo Caliente 7.5' quad in 1960. Remarkably, when STATEMAP remapped the quad a few years ago, Bill was a coauthor 45 years after he thought the quad was done. Two of Bill's 15' quads (Chama, 1967; Brazos, 1968) are still in print. In 1982, Bill and Sally wrote a lovely guidebook to the region–the famous "red chile" scenic trip–which became another bestseller for our publications program. We're now working with Bill on a revised edition.

<u>Phase 3</u>: Taos to the Moon (1970-2005). After Bill was appointed Principal Investigator for Field Geology for the Apollo 16 and 17 missions in 1970, he and Lee Silver chose the Rio Grande Gorge as a geologic training analog for the Apollo 15 and 16 lunar landings. Beginning in 1980, Bill began teaching a four-day geo-tour of northern New Mexico, which virtually all of the Shuttle and Space Station astronauts have now attended. Bill and Sally's "red chile" guidebook became the textbook for the training. Although Bill has retired from astronaut training in New Mexico, his vigorous program lives on.

<u>Phase 4</u>: The Rio Grande rift near Taos (1978-1985). At the age of 55, Bill staked claim to one of the most spectacular field areas in the country. In a rather short time, he and his five graduate students had explored its Proterozoic sedimentology, Pennsylvanian stratigraphy, Laramide orogeny, rift evolution, Cenozoic volcanism, Neogene deformation, tectonic geomorphology, and Quaternary geology. Bill recognized the significance and complex character of rift accommodation zones, and he deciphered the elaborate interplay among rift tectonics, sedimentation, volcanism, and geomorphology, all of which were presented in a suite of papers.

In the late 1980s, as a new geologist with the NM Bureau of Geology, I was assigned to map quads in the Taos region. Lucky for me that I discovered the readable and insightful body of literature with the name Muehlberger attached. Shortly thereafter I met Bill in the field and we have been friends ever since. Even though I continue to refer to his books, papers, and maps on a regular basis, I now value his camaraderie and spirit even more than his scientific legacy. Clearly, Bill's dedication to the Land of Enchantment was not inspired by a desire to study any single geologic topic, but rather by his yearning to be working in the glorious landscapes of northern New Mexico, on whatever topic happened to be on hand. It is not unreasonable to speculate that had a teaching job opened up at UNM in 1954, this symposium would be taking place in Albuquerque rather than in Austin. Those of us who have tracked Bill Muehlberger's sizable boot prints across northern New Mexico are profoundly appreciative of his many contributions, and are honored to offer him the rank of Honorary New Mexican Field Geologist.

Compressive Structures in the Shoshone and Cortez Ranges, Lander and Eureka Counties, Nevada

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This study discusses three phases of deformation in the Shoshone and Cortezranges of northeastern Nevada. Barrick Gold Corp has a 1,500 km^3 land package that straddles the Eureka-Battle Mountain Trend, centered on the Cortez and Gold Acres mining camps. Four windows of lower plate carbonate rocks are exposed which are overthrust by at least five plates of western facies. Systematic mapping and drill evidence collected during exploration of the mining camp provides the opportunity to look at a 50km long cross-section striking NW through the Roberts Mountain thrust belt which extends 140km from Battle Mountain to Eureka.

The lower plate carbonate rocks and the upper plate siliciclastic sequences exhibit well organized sequence stratigraphy. However, near the Roberts Mountain thrust, the upper plate and lower plate formations are found to be folded to an extreme degree both perpendicular and parallel to formation boundaries while maintaining stratigraphic integrity. The intensity of the folding suggests that up to five hundred percent shortening of the strata occurred prior to the obduction of the upper plate thrust complex. It is proposed that the first phase of obduction required the dewatering, thickening and folding of the marine strata including some of the carbonate apron. The strata are folded until they are perpendicular to the strain direction much like a shutting accordion. At this point, ductile processes cease and phase two brittle deformation begins as the rocks obduct onto the continent along a decollement zone. In the Pipeline Pit the decollement zone has 50 meters of augen mylonite between the upper plate rocks and lower plate rocks. On either side of the decollement, the upper plate and lower plate rocks are ripped up and shuffled to form a shingled stack of out of sequence strata up to 600 meters thick. In the Cortez Range the decollement mylonite is 10-20m thick and the imbricated zone ranges from 50-100m. In the Shoshone Range two to four coherent thrust sheets are emplaced over the imbricated zone, and at least two of these sheets are identified in the Cortez Range.

During the third phase of deformation, the overburden strain rate exceeds the competence of the continental margin and large-scale blind thrusts are formed. Asymmetric, eastward vergent, overturned folds with amplitudes up to 5km are located over the blind thrusts that cut through the RMT, but only the first, second and third thrust plates are affected. In the Shoshone Range, the Penn/Perm rocks of the overlap sequence lie on top of the fourth and fifth plates that are not involved in this latter deformation providing evidence that the folding affecting the three earlier plates is Antler in age.

This style of deformation probably affects all the pre Antler rocks that lie west of the study area and possibly east into the Simpson Park Range and represents at least 75% of the Roberts Mountain thrust belt. A similar style of deformation is present in the Independence Range around the Jerritt Canyon mine camp. Extensive surface mapping and subsurface drill interpretation has documented significant thrust related stratigraphic thickening and thinning at the Cortez and Gold Acres camps. Application of mathematical section techniques with constant stratigraphic thicknesses does not appear to accurately model the structural complexity of the camps.

High-Level Nuclear Waste Disposal in Japan: The Problem and the Plan

Mark Cloos
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The scientific, technical, and sociopolitical challenges of finding a secure site for a geological repository for radioactive wastes are daunting. Perhaps the extreme case is the nation of Japan, located in a very active segment of the Pacific "Ring of Fire, " which produces nearly 35% of its electrical power from 55 nuclear reactors. Japan has carried out many years of research into waste reprocessing, storage, and disposal. In 2000, the government created the Nuclear Waste Management Organization of Japan (NUMO) to find a repository site for high-level waste (HLW). The decision was made to recycle spent fuel via reprocessing. The remaining waste will be immobilized as a glass. The vitrified material will be put into at least two metal containers (including stainless steel overpacks) which will be stored in an above-round storage facility for at least 30 years, a period over, which the heat generating capacity of the waste will have decreased by about 50%. The metal containers will be inserted into stable bedrock and encased in a layer of bentonite clay, which will retard any influx of groundwater or the escape of radionuclides from compromised containers. Extensive work has been completed on the engineered barrier system. Japanese regulators have mandated that a waste repository will have to be located at least 300 m below the surface and at least 15 km away from Quaternary volcanic centers. Other excluding factors include high uplift rates, inappropriate rock formations, or potential mineral resources in the area that could attract exploration activities that could compromise a repository. The area needed for a repository capable of storing a centuries worth of Japan's HLW at present production rates is less than one square kilometer. The combination of engineered and passive geologic barriers will ensure the containment of HLW for many tens of thousands of years.

NUMO's task centers on finding a geologically stable site that is in a politically acceptable location. Assessing the geologic stability of square kilometer areas is the focus of this talk. The fundamental strategy in site selection in Japan is the avoidance of potential tectonic hazards. The first-cut avoidance criteria for magmatism are the 15-km-radius circles around the ~350 volcanic centers listed in the Japan Catalogue of Quaternary Volcanoes. The systematic analysis of satellite vents and dike propagation distances in Japan and elsewhere is under investigation. Notably, northeast Honshu has no late Cenozoic activity to the east of a distinct line known as the volcanic front that lies about 85 km above the Wadati-Benioff seismic zone. Most Quaternary volcanic activity occurs in clusters with amagmatic gaps many tens of kilometers wide.

Active faults are to be avoided, but no exclusion distance criteria has been established. Japan has many well mapped active faults that must be avoided. One concern is that active faults evolve with time and the locus of movement can switch from one strand to another as well as fault tip extensions into unbroken rock. However, the fundamental concern is for earthquake ruptures during events that are greater than about

M6.8. Smaller events very rarely have ruptures that reach the surface. Japan has a remarkable historical record that extends back to about 1580 for events larger than M7. The instrumental record in Japan extends back to 1880. All events larger than M5 have been recorded and located since the 1920s. Geologic mapping and an extensive program of trenching has resulted in a comprehensive active fault map of movements over the past 10,000 years. In some areas, strata directly record local stability into the Miocene or even before. The nation of Japan began a national triangulation network in 1883 with about 300 stations spaced 50 km apart. In 1973, a precise geodetic network with 2760 stations measuring 7700 line distances and 950 angles was established in 1973 in the name of improved earthquake prediction. Since 1997, Japan has a continuously monitoring GPS network of 1200 stations spaced in a grid about 25 km apart (GEONET) that enables detection of movements with a precision approaching 0.1 ppm/yr. This corresponds to direction detection of crustal motions at rates less than 1 mm/yr. The Japanese Seismic Hazard Classification is three-fold with Class A faults having displacement rates between 1 to 10 mm/yr. Class B faults have displacements rates of 0.1 to 1 mm/yr. All regions with Class A fault activity, and most with Class B are directly detectable with GPS monitoring.

Active tectonic movements around the world are now monitored with GPS technology. These movements have been, and will be routinely, compared to the recent geologic history across broad regions. It is now clear that about 80% of the Earth surface is just translating along, internally undistorted for many millions to, in the interior of some continents, more than one billion years. From the point of view of tectonic stability, there are large areas suitable for siting nuclear power plants or hosting HLW repositories. Nevertheless, countries such as Japan will have to locate their waste repositories in and near zones of active deformation. Parts of plates that have internal movements are now measurably different with GPS technology from the bulk of the plate are known as subplates or diffuse deformation zones. The problem of site selection in such areas is a challenge, but solvable because even within diffuse deformation zones there are blocks of crust with dimensions of tens of kilometers and more across, which will not undergo permanent internal distortion over the next 100,000 years.

The demonstration that a site is tectonically stable and thus suitable to host a nuclear power plant or a HLW repository will arise from the integration of traditional geologic analyses that indicate negligible local deformational activity in the past million years or more with confirmatory GPS measurements. The prediction of future stability is bolstered by GPS measurements across the region because they enable the identification of the locations where current tectonic movements are accomodated. Tectonically suitable sites for the permanent disposal of high-level nuclear waste are widespread, even near regions with active fault activity. The larger problem in the matter of tectonic hazards and radioactive waste disposal is the issue of increasing the public awareness of how the crust of the Earth actually behaves.

Reference

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Hell’s Half Acre Thrust, Marathon Basin, Texas: History of Understanding Out-of-Sequence Thrusting

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The Hell’s Half Acre Thrust Fault (HHATF) is the major boundary between structural domains in the Marathon basin (Muehlberger et al, 1984). It separates gently folded rocks to the north from tightly folded and intensely faulted Hell’s Half Acre Thrust Sheet. The HHATF has long been documented to cut down stratigraphic section and across older, open folds in the foot-wall, thereby documenting thrusting after folding (King, 1937). Detailed mapping (King, 1937; DeMis, 1982) shows the HHATF is bounded by Mississippian Tesnus Formation and includes blocks of older Caballos and younger Dimple Formations. Therefore, the basal detachment cannot be located in a single over-pressured shale horizon, but truncates folds at depth. DeMis (1983; 1985) showed “non-classic” structural styles within the HHAT sheet. Out-of-sequence thrusts (OOST) cut folds in the footwall, and blocks of younger Dimple Limestone are lodged in fault zones bounded by older Tesnus Formation.

Classic thrust belt concepts (e.g., Dhalstrom, 1970; Suppe, 1983) do not apply to the Marathon basin (DeMis, 1985) because their simplistic premise was that mechanical stratigraphy is identical for every thrust belt. Thick, rigid lower Paleozoic rocks dominated the “miogeoclinal” sequence of the Canadian overthrust, and create a unique mechanical stratigraphy and structural style. Marathon basin stratigraphy contains thinly bedded limestones and cherts, and sandstones with low sand-shale ratios and numerous thick shale layers in a “eugeoclinal” succession (DeMis, 1984). Advancements in understanding mechanics of thrust propagation (e.g., Nieuwland et al, 2000 and references therein) show a relationship between OOST and the taper angle whereby OOST in the hinterland maintain the critical taper angle.

Since the mid-1980s, numerous papers show that OOST are common in thrust belts (e.g., Morley, 1988, and references therein). An OOST can develop where a pinning point forms in front of the advancing thrust sheet (Figure 1). DeMis (1982) suggested a similar mechanism where crowding by the emerging Dagger Flat anticlinoium acted as a buttress to the HHATF. Out-of-sequence thrusting is documented in active mountain belts (e.g., Wobus et al, 2004). In accretionary prisms, such as the Nankai trench, OOST cause major earthquakes and provide the mechanism for transporting deeply buried rock to surface where they slump into the fore-basin (Moore et al, 2007).

The Pennsylvanian Haymond boulder beds include a variety of Marathon basin rocks, plus igneous and metamorphic rocks, and unique middle Cambrian rocks of North American affinity (DeMis, 1983; Palmer et al, 1984). In the Marathon Basin, a deep OOST thrust cut North American strata in the footwall of the orogenic belt and “re-cycled” these middle Cambrian rocks into the Pennsylvanian boulder beds. The geometries of the Hell’s Acre Thrust Sheet are a result of the mechanical stratigraphy and out-of-sequence thrusting. The Hell’s Half Acre Thrust Sheet provides a wonderfully well-exposed example of out-of-sequence thrusting in the hinterland of an orogenic belt.

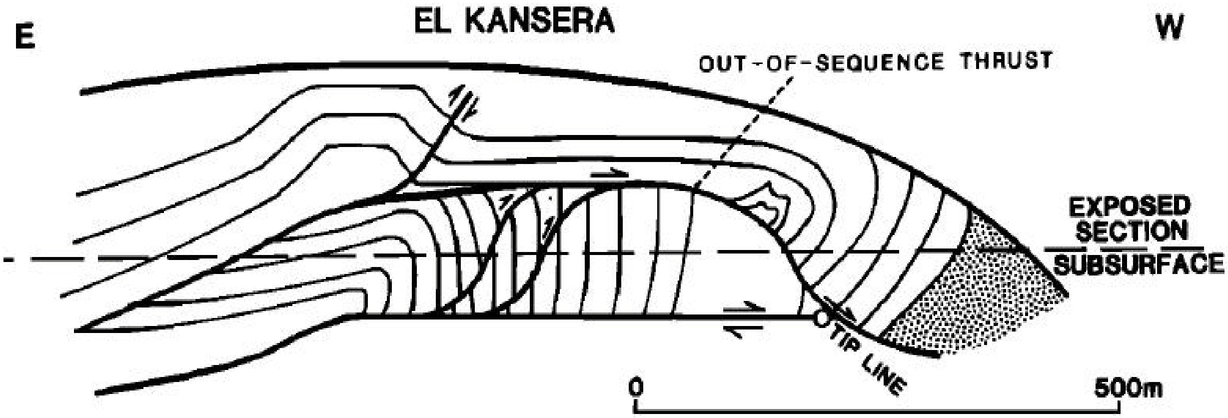

Figure: The El Kansera locality of the Morooccan Rif shows beheaded folds in the footwall and hanging wall of the OOST (Figure from Morley, 1988; figure 10).

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Buried Basement Rocks Uncovered, 1962-1964

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The Cold War competition had a curiously beneficial effect on the earth sciences. The press to distinguish underground nuclear tests from earthquakes led to enormous funding for fundamental deep earth geophysics. It was determined that an understanding of the basement rock largely covered by Phanerozoic rocks in the vast Continental Interior might be helpful in reaching a solution. The project was administered by the U.S. Air Force under VELA UNIFORM..

W.R. Muehlberger of The University of Texas got the funding to do the job in late 1961. Flawn's 1956 study of the basement rocks in Texas and southeast New Mexico had shown that the petrographic study of samples, drilled largely in search of oil and gas, could be used to construct a rock distribution map of the Precambrian. The challenge was to look at all available samples from wells to basement throughout the vast Continental Interior. There were thousands of wells. In order to get an age framework the USGS, under S.S. Goldich, teamed with the petrographic study to offer Rb/Sr and K/Ar analyses of representative rock types.

It was the best of times for the basement group, going to all the national meetings and interacting with what was probably the most distinguished group of deep-earth geophysicists ever assembled to study a single problem.

The basement surface on which the Phanerozoic seas transgressed, with rare exceptions, was an incredibly flat. The basement was composed largely of silicic igneous rocks >1000 Ma in age and typical of the scattered present day outcrop exposures in the Interior. Except for the intercratonic basins the basement today is buried at shallow depth by largely Paleozoic strata.

Thinking about the Precambrian had been dominated by studies on the Canadian Shield where pioneer K/Ar studies had shown consistent age patterns. The rocks exposed had been formed at great depth. This extended into the northern Interior where, using potential field geophysics and sample examination, the Shield units could be carried beneath sedimentary cover. To the south the level of erosion and deformation seen in the basement diminished. In the extreme, typified by the vast rhyolite fields found in Texas and Oklahoma

The study showed that a true geologic map of the buried basement could be drawn. The final report synthesizing the basement rock examinations and ages was delivered to the Air Force in September of 1964. The summary basement text was published by the AAPG in 1967 and the basement rock map by the USGS in 1968. The basement rock framework had been set for the Interior.

Big Bend of the Rio Grande: Geologic Mapping by the Muehlberger Cohort and Research Prospects

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Most recent mapping has focused on the Glenn Spring and Mariscal Mt. quadrangles, Big Bend National Park, West Texas (Collins et al., 2008; Dickerson et al., in press). Three NNE-aligned felsic intrusions dominate the bedrock geology of the Glenn Spring area: Chilicotal Mt. (~6.8 sq km), Glenn Spring (~3.3 sq km), and Talley Mt. (~1.9 sq km) sills. They were emplaced in Upper Cretaceous to Paleocene siliciclastics, and the outer few meters of all are strikingly liesegang-banded. The age of the Glenn Spring porphyritic microgranite is 30.5 Ma (Ar-40/Ar-39, K-feldspars; D. Miggins, USGS), falling within the regional Eocene-Oligocene magmatic episode; Chilicotal Mt. alkali syenite and Talley Mt. porphyritic microgranite remain undated. All are Ti-rich (titanaugite, titanite, Ti-biotite); sodic amphibole is abundant and olivine is present in the Chilicotal sill, but both are absent from the other two. The Glenn Spring and Talley Mt. masses may be comagmatic (analyses in progress). The massive syenite that caps Chilicotal Mt. is intruded by a distinctive basalt porphyry sill, and dikes of that composition cut both the Chilicotal and Tally Mt. bodies.

Magmas feeding the intrusions ascended through lithosphere that was accreted to Laurentia during the late Paleozoic collision with Gondwana. Subangular to subrounded microxenoliths to boulders (>1 m) of quartzite, schist, and marble throughout the Chilicotal Mt., Glenn Spring and Talley Mt. sills attest to tectonism at the ancient margin. In inventoried areas of Glenn Spring sill, abundances ranged from 3 or 4 to 9 or 10 xenoliths per sq m, increasing toward the center of the intrusion. Compositions, metamorphic grade, and deformational history are essentially identical to those of Ouachita metamorphic rocks (~277 Ma) exposed in the Sierra del Carmen, Coahuila, ~35 km farther east. In addition, the xenolith suite includes meta-quartz monzonite, which is not yet documented from Coahuila outcrops, and which requires geochemical/geochronological assessment of this possible evidence of collisional anatectic melting.

Neogene-Quaternary structures in Glenn Spring quadrangle include N-striking normal faults, related folds. Multiple Quaternary landslide episodes are documented on Chilicotal and Tally Mts. Holocene landsliding in the SE Chisos Mts. was followed by the flooding of Juniper Draw, recorded in a 15-mi-long debris flow of diagnostic coarsely crystalline granite boulders.

The portion of Mariscal Mt. within Big Bend NP is a ~15-km-long anticline that is well expressed in Lower Cretaceous carbonate rocks, in an Eocene gabbro sill, and in undated rhyolite sills. At least eight geologic events are recorded on the mountain: Early Cretaceous marine sedimentation is represented by carbonate and argillaceous strata of the Del Carmen, Sue Peaks, Santa Elena, Del Rio, Buda, and Boquillas Formations. Late Cretaceous marine and continental sedimentation gave way to early Tertiary (Paleocene) continental deposition; the Pen, Aguja, Javelina, and Black Peaks formations are products of that progression. Late

Cretaceous – early Tertiary (Laramide) contractional deformation has been considered responsible for the folding and thrust faulting on Mariscal Mountain. The youngest folded formation preserved in the map area is the Aguja; Javelina strata, however, are folded farther north where the NNW-striking anticlinal axis extends into the Glenn Spring quadrangle (Collins and others, 2008). The extensive gabbro sill in the anticline (46.7 ± 0.3 Ma, Eocene) postdates Laramide orogenesis and has been interpreted as an intrusion into a preexisting structure, in part on the basis of paleomagnetic data (Harlan et al., 1995). The large rhyolite sills in the anticline remain undated; thinner rhyolite and basalt sills are thrust-faulted in the nose of the fold. Questions remain regarding timing of, and relations among, contractional deformation and magmatism.

Post-Cretaceous densely welded rhyolite tuff (undated) on the floor of Mariscal Canyon is likely a remnant of a more widespread deposit, which was preserved in a depression in Cretaceous rocks. The tuff mass could have foundered into a solution-collapse cavity, as are common on the mountain and in the canyon. It may also have been let down in response to undercutting by the Rio Grande and removal of fractured and less resistant Cretaceous rocks. Eocene time was marked by emplacement of the major gabbro sill (46.7 ± 0.3 Ma; post-Laramide) in Boquillas through Pen strata (LK). Undated Tertiary intrusions include extensive rhyolite sills, as well as lesser rhyolite and basalt dikes and sills on the east flank and in the nose of Mariscal anticline.

Neogene to Quaternary extensional deformation has occurred during evolution of the Sunken Block graben system of the Rio Grande rift; dominantly N-striking normal faults disrupt preexisting structures and displace Quaternary alluvium. Solis graben (Quaternary) lies along the east side of Mariscal Mountain (just off map). Neogene(?) to Quaternary solution collapse features in folded, faulted, and fractured Santa Elena Limestone, Buda and Boquillas formations (LK) formed on both the crest and the flanks of the mountain. In the eastern sinkhole shown on cross section B-B', both Boquillas and segments of Tertiary rhyolite sills have been dropped into the void. Quaternary landslides on the southern apron of Talley Mountain (northern map area) record multiple episodes of sliding. Detachment has generally been in bentonitic clays of the Javelina (UK) and Black Peaks (Paleocene) Formations.

Muehlberger students who have conducted research in the Big Bend (*see* list of theses and dissertations, this volume) include: Bumgardner (Mariscal Mt.), Cobb (Santiago Mts.), DeCamp (Mesa de Anguila), Dickerson (Tascotal Mesa fault zone), Erdlac (Terlingua Uplift), Maler (Boquillas Canyon), Mustafa (Sierra del Carmen), Poth (Santiago-Sierra Del Carmen), and St. John (Black Gap).

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Magmatism in the Western Ouachita-Cuyania Basin and Evolution of the South-Central Laurentian Margin

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Neoproterozoic through early Paleozoic times witnessed the sundering of Rodinia and the amalgamation of several allochthonous and parautochthonous blocks with Western Gondwana; Cuyania was one such terrane, which originated as an element of the central-southern Laurentian margin. The western Ouachita basin (Marathon basin, west Texas) and Cuyania (greater Precordillera, western Argentina) have fundaments of Laurentian Mesoproterozoic (Grenvillian) basement and evolved together, as evidenced by isotopic, litho-, bio- and chronostratigraphic data, as well as by recent paleomagnetic determinations. Ages, isotopic and geochemical data correspond well for Cuyania (Western Sierras Pampeanas, anorthosite massif of Sierra de Umango) and for west-central Texas crystalline basement rocks (Llano Uplift, Pecos layered mafic complex). Proterozoic through Eocambrian outcrops around the northern basin rim supplied detrital zircons to Middle Cambrian sandstones of Cuyania.

Fully correlative Ordovician carbonate successions developed on platforms of both the northern and southern basin and hosted homologous sponge-algae-stromatoporoid bioherms. Within the off-shelf calcarenite debris flows and bentonitic shales of the Marathon Fm. (Floian) is an interval of mega-olistoliths of shelf carbonate rocks (limestone cobble to boulder conglomerates) that were likely shed from fault-bounded blocks during extension/transtension in the basin. The olistostrome (Monument Spring Mbr.) extends more than 20 km along strike and foundered into sediments belonging to a single graptolite zone (*Tetragraptus approximatus*; Toomey, 1978). Along with conglomerate the unit includes abundant megaclasts of lime wackestone, many of which show unusually pervasive silicification. Immediately beneath those megaclasts, a 0.7-m basalt boulder has been found within a limestone cobble conglomerate; the basalt has also undergone pervasive silicification. The extensive silicification of limestone megaclasts is suggestive of low-T hydrothermal processes at shallow levels beneath the seafloor, which could conceivably be related to volcanism in the source area for both the boulders and blocks.

At the base of the superjacent Ft. Peña Fm. (Dariwillian) additional cobbles and boulders up to ~0.5 m across of volcanic rock (basalt to trachyte) and volcaniclastic lithic wackestone have recently been discovered within an 8.5-m-thick limestone conglomerate layer. Six boulders, including that from the underlying Marathon Fm., have so far been analyzed for major and trace elements; with these ancient altered volcanic rocks, emphasis has been on trace elements that are resistant to secondary alteration. (Analyses of additional boulders are in progress.) Preliminary geochemical data for all six basalt to trachyte boulders indicate a within-plate setting for the magmatism.

Evidence of explosive volcanism is found in metabentonites of the western Ouachita-Cuyania basin. Metabentonite intervals of the Marathon (Floian) and Ft. Peña (Dariwillian) Formations are within identical faunal zones to those for ash beds within the San Juan and Gualcamayo Formations, respectively, of Cuyania. Precordilleran metabentonites have been dated at 469.5 ± 3.2 to 470.1 ± 3.3 Ma (U-Pb, SHRIMP, zircons; Fanning et al., 2004). Notably, all these pyroclastic deposits belong to a distinctly older (by ~14 Ma) suite than the well-known Deicke-Millbrig-Kinnekulle metabentonites of the central Appalachians and Baltica.

New preliminary geochronologic data (U-Pb, SHRIMP) for zoned igneous zircons from a basalt boulder within the basal Ft. Peña Fm. and from superjacent metabentonite and porcellanite revealed a strong Neoproterozoic (669 – 740 Ma; Cryogenian) population. A few Grenvillian (1.0 – 1.2 Ga) grains were present in both, but neither contained Ordovician zircons. However, in southernmost exposures of the Ft. Peña, initial results indicate the presence of a 470 ± 6 Ma zircon component, as well as Grenvillian grains (U-Pb, SHRIMP), in a metabentonite containing Dariwillian graptolites. If supported by further dating, the Ft. Peña metabentonite would be coeval with San Juan Fm. metabentonites of the Precordillera.

Recent paleomagnetically derived plate reconstructions for Neoproterozoic through medial Ordovician time place Cuyania and Western Gondwana at low southern latitudes (~26º S) and adjacent to southern Laurentia (Rapalini, 2005; 2008, written comm.). The Western Gondwanan margin trended west – that is, ~90º clockwise from its present orientation – and faced southern Laurentia.

Western Ouachita-Cuyania deformation, sedimentation, and volcanism are consonant with dextral transtension in response to north-northeastward translation of Laurentia and counterclockwise rotation of Gondwana – a regime that evolved from the dextral transpressional situation which had prevailed in Early Cambrian time, as other Laurentia-derived blocks (Arequipa-Antofalla, Western Sierras Pampeanas, Amazonia) were accreted to Gondwana. With continued oblique dextral separation of the two supercontinental masses, the attenuated Laurentian slab broke apart and Cuyania was severed from Laurentia.

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Exploring the Descartes Highlands of the Moon

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This presentation will cover the geology training that the crew received over a 6-year period. The lecture will provide an overview of the Apollo 16 landing site and the reasons for the selection of the site and the traverses as planned. Previous missions had landed on the Mare so Descartes was selected as a highlands site due to its accessibility and the intersection of two major geologic features. Through power point and DVD, you will see the variety of the terrain and topography of the landing site. The various scientific experiments and equipment will be discussed.

Overview of WRM's Research in Mexico, Guatemala and Honduras

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Bill Muehlberger's research in Latin America spanned five decades of field-oriented mapping investigations during which time he directed the research of 12 doctoral and 8 masters students, and significantly influenced 7 others. Completion dates of thesis studies directed or significantly influenced by Muehlberger range from 1958 (Jack Walper) to 2003 (Rob Rogers). Early studies focused on Guatemala and northern Mexico, adjacent to the areas studied by Bill's West Texas students, and later expanded to include large parts of Honduras and Mexico. Rogers' thesis title includes 'Nicaragua', thus giving "El Patron" a legitimate claim to all of northern Central America!

Muehlberger and his students took on entire mountain ranges (for example, the Alta Verapaz of Guatemala, the Sierra de Comayagua of Honduras and the Sierra Madre Oriental of Mexico) but in most cases these studies produced two important and very tangible deliverable products: a geological quadrangle map and thesis report to explain and document the principal geological findings. These 'postage-stamp" maps must have had an important influence on Muehlberger's more ambitious regional mapping projects (Basement Map of the United States, Tectonic Map of North America). Muehlberger's investigations in Latin America were performed in collaboration with, and in support of, local experts and institutions. Field mapping in Guatemala and Honduras benefitted from collaboration with Gabriel Dengo and his colleagues at the Instituto Centramericano de Investigacion y Technologia Industrial (ICAITI). Dengo proposed a program in which Muehlberger's students produced the first detailed geologic quadrangle maps of Honduras. The Honduran Directorate of Mines and Hydrocarbons and the National Geographic Institute provided invaluable logistical help in making that project a success. At the time little was known about the stratigraphy or structure of Honduras. A view of the plate tectonic setting of the Caribbean and Central America was clearly in its infancy (as evidenced by repeated references to the Mesozoic and Paleozoic geosynclines). Detailed geologic maps were virtually non-existent; however a series of 1:50,000 topographic quadrangle maps (CI=20m) had been recently made and provided a fine base map for the geologic mapping that was undertaken. Later work performed in collaboration with Pemex focused on Mexico, principally the eastern cordillera (Sierra Madre Oriental) and the thrust-fold structures of Chiapas and southern Mexico.

Muehlberger's legacy is that he provided an opportunity for many students to work in remote places where geological maps either did not exist or else were in need of serious revision, and he supported their often slow and painstaking work with patience and with passion. It should be a point of pride to Bill that many of his Latin American students (we count eight) have dedicated their careers to higher education and have kept Bill's passion for geology and for mapping studies alive for the next generation of students.

Structure and Stratigraphy: A Comparison of Onshore and Offshore Honduras

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I came to 'Texas' on a recruiting visit looking for a program that would enable me to become a competent field geologist. On a whim I had applied to the graduate program at UT, but having spent twenty minutes with Muehlberger I knew that I would sign up to do a masters thesis on 'Structure and Stratigraphy' with him. Having studied Spanish - I had been a Linguistics major at Cal - I knew that I wanted to work somewhere in Latin America. Mexico was close and familiar. Guatemala was politically unstable. Honduras loomed as a logical choice. Will Logan, a like-minded masters student with an interest in economic geology, elected to join me for a reconnaissance visit to Honduras in the fall of 1980. Muehlberger and Will's thesis advisor, Rich Kyle, gave us complete freedom to identify a suitable geological problem and to negotiate local support for a joint thesis project. We found an interesting quadrangle with an ore body in it. Overall my masters thesis project still ranks as the most independent professional work that I've done in my career as a geoscientist, and that's because Bill allowed me to have control of my destiny. Logan and I packed our bags for a long stay and began our field work in the Agalteca quadrangle in January of 1981.

The first wave of Muehlberger students in west-central Honduras (1968-1975) had done heroic work in clarifying the Mesozoic stratigraphy and the major structural styles (extension overprinted by strike-slip) and trends (WNW). It must be understood that in this part of the world the vegetation is heavy, exposure is much reduced by landslides and lateritic soils, and Tertiary volcanic cover is ubiquitous. Nonetheless they documented a syn-rift clastic (redbed) sequence of Jurassic-Cretaceous age overlain by a regional carbonate platform of Aptian-Albian age, overlain in turn by an enigmatic, locally-thick, redbed unit with intercalated carbonates and associated evaporates of Cenomanian age. This sounds easy now. But many of the carbonates and almost all of the clastics lacked any age-diagnostic fossils, and there were logistical problems getting samples to labs for analysis. Oh, and if you needed to go to the grocery story you had to hire a mule… Did I mention that? Logan and I followed the first wave and made incremental additions to the regional database. Our main contribution was to fill in an important void in the mapping of key Mesozoic exposures and this permitted us to compile perhaps a dozen existing 1:50,000 scale geological quadrangles into a single map at 1:250,000 and that really did help to illuminate the regional picture at that time.

Fast-forward 30 years. I am currently working with Paul Mann to interpret legacy 2D seismic and exploration well data from offshore Honduras. No seismic or drilling activity has occurred in offshore Honduras since the time that I was working in the field in the early 1980s. Our review of legacy exploration data is also benefiting from our interpretation of newly-acquired deep penetration (15 sec record length) and long-offset (10 km cable) 2D seismic lines shot by PGS offshore Honduras in 2008-2009. The new research is permitting a reconciliation of what had been perceived to be major differences between onshore and offshore “structure” and “stratigraphy”. The common theme that is emerging is the similarity onshore and offshore of the Mesozoic stratigraphy. We can now document that continental crust extends far into the offshore of Eastern Honduras. The Jurassic-Cretaceous rift architecture that is beginning to be well-imaged offshore cannot be seen except superficially onshore due to the strong strike-slip overprint, volcanic cover and the lack of subsurface data. The offshore seismic data are showing us that an early compressional event inverted at least some of the Jurassic-Cretaceous syn-rift structures in the Cenomanian. Thus, the Cenomanian clastics represent syn-inversion deposits that, although they may be locally very thick, are present only in or near successor basins that formed adjacent to inversion uplifts, and the Cenomanian limestones would have formed in the most subsidence-prone of these basins. The Cenomanian redbeds, at least where I have looked at them carefully, are almost entirely comprised of limestone and chert clasts (from boulders to fine sand). Chert nodules are abundant in the upper part of the Albian platform carbonates. It appears inescapable now that the Lower Cretaceous carbonates were cannibalized from local inversion uplifts to form the upper redbeds, and no massive hinterland area need be uplifted as a sediment source. The Cenomanian carbonates with high TOC values are now recognized as an especially important source rock for hydrocarbon exploration onshore and offshore and a robust exploration strategy is emerging for predicting their presence in the subsurface. The most perplexing difference between the onshore and offshore is the ubiquity of Eocene non-marine and marine strata offshore and the apparent absence of Eocene strata onshore.   By analogy to the offshore, it may that Eocene strata are present onshore beneath Neogene volcanic cover and alluvium in north-trending grabens that overprint the mostly westerly and easterly fold and fault trends in the Mesozoic strata.

Structure and Tectonics of Permian Basin and Trans-Pecos Texas – A Review of Published and Unpublished Oddities

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The Permian Basin/Trans-Pecos province has been among the most important regions in the United States due to its vast energy and mineral development, and its future resource holdings that include geothermal, solar, and wind. However, the tectonic history of the region, with but a few exceptions, has not been well understood. Most past investigators consistently hold to a belief that all Permian Basin structures formed almost exclusively during Marathon-Ouachita orogenic time. Subtle but continuing evidence points to multiple (eight?) tectonic events affecting the history of the region.

Regional gravity and magnetic data display the trace of the Grenville Front trending NE-SW through the heart of the Permian Basin. This feature is displayed as a massive gravity and magnetic low observed back in the 1950's as the Abilene Minimum but not generally taken into account in later studies of Permian Basin history. The magnetic and gravity signatures indicate very different Precambrian terranes to the north and south of this feature. Large, circular and complex intrusives are along the northern margin with much smaller and elongate magnetic features lying south of the low and parallel to the trend of the Front. This low splits and offsets the trend of the Central Basin Platform in a right-lateral sense in the Winkler-Lea County area of Texas and New Mexico. Seismic data in the region between Dollarhide and Keystone Fields demonstrate a NE-SW Pennsylvanian structural low controlled by faulting along the N and S sides of this depression. Faulting was first alluded to in the literature by Flawn through the mention of a cataclasis zone between these two fields in Precambrian cuttings.

From Precambrian to Late Mississippian the Tabosa Basin has been quiescent with no tectonic activity, or so the story has been told. But subsurface and local surface evidence throws considerable doubt on this description. The work identifying the Precordillera connection with the southern margin of North America in the Marathon Basin and possibly eastward into the Devils River Uplift demonstrate a Cambrian to mid-Ordovician (Simpson) event in this region. For example, Denison age dated (Rb-Sr) metavolcanics and metaigneous rocks within a 2500+ foot thickness below Upper Cambrian within the Shell #1 Stewart at 692 + 36 m.y. and 712 + 95 m.y. respectively. Shell Oil used Rb-Sr to date three metasedimentary and one metavolcanic zone within the same interval below Upper Cambrian at between 481 to 529 m.y., suggesting a metamorphic event ranging from Cambrian into Ordovician time. Additional dating using K-Ar techniques by Shell and Denison independently also suggest a mid-Upper Devonian to Upper Early Silurian event affecting these same rocks. This corresponds with numerous areas in the Delaware Basin where the stratigraphy demonstrates upper part of the Devonian limestone and chert is missing and where the Woodford Shale is thin over structural highs that were buried when Woodford was deposited. Thus scattered but consistent evidence exists for a Cambro-Ordovician tectonic event followed by a later Silurian-Devonian event.

The Mississippian/Pennsylvanian/Permian Ouachita-Marathon orogeny followed these earlier Paleozoic events to establish the fold and thrust trend found in outcrop locally and in the subsurface predominantly around the southern edge of the Texas craton. Earlier writers have ascribed all of the structures north of this orogenic belt to have also been developed during this same time period. But as Denison and others have pointed out the orientation of many of the structures and subsurface faults are perpendicular to structures along the Ouachita-Marathon belt. Older tectonic events may have contributed significantly to subsurface structuring within the heart of the Permian Basin.

The Middle Guadalupian hosts what has been suggested to be a "Cherry Canyon tectonic event" and may be the most obscure of the tectonic events so far mentioned. This tectonism is characterized by volcanic ash deposits, the most well known of which, the Manzanita marker, forms a characteristic log signature traced over much of the Delaware Basin. King noted ash beds scattered throughout the Cherry Canyon Formation are on average about a foot thick and have been recognized in numerous wells. The ash, or bentonite, is often altered to a green chert that resembles turquoise. King indicated that although ash beds are encountered in other formations of the Delaware Mountain group, the ash within the Cherry Canyon is thickest. Whether these ash beds represent volcanic activity at the close of the Ouachita-Marathon event or whether they are a separate event is unknown. It may be significant that the timing of the ash falls coincides with various debris flows, such as the Manzanita and Hegler debris flows in the Basin, with "nearby" volcanic activity not only producing the ash but earthquakes that assisted in causing the debris flows.

Little remains in the Delaware Basin of Triassic or Jurassic strata that may have been present. However local outcrops of Triassic shale, siltstones, sandstones, and gravels that immediately overly older Permian strata are scattered south and west of the Midland-Odessa area. Some of these outcrops, such as along Highway 1053 north of Imperial at the Pecos River, retain conjugate thrust faulting in outcrop and are close to local oil fields. Studies of Triassic strata farther north by Lehman identified unconformities that are of probable tectonic origin, suggesting that Triassic deformation affected the Permian Basin.

Numerous authors have identified Laramide and Basin and Range age structures throughout the Trans-Pecos region. Anticlines, monoclines, strike-slip, reverse, and thrust faulting can be found throughout related to Laramide orogenic activity that have been reactivated by later Basin and Range deformation. Mapping of the generally E-W-trending Terlingua monocline fault zone documents Laramide followed by Basin and Range deformation. The nearly parallel Tascotal Mesa fault system shows prominent Basin and Range deformation, though older Laramide is not impossible. Dickerson has identified numerous other E-W-trending features northward within the Trans-Pecos, some of which extend eastward into the Delaware Basin where they demonstrate much older offset, such as the South Hueco structural zone that becomes the Grisham Fault zone in the Basin. Farther east in Val Verde Basin, faults in road and railroad cuts trend NE and document probable Laramide strike-slip displacement. Though incomplete, sufficient evidence suggests that western Texas has undergone numerous tectonic events from Precambrian to most recent times. Further work would support or refute a longer, more active tectonic history of the Permian Basin and of Trans-Pecos Texas.

Possible Extra-Solar-System Cause for Certain Lunar Seismic Events

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The Apollo missions emplaced a four-station seismic network on the Moon's near side that operated from 1969 to 1977. Subsequent analyses of long-period records found about 12,500 events, including almost 8500 categorized as deep moonquakes or meteoroid impacts and 4000 that were uncategorized. In addition, short-period seismometers that operated between 1971 and 1977 at three stations recorded many thousands of tiny events, many of which appear to be small meteoroid impacts, and others that occur commonly near the times of lunar sunrise and sunset and are small moonquakes generated by temperature changes. A fourth, rare category of lunar seismic events consists of 28 events originally called high-frequency teleseismic (HFT) events, sometimes also called shallow moonquakes. Among these are the largest seismic events recorded on the Moon, as two had energies corresponding approximately to terrestrial earthquakes with magnitude 5.

Reanalysis of lunar seismic data collected during the Apollo program indicates that 23 of the 28 HFT events occurred during one-half of the sidereal month when the seismic network on the Moon's near side faced approximately towards the constellations Leo and Virgo on the celestial sphere. Statistical analysis demonstrates that there is about a 1 per cent probability that this pattern would occur by chance.

An alternate possibility is that high-energy objects from a fixed source outside the solar system trigger or even cause the HFT events. There is speculation in the astrophysics literature concerning the existence of 'nuggets of strange quark matter' (SQM) consisting of massive (up to a kg or more) nuclear particles. Also, seismologists have searched unsuccessfully in terrestrial earthquake catalogs for seismic signals produced by cosmic SQM particles interacting with Earth. The Moon, which is seismically much quieter than Earth, may be a better place to detect SQM particles.

Determining definitively whether HFT events may be caused/triggered by an extra-solar-system source requires identifying more HFT events. At present we are searching for previously undetected HFT events in the Apollo seismic data. However, the final resolution of this question may have to await the emplacement of a seismic network on the Moon in future lunar missions.

Tectonic Evolution of the Chortís Block: Age Constraints

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The Chortís block is the only continental crust that is currently part of the Caribbean plate. Hence, it has a critical role in regional tectonic reconstructions. However, the age and character of the Chortís basement is poorly constrained. Isotopic ages from the Chortís block are fewer in number and more open to interpretation than adjacent terranes in Guatemala and Mexico. Initially, we sought to date the timing of crust formation and metamorphism on the Chortís block. By including fission track dating, we also establish the timing of the most recent exhumation. If possible, we dated single rock bodies with U-Pb zircon, $^{40}Ar/^{39}Ar$ amphibole, white mica and biotite, zircon fission track and apatite fission track methods. This suite of methods yields a thorough thermal history of the rock units. However, we were unable to get a complete suite on all samples due to absence or lack of abundance of some mineral phases, or other technical problems.

The Cacaguapa Schist forms the oldest unit of the Chortís block. Although it clearly underlies the well-dated Jurassic to Cretaceous sedimentary strata, little age data is available, especially from the central portion of the Chortís block. The Cacaguapa Schist crops out from the Comayagua area across most of central Honduras to the Valle de Catacamas. The outcrop area is dominated by fine grained phyllite altered to saprolite which can be tens of meters thick. Simonson (1981) mapped metaplutonic units in the El Porvenir. The augen schist and the member rich in potassium feldspar yielded U-Pb ages (Ratschbacher et al., 2009) with lower intercepts of about 400 Ma and upper intercepts of 1Ga (Grenvillian). A fresh, coarse grained white mica from the Cacaguapa Schist has an $^{40}Ar/^{39}Ar$ age of 330 Ma. A metagranite south of the Valle de Catacamas has a lower intercept age of about 270 Ma. In total, these ages show that the central core of the Chortís block has a Paleozoic history of plutonism and metamorphism with a Grenville inheritance.

Although evidence for a substantially higher metamorphic grade exists along the northern margin of the Chortís block, these rocks are generally younger than the rocks from the central part of the Chortís block. North of the Chamelecón fault in the Sula graben, the Mesozoic rocks do not overlie the metamorphic rocks. In fact, Mesozoic limestone is entrained with metamorphic rocks at Sanarate in Guatemala (Wilson, 1974) and on Roatán (Avé Lallemant and Gordon, 1999). The large marble exposure at Baracoa in the Sula graben may also be Mesozoic. A tonalite that crops out south of San Pedro Sula has a concordant U-Pb zircon age of 168 ± 0.46 Ma (Ratschbacher et al., 2009). Further north, metamorphic rocks crop out. An amphibolite, probably a metagabbro, has a concordant U-Pb age of 88.27 ± 0.56 Ma whereas a metagranite has a concordant U-Pb zircon age of 38.3 ± 0.53 Ma (Ratschbacher et al., 2009). The metagabbro has an amphibole $^{40}Ar/^{39}Ar$ age of 40.5 ± 0.5 Ma. Further evidence of 40 Ma tectono-thermal event comes from Roatán where the amphibolite has a

^{40}Ar/^{39}Ar age of 36.0 ± 1.2 Ma and a porphry has a zircon fission track age of 38.9 ± 2.8 Ma (Avé Lallemant and Gordon, 1999).

Although the rocks were sampled for dating methods with high blocking temperatures, zircon and apatite fission track age data yield much information about the exhumation history of the rocks and one can use the same mineral separates to do the fission track work. The samples from the footwalls of the major grabens yielded the youngest ages whereas samples from the middle of mountainous terrain yielded ages that probably just show slow cooling and exhumation. The member rich in sodic feldspar (Simonson, 1981) has a zircon fission track age of 177 ± 27 Ma (this sample did not contain enough zircon for U-Pb work). The augen schist has a zircon fission track age of 165 ± 12 Ma and the member rich in potassium feldspar has a zircon fission track age of 91.7 ± 11.1 Ma. This same unit has the oldest apatite fission track age of 51.3 ± 2.9 Ma. This age probably represents slow cooling and exhumation of the Chortís block. However, the augen schist (24.1 ± 1.8 Ma) and the member rich in sodic feldspar (14.6 ± 2.7 Ma) have much younger ages which may date the exhumation of the footwall of the Siria graben. The metagranite from the Valle de Catacamas also has a relatively young apatite fission track age (20.3 ± 1.0 Ma).

The igneous and metamorphic rocks of the Sula graben show rapid exhumation from the blocking temperature of zircon fission track and biotite ^{40}Ar/^{39}Ar. Zircon fission track ages range from 26.7 ± 1.5 for the tonalite to 14.6 ± 1.0 for the metagranite. Apatite fission track ages for the Sula graben range from 14.4 ± 1.9 Ma for the San Pedro Sula batholith to 10.0 ± 0.7 Ma for the amphibolite. These ages attest to the late Tertiary exhumation of the Sula graben footwall. The isotopic ages reported here illuminate the tectonic history of the Chortís block. The central core of the Chortís block developed in the Paleozoic with a Grenville inheritance. This is consistent with the block being derived from Laurentia. The northern margin of the Chortís block experienced tectono-thermal activity in the late Cretaceous and Eocene. The central core of the Chortís block was relatively cool and stable in the Mesozoic. Both the northern margin and the central core experienced late Cenozoic exhumation of fault blocks.

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Transcontinental Geologic Cross Section of the North American Plate near 36° Latitude: Atlantic Ocean Crust to Pacific Ocean Crust

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The concept of a transcontinental cross section originated with then AGI Executive Director Marcus E. Milling during the early 2000s. Bill Muehlberger and Cindy Martinez met with Bob Hatcher and Karl Karlstrom at the 2005 GSA Annual Meeting in Salt Lake City. We agreed to produce a geologic cross section of the North American Plate near latitude 36°, and in 2006 decided to dedicate it to the memory of Marcus Milling following his death. Others were added to the team to complete the west end of the section (Saleebys) and geophysical components (Keller and van der Lee). We have produced a technical cross section across the continent for researchers and graduate students, and will produce a geologic section useful for K-12 education, the general public, and introductory college geology classes, to provide better understanding of the tectonic processes that produced southern half of our continent. The technical product consists of the cross section at a 4:1 vertical exaggeration to 150 km, and a section at 1:1 that portrays the geology to depths of 250 km, with an oblique DEM, adding a 3D component.

The eastern segment extends westward from 67° to 99° W, from Atlantic Ocean crust E of the Blake Spur magnetic anomaly (BSMA) across the East Coast magnetic anomaly (ECMA) and modern continental margin; across the Appalachians, the Nashville dome, Mississippi Embayment and into the Mid-Continent. The modern continental margin records the Mesozoic rift-to-drift transition following breakup of Pangea, which includes the enigmatic BSMA (abandoned ridge segment?) and ECMA (mafic intrusions formed by decompression melting as Africa separated from Laurentia?); the southern Appalachians accreted through three Paleozoic orogenies to the Neoproterozoic-early Paleozoic Laurentian margin, and the subsurface Grenville front, recording two complete Wilson cycles; then crosses much of the Mid-Continent, which records accretion of the Mid-Proterozoic Mazatzal and Yavapai arcs and late plutons. The Mid-Continent component illustrates cratonic stability despite major Phanerozoic tectonic events along its southern and eastern margins. Relatively thin Phanerozoic cover characterizes the continental interior, with local thickening across the Mississippi Embayment and Reelfoot rift. The E section also crosses the New Madrid and East Tennessee seismic zones, the two most active in the eastern U.S. Recorded here is a history and crustal formation processes spanning almost 2 Ga, with normal-thickness crust (30-40 km) beneath the E segment, except beneath the topographically high southern Appalachians (~50 km), suggesting that the eastern U.S. highlands may be explained by local isostatic imbalance.

The western half of the cross section extends from the coastal Franciscan accretionary complex, across the Salinia forearc microplate, the San Andreas fault, the Cretaceous forearc basin, the Sierra Nevada Mesozoic magmatic arc, the eastern California shear zone of the Basin and Range province, the Colorado Plateau, the Rio Grande rift, the Rocky Mountains, and the western Great Plains. In this region, plate boundary deformation is inducing and interacting with a complex intraplate deformational field in a 1000-km-wide uplifted orogenic plateau that extends as far east as the Great Plains. The scientific "punchline" for this part of the cross section is that the western North American plate is dynamically uplifting and tectonically active because of interactions with flowing mantle near its base. Both halves of the cross section emphasize that North America provides an outstanding field laboratory for understanding the structure and evolution of continental plates. The continent is profoundly segmented because of its >4 billion-year history, and has been built progressively by collision of continental fragments and oceanic terranes to the existing continental nucleus. The overall theme for North America (and for all continents) involves a history where active plate tectonic processes are superimposed on a heterogeneous existing structure developed during their billion-year evolution.

Basin Formation on the Moon: New Insights Since Apollo

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Introduction**.** The 930-km-diameter Orientale basin is the youngest and best-preserved large multi-ringed impact basin on the Moon [1-10]; it has not been significantly filled with mare basalts and thus the nature of the basin interior deposits and ring structures are very well-exposed and provide major insight into the formation and evolution of planetary multi-ringed impact basins [1-10] (Fig. 1). New data from the armada of recent and ongoing lunar spacecraft are providing multiple data sets, new characterization, and new insights into Orientale basin origin and evolution [11-15].

Lunar Orbiting Laser Altimeter (LOLA) Data**.** We use Lunar Reconnaissance Orbiter LOLA data (Fig. 1,2) to analyze the new topography, characterize the pre-basin, basin and ring topography, and outline new insights into basin formation and evolution.

Pre-basin topography**.** There is a broad W-E decrease in elevation, consistent with regional changes in crustal thickness [15]. Pre-basin topography had a major effect on the formation of Orientale; The Mendel-Rydberg basin (Fig. 2;3-left) and dozens of impact craters underlie the Hevelius Formation (HF) (Fig. 2) and the unit between the basin rim (Cordillera ring-CR) and the Outer Rook ring (OR). A dark ring previously thought to represent a crater partly located inside the IR [16] is now known to be a pyroclastic deposit from an eruption plume [17]. Deposits inside the OR are dominated by the Maunder Formation (MF) (Fig. 1); this topographic configuration supports the interpretation that the MF consists of different facies of impact melt.

Basin Interior Topography**.** Total basin interior topography typically ranges ~6-7 km below the pre-basin surface (Fig. 1-3). The CR consists of linear and cuspate inward-facing scarps; continuity is interrupted by radial crater chains, and amplitude varies due to pre-existing topography. Between the OR and CR, topography dips away from the OR to the base of the CR; lowest depressions are often filled with mare. The OR is generally continuous topographically and consists of a set of asymmetrical massifs with steeper scarps facing inward, prominent near-rim crest topography, and transitioning outward to the outward sloping MRF surface. Compared to the CR, the OR is often much more sinuous in outline, with numerous re-entrants. The IR ring is characterized by a ring of peaks and

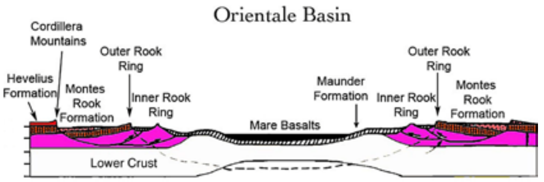

Fig. 1. Schematic cross section of the Orientale basin illustrating the relation of the basin rings to basin deposits (interior and exterior) [4].

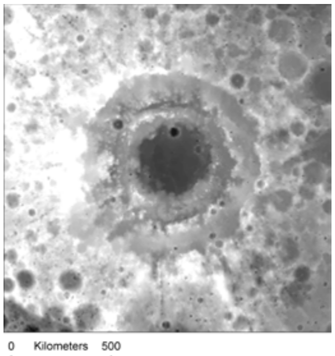

Fig. 2. LOLA altimetry map of the Orientale basin region (1/16th degree resolution).

massifs situated on a broad plateau between the inner depression and the OR, surrounded and sometimes covered by Maunder Formation, interpreted to be impact melt. LOLA data (Fig. 2-3) reveal a 10-25 km wide depression (often over a km deep, and floored by impact melt and mare deposits), between the plateau and the OR ring base.

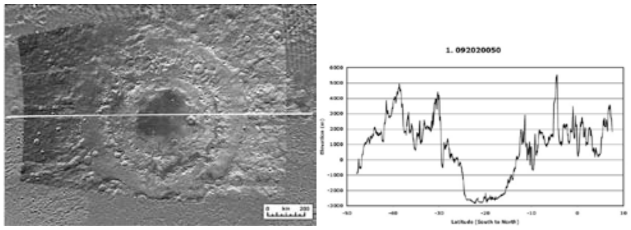

Fig. 3. LOLA profile 092020050 through the center of the Orientale basin and into the pre-Orientale Mendel-Rydberg basin to the south (left).

Nature of the inner basin depression**.** The inner basin depression is about 2-4 km deep below the IR plateau (Fig. 2); although some of this topography is due to post-basin-formation thermal response to impact energy input and uplifted isotherms [5], a significant part of it may be related to the initial short-term collapse of an inner melt cavity, as outlined in the nested melt cavity model of ringed basin formation [18-19].

Location of the basin rim and excavation cavity**.** In contrast to some previous interpretations [see summary in 16], the distribution of these features and deposits supports the interpretation that the OR ring (Fig. 1) is the closest approximation to the basin excavation cavity. The prominence of the pre-Orientale craters right up to the Cordillera ring, the outward-sloping surface of the MRF, the ghost craters between the Cordillera and Outer Rook, all support the model that the Cordillera ring represents failure of the rim crest (Outer Rook ring) at the structural uplift hinge line, and collapse inward to form a megaterrace [1,4,19].

Origin of basin rings in multi-ringed basins**.** These new data for the Orientale basin provide insight into basin ring formation, supporting a model that includes the expansion of a peak-ring basin by addition of an outer (Cordillera) ring by inward collapse at the edge of structural uplift along the base of the displaced zone, and the addition of an inner depression formed from an expanding nested melt cavity, and its collapse [18,19]. The newly documented annular depression at the base of the OR is interpreted to be formed during the inward collapse of the peak-ring bounded inner melt cavity.

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Astronaut Field Training for a Return to the Moon – WRM and the Field Exploration Analysis Team (FEAT)

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As Principle Investigator of the Lunar Geology Experiment for Apollo 16 and 17, William R. Muehlberger (WRM) planned and oversaw the geological and geophysical field training of two Apollo crews and their backups. Nearly 40 years later, with a US vision for space exploration that included returning astronauts to the moon, WRM, Apollo 17 astronaut/geologist Harrison “Jack” Schmitt and Patricia W. Dickerson formed the Field Exploration Analysis Team (FEAT). As originally envisioned, FEAT would recruit a small number of highly experienced field geologists that could provide NASA with expert advice and assistance in preparing astronauts for geological and geophysical fieldwork on the Moon. This group would also be responsible for raising awareness about the importance of rigorous, comprehensive training, and of the necessity of beginning a field training program well before a return to the moon. Such a program had not existed since Apollo and there were no indications that any training of the sort was being considered. Drs. Art Snoke (U. of Wyoming) and Mark Helper were recruited as co-chairs and an inaugural FEAT meeting was held at the annual GSA meeting in Philadelphia in 2006.

Since that time, membership has grown to include planetary scientists, geophysicists, engineers and others interested in the role of field geology in the future exploration of the Moon. In addition to providing NASA with expert advice and personnel for field geologic training, FEAT has provided forums to discuss, evaluate, and recommend various strategies for fieldwork on the lunar surface. FEAT members have convened or participated in workshops, meetings and field experiments that have considered: astronaut geological/geophysical training in the field and classroom; possible lunar-analog sites and field exercises; lessons from the Apollo; geologic exploration equipment including roving vehicles, sampling tools, fieldwork in pressurized suits, and field analytical equipment; analog field testing of equipment; hypothetical lunar traverse scenarios; the nature of geophysical experiments to be deployed on the Moon; the role of robotic reconnaissance and follow-up to human field work; and fundamental science questions that will be addressed by a return to the Moon. FEAT has regularly held open meetings at the annual meetings of the AAPG and GSA and, with less frequency, in coordination with other lunar advisory groups or NASA workshops.

In efforts to raise awareness about the importance and nature of geologic fieldwork, FEAT has also sponsored and participated in field training exercises for personnel of NASA’s Science Mission and Exploration Systems Mission Directorates, and for other NASA scientists, engineers and astronauts. FEAT also actively recruits young, field-oriented geoscientists to participate in ongoing discussions and experiments that address the nature of fieldwork on the Moon.

WRM’s legacy lives on in FEAT and in a newly developing NASA geology and geophysics training curriculum. The 2009 astronaut candidate class will be the first in nearly forty years to receive training in geological mapping and in 2010 will participate in FEAT-member-led field geological and geophysical exercises in New Mexico, Texas and Arizona. These field activities are in association with a new, greatly expanded classroom component, based in part on contributions by FEAT members.

Geometry of Thrusts and Folds in the Chihuahua Tectonic Belt

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Laramide tectonism structurally inverted the Chihuahua trough forming the Chihuahua Tectonic Belt which stretches 1,200 km from SE Arizona to Nuevo Leon, Mexico. Structures produced along the deformation front are nicely exposed straddling the TX-Chihuahua border. A view into the internal architecture of the belt is evident along a transect between Presidio, TX and Aldama, Chi. These two areas are considered in this analysis.

The eastern front may be divided into two tectonic domains: a frontal zone with emergent imbricate thrusts and ramp-related structures which lie to the east of main ranges characterized by salt-cored anticlines. Folds of the main ranges can exceed 5 km in amplitude. The eastern boundary of the main ranges occurs where the décollement steps down-section to the west from Cretaceous clastic rocks to Jurassic evaporites. The geometry of the frontal zone was controlled by a NW-trending basement grain that was established by late Paleozoic time. This fabric manifested itself as down-to-the-west normal faults which controlled Mesozoic subsidence, deposition, and facies along the eastern Chihuahua trough. The Mesozoic normal faults later localized Laramide thrust ramps and acted as restraining features resisting thrust motion. Regional thrust transport was to the ENE resulting in sub-orthogonal convergence against this basement grain along the central segment of the eastern front. However, oblique convergence against this grain in the northern and southern segments resulted in counter-clockwise rotation of structural vergence. Shortening across the northern segment is 40 percent but diminishes to less than 10 percent in segments to the south.

Along the transect, the Chihuahua Tectonic Belt is a symmetrically inverted basin that can be divided into eastern and western allochthons which were transported in those respective directions. In the eastern allochthon to the east of the basin axis, salt-cored anticlines and associated salt-withdrawal synclines predominate. The décollement cuts up-section into Lower Cretaceous carbonates in the eastern frontal zone. In the western allochthon to the west of the basin axis, the décollement shallows from Precambrian basement through Paleozoic rocks and into the Cretaceous section carrying the structurally complex Plomosas Uplift in its hanging wall. The décollement continues to cut up-section to the west forming a western frontal zone with ramp-related structures. The décollement remains blind to the surface east of Aldama. Shortening across the belt totals 13 percent.

World Oil Reserves, Potential Additions and Future Production Levels

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World oil reserves and future potential estimates are a subject of great economic and political significance, although the basis of the calculations is in reality dependent on geology and petroleum engineering. Until recently, the ultimately recoverable estimate amount has consistently grown; however, a general consensus of a cap seems to have been reached by extrapolating past trends.

The history of exploration and reserve growth has been a combined story of new geological concepts, technological breakthroughs and access to new areas to explore. The eventual cap on reserves growth is a logical endpoint of factors such as geochemical understanding of an "oil floor" (deeper drilling won't find more oil) current ability to explore in 3000-meter water depth (areas with deeper water depth do not have requisite sedimentary sections) and the opening of the Former Soviet Union to western concepts and technologies. (except for Antarctica, where else do we have on land to go?) Reserve growth on existing fields, which in the past 25 years has provided two new barrels for every one discovered by exploration, also has a finite limit, which is increasingly being reached when the latest technology is available.

World oil production is a very different matter, in which economic and political factors actually overshadow the geologic and petroleum engineering limits. The producing oil world is divided into three sectors; OPEC, the former Soviet Union (FSU) and the rest of the world (ROW). OPEC production is completely controlled, and production in the FSU, dominated by Russia, is almost in the same category. Production in the ROW peaked in 2001 to 2004 and is beginning an accelerating decline. The world is facing a practical production limit of 90 MMBO/D which, as the world recovers from the recent recession, will be strongly tested by demand, resulting in sharply increased prices in the coming years.

Because of the economic and political tensions arising from the rising costs and economic imbalances, it will be vitally important for future petroleum geoscientists and engineers to both honestly face the limitations of the resource and at the same time apply the creative thinking, technologies and discipline to extract the maximum from the available resources, particularly in the ROW, to allow the smooth eventual transition to other energy resources.

Why Geologic Field Work Is Still Important in the Caribbean and Other Areas

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We are now in the era of the computerized geologist: analytical, equipment-heavy, but sometimes office-bound and fieldwork-averse. During the January 12, 2010, Haiti earthquake, satellites were re-positioned over the epicentral area, a sensor-laden jet was flown overhead, and a dizzying array of remotely sensed were made available - including high resolution imagery provided post-earthquake by Google. Despite all the remotely sensed data, key observations were made by geologists slogging up rivers, diving along uplifted and subsided coastlines wearing fins and snorkels, and hand digging trenches across faults. Many of these observations were either not apparent or were ambiguous from these remote sensing data. This talk will describe some of this field information and how field workers maximized their efforts using remote sensing products.

Advances in Understanding of Grenvillian Orogenesis in Texas

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Research on Precambrian exposures in Texas over the last 25 years has radically changed our understanding of the nature and evolution of the southern margin of North America. The Texas Precambrian basement records Grenville-aged orogenesis along a long-lived active plate boundary, including 1) early extension between 1380 – 1327 Ma associated with formation of the Granite-Rhyolite terrane in west Texas, 2) formation of a continental margin arc and back arc basin from ~1288 – 1232 Ma, 3) collision of an exotic arc and southern continent from ~1150 – 1116 Ma in central Texas followed by intrusion of late syn- to post-tectonic granites from 1119 – 1070 Ma, and 4) final collision and transpression in west Texas from ~1057 – 980 Ma.

The Llano uplift in Central Texas is comprised of a tonalitic to dioritic plutonic complex, dated at 1336 – 1275 Ma, and associated ophiolitic rocks, the Coal Creek domain; a plutonic and volcanic complex, dated at 1288 – 1232 Ma, associated with basinal sedimentary rocks, the Valley Spring and Packsaddle domains; and voluminous late syn- to post-tectonic granites dated at 1119 – 1070 Ma. The Coal Creek domain has a geochemical, isotopic, petrologic and early deformation history distinct from the rest of the uplift and is interpreted to be an exotic arc terrane, whereas the Valley Spring and Packsaddle domains are interpreted on the basis of lithology, field relations, and geochemistry to be a continental margin arc and forearc basin along the margin of North America.

The Llano uplift records a complex metamorphic and deformation history attributed to arc-continent and continent-continent collision between 1150 – 1116 Ma. Early in situ medium T eclogites yield pressures as high as ~2.4 GPa, indicative of early subduction of continental crust. Widespread regional upper amphibolite facies, dynamothermal metamorphism, tectonic stacking of the three lithotectonic domains, and intense polyphase deformation of both the exotic arc and rocks of North American affinities over a short timeframe requires collision of the exotic arc as well as another southern continental block. Rapid exhumation and cooling accompanied by intrusion of granites with a juvenile signature and by low P metamorphism at 1119 – 1070 Ma was potentially related to slab break-off.

In West Texas a more prolonged history is recorded. Voluminous rhyolite flows and welded ash flow tuffs dated at 1380 – 1327 Ma are interlayered with basinal sedimentary rocks, together comprising the Carrizo Mountain Group. The volcanic rocks have geochemistries indicative of intra-plate rifting, which coupled with their isotopic signatures, indicate that these units form the southwestern extent of the Granite-Rhyolite terrane in Texas. Intrusive metabasite sills are younger (~1286 Ma) and most likely unrelated given their age and geochemistry. Farther north, sedimentary and volcanic rocks of the Allamoore and Tumbledown Formations were deposited within a continental marginal basin *ca.* 1250 Ma, interpreted a back arc basin to the Llano arc.

Deformation and metamorphism in West Texas occurred significantly later than in Central Texas. The Carrizo Mountain Group records polyphase deformation and ductile shearing with NW transport and dextral transpression at 1057-1035 Ma, associated with amphibolite to greenschist facies metamorphism that decreases in intensity northward. In the foreland, polyphase folding with northward transport at mid to lower greenschist facies conditions and cross-cutting oblique dextral slip along brittle/ductile WNW-trending faults occurred at depth. Thrusting at the surface formed the synorogenic Hazel conglomerates. Late out-of-sequence, brittle thrusts, including the Streeruwitz thrust, uplifted and juxtaposed Carrizo Mountain Group rocks with those of the foreland at 1000 - 980 Ma. Lastly a series of complex domes and basins formed, most likely as a result of transcurrent motion on variously oriented faults. Thus northward propagating progressive continental convergence changed to a complex tranpressional deformation that most likely resulted from complex plate interactions along the edge of an indentor subsequent to continental collision in the Llano region.

In sum, the Mesoproterozoic southern margin of North America, as exposed in Texas, records tectonic activity similar in nature and complexity to that of the Grenville Province of Canada which forms the northeastern continental margin of North America. Further research over the next 25 years will undoubtedly continue to advance our understanding of the nature and evolution of this continental margin.

A Muehlberger-Trained Geologist

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How did I become a Muehlberger-Trained Geologist? Geology has been in my blood from early childhood. The first phase of my early and informal geologic education consisted of watching and listening to my father, Dr. William R. Muehlberger enthusiastically pointing out geologic formations in road cuts (explains where I learned how to drive), describing how various structures had been formed and left in place as puzzle pieces of the geologic history of the earth. The second phase of my education included spending summers in Ojo Caliente and Socorro, New Mexico, playing around fluvial deposits (dry river beds), and being further exposed to the raw beauty of New Mexico. During the third phase of my education (now training), I was fortunate to go to Hawaii, meeting NASA astronauts after completion of their field camp in the volcanic badlands of the Big Island. In the fourth phase of my training, after we moved back to Texas, I was fortunate enough to travel with Dad to Big Bend National Park and Big Bend Ranch State Park, where we mapped various units in the Solitario, and gained a further understanding of the geologic variety this planet has to offer.

My formal education is varied, with a Bachelors degree in Business Management from Texas Tech University, and a Bachelor and Masters Degree in Geology from Northern Arizona University. My Master's thesis was a mapping thesis of the structure and stratigraphy of a portion of the Payson Basin, located in the Arizona Transition Zone (between the Colorado Plateau and the Basin and Range Provinces). Again, I was fortunate to have Dad spend a long weekend with us in the field, ground-truthing my map.

In my professional geological career, I have worked for the U.S. Geological Survey in Flagstaff, where I was exposed to thin sectioning, sieving, and x-ray diffraction, plus access to a wonderful library associated with the USGS Planetary Science program. Since 1986, I have been a Hydrogeologist working for a variety of private consulting firms in Arizona and Texas. For the past ten years, I have been a consultant with Delta Consultants in Austin, Texas. Our clients range from the Texas Commission on Environmental Quality (state regulatory agency) to major oil companies, to a variety of international and domestic clients. Our services include running a statewide program for the collection of drinking water compliance samples, assessment and remediation of soil and groundwater issues for refineries, retail gasoline stations, and product terminals, to a variety of issues for our large international clients having air, soil, and groundwater concerns that require our assistance to comply with environmental regulations.

Since my training is hydrogeology, I would like to summarize a couple of projects that illustrate how my geologic service is somewhat different from the training by Dad. The first project, completed in 2005, was located in east central Arizona in the White Mountains area. This project involved the investigation, remediation, and long-term compliance monitoring of an Arizona lumber mill, where three above ground petroleum storage tanks and two underground storage tanks leaked a minimum of 25,000 gallons of gasoline, over at least a two year period in the late 1980's. During the course of the investigation, other contaminants were identified, including diesel fuel, motor oil, volatile organic compounds, and phenols. Contamination was initially discovered off-site and down gradient when free product was detected in a private landowner's pond. Investigation techniques included: a soil gas survey; soil borings; monitor well installations; air, soil, groundwater and surface water sampling, and trenching. Site remediation included groundwater extraction and treatment using UV-peroxidation and soil excavation/remediation through land farming and soil composting. An air sparge/soil vapor extraction remediation system was installed in 1996 to replace the UV-peroxidation system. In 1997, the system was turned off in order to observe natural attenuation of the remaining dissolved-phase constituents. Ongoing, long-term compliance monitoring included periodic groundwater elevation measurement, sampling and analysis, reporting to the State of Arizona on the site progress, and abandoning unused or unneeded monitoring wells as needed. The project site was formally closed in 2005, when the groundwater concentrations remained below Arizona water quality standards for over a year of quarterly monitoring.

The second project involves environmental consulting services for a light manufacturing facility located in an industrialized section of Stockton, California. The site formerly held two underground storage tanks that had leaked gasoline in the late 80’s and early 90’s. The site investigation included the drilling of soil borings, installation of monitor wells, soil and groundwater sampling and analysis, and quarterly sampling, analysis, and reporting. A feasibility study was completed after pilot testing, which included soil vapor extraction, air sparging, soil treatability testing, and a 24-hour aquifer test and analysis. The pilot testing resulted in a detailed remedial design; including air sparge and soil vapor extraction wells, and enhanced bioremediation. This system was installed and operations begun in 2004. We are currently in the operations and maintenance stage for the remediation system, and in ongoing compliance groundwater monitoring and reporting to the local regulatory agency. Closure will be requested when groundwater concentrations of the environmental contaminants are below California drinking water standards, currently estimated to be at least five more years.

Rio Grande Rift of Northern New Mexico – Geological and Geophysical Training Ground for Astronauts From Apollo Missions to the Present

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The Rio Grande rift is a fertile field for astronaut training, It displays a wide variety of geologic processes and features at a scale observable from orbit and all are accessible via one-day trips from a base in Taos. . Adjoining the rift on the west is the Colorado Plateau and the San Juan Volcanic Field- which record processes unrelated to rifting--- dune fields, floodplain deposits, widespread explosive volcanism. The Sangre de Cristo Mountains on the east preserve a window into the formation of continents as well as the effects of glaciers and steep rivers in the shaping of the range.

The Rio Grande Gorge, west of Taos, NM is a perfect analogue to the Apollo 15 landing site- a broad lava plain cut by a deep canyon (Hadley Rille). It also furnished a variety of volcanic features for the volcanic interpretation of the Apollo 16 landing site (proven wrong during the mission}. The Apollo-Soyuz and Skylab earth-orbiting missions had only lectures in their training cycle.

The field trip that virtually all of the Shuttle and International Space Station astronauts was taken on was developed by long conversations with Sally Ride [one of the first class of Shuttle astronauts} and me. There is no better way to learn geology than by field trips to important areas that illustrate the main processes of earth formation and change. Northern New Mexico is one of those regions.

Major themes on the trip include

1] rifting with associated volcanism,{from cinder cones to shield volcanoes}, hot springs (possible habitats for life};
2] rivers [both in liquid and solid states] and the resulting landforms;
3] deposition of sedimentary rocks {by wind, rivers, glaciers, etc}. and their
4} metamorphism and mountain building.

Since 1999 an additional day was added to the trip to do gravity and magnetic traverses in the Taos Valley as part of an ongoing groundwater research project by members of the New Mexico Bureau of Mines and Geology and the U.S. Geological Survey.

Future Challenges in Lunar and Planetary Seismology

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More than thirty years have passed since any seismic data were acquired on a planetary body other than our own Earth. The Apollo Passive Seismic Experiment (PSE) operated a network of four seismic stations on the near side of the Moon from 1969 to 1977 and was highly successful, providing many useful, and some quite unexpected, pieces of information on the internal structure and current dynamic state of the Moon. However, many questions remain because of certain unavoidable limitations of the network at the time. The Viking seismic experiment on Mars, from 1976 to 1978, suffered from many more strict limitations and provided essentially no information about the internal structure and seismicity of Mars.

Major questions that remain to be answered about the Moon include (1) seismic velocity distribution that is precise enough to narrowly constrain the mineralogical composition of the Moon, (2) lateral variation of seismic velocities that corresponds to recent orbital observations, (3) size, property and composition of a possible lunar core, (4) existence or absence of deep moonquakes on the lunar far side, (5) physical cause of deep moonquakes and its relationship to deep internal structure, and (6) real cause of shallow moonquakes and its implications for lunar tectonics and possibly other phenomena. For Mars and other planetary bodies, no direct data to infer their deep interior are yet to exist.

Recent re-analyses of the old Apollo seismic data, made possible by newly developed analysis techniques and greatly improved computer capabilities, are addressing some of these questions, and are finding new answers. Extracting important information still hidden in the Apollo data set certainly constitutes an important challenge to all of us in the near future.

Answers to many other questions, however, must wait until we acquire new data to remove the basic limitations of the data we now have. Such limitations for the Apollo data include (a) limited aerial coverage of the network, (b) paucity of seismic stations, (c) limited observation time, (d) limited bandwidth, (e) a high level of noise and signal distortion due to surface deployment of seismometers, and (f) limited instrumental sensitivity. For the Viking data, all of the above limitations apply, and they are more severe. We must try to remove all these limitations when we go back to the Moon, Mars and beyond.

A lunar/planetary mission to establish a seismic network on the surface of an extraterrestrial body is expensive compared with orbital and other landing missions. Because of this, none has been carried out since the Viking Mars landing mission, even though everyone agrees that seismic observation is the most direct way to explore the deep interior of a planetary body. Acquiring a meaningful new seismic data set, removing the limitations of the old data set, to answer the remaining questions with the available financial resources is a big challenge to us all. We may need an open-minded approach, where we can go beyond conventional techniques appropriate for seismology on Earth.

A New Lunar Roadmap for a New Era of Exploration: Building upon the Past for a Productive Future

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Going back to the Moon with humans appears to be a cyclic endeavor ever since the Apollo program was canceled in the early 1970s. The Vision for Space Exploration speech by President Bush spurred the latest surge of interest in having a permanent human presence on the Moon and to use the Moon to learn how to explore further. The Lunar Exploration Analysis Group (LEAG) was tasked by the NASA Advisory Council in 2007 to develop a comprehensive "Lunar Exploration Roadmap" that would involve science, exploration, feed-forward activities, and to highlight commercial on-ramps. When the LEAG accepted this task, we endeavored to learn from the past and set the following ground rules:

- Any roadmap should be a living document that must be reviewed regularly and updated to reflect new data, political developments, and technological advances;
- The roadmap should expand upon, and be traceable to, previous work;
- The roadmap must include feed-forward aspects to other planetary destinations;
- The roadmap must be comprehensive and include avenues for international and commercial partnerships.

The first version of the roadmap was released in 2009 and can be downloaded from the LEAG website (http://www.lpi.usra.edu/leag/ler_draft.shtml). The first review and update will occur in July 2010. As will be shown in this presentation, while recent NASA budget run outs from the present administration would appear to remove the Moon from the human space flight manifest, there are still plenty of opportunities for lunar exploration.

Continental Crust Spreading: A Process for Synextensional Creation of Continental Crust Inferred from Analysis of the Evolution of Death Valley

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Death Valley (DV) is a rift basin that lies in two overlapping tectonic provinces, the Basin and Range (B&R) and the Walker Lane/Eastern California Shear Zone (WL/ECSZ). The B&R is characterized by large-magnitude extension, often associated with core complex formation. The WL/ECSZ is a younger shear zone system that is evolving into the Pacific-North America plate boundary. Death Valley has some of the most extreme topography within the shear zone. It is bounded to the west by the Panamint Range. This large mountain block, 80 km long, 25 km wide and reaching an elevation of 3368 m, is commonly interpreted as the hanging wall of a detachment fault that moved the Panamint Range across the Black Mountains, a smaller mountain range that today bounds DV to the east. This interpretation implies that there is a B&R detachment surface underneath the Panamint Range. A different interpretation presented here is that the detachment surface tracks over the top of the Panamint Range, as is seen in Tucki Mountain which is a core complex at the northern end of the range. In this new interpretation, the present extreme topography of DV formed within the past 3 my as a result of strike slip faulting within the WL/ECSZ. DV itself is interpreted to be a young pull-apart basin formed by high-angle faults that cut the older low-angle B&R detachment surfaces. Remnants of earlier B&R extension are seen in allochthons consisting of early Paleozoic miogeoclinal section perched on the eastern flank of the Panamint Range, similar to allochthons seen in mountain ranges east of DV. Several strain markers within these allochthons suggest 80 to 100 km of displacement due to B&R extension in the DV region. Crustal thickness, though, remains about 30 km, a paradox as such large-magnitude extension should result in much thinner crust. It is notable that within and east of DV there are large areas of volcanics which recent dating has shown to be mostly late extensional. Along a profile linking the most convincing of the strain markers, 40% of the profile consists of volcanics. Although it is feasible that pre-extensional, highly stretched continental crust underlies all of the volcanics, it is suggested that the volcanics consist essentially of new crust created during extension, in a process which could be called ‘continental crust spreading’. In this process, some of the 80 to 100 km of offset of the strain markers would be due to mechanical extension, with the balance the result of creation of new magmatic crust, including underplating and magmatic crustal thickening. This concept makes it easier to understand how such large apparent extension amounts can be accommodated with little crustal thinning. On a larger scale, nearly 50% of the total area of the B&R province consists of surface volcanics. It is further suggested that a significant fraction of this crust is newly formed by continental crust spreading.

Tectonics of Eastern Mexico, 1980 to 2010 – What We Knew Then, What We Know Now

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During the early 1980's, both USA and Mexico had tectonic maps that had been published twenty years before; both maps were supervised by P.B. King; and both focused on a general philosophy of mapping formational rock units. Bill proposed an innovative way to compile a new tectonic map for half the American continent: Canada, the United States, Mexico, Central America, the Antilles Archipelago, and northern South America. To compile the tectonic data for almost 30 countries was an impressive task, mainly because of the different ways in which each country had mapped its rock units. For example, the stratigraphic formations across the Mexican borders with the United States, Guatemala and Belize, didn't match – why? Mainly because they were defined with different criteria, names and ages, and the same groups of lithologies were not always represented on the respective maps. Thus, one Bill's major efforts was to identify a systematic procedure that allowed everyone to map the same rock units that reflected the same tectonic genesis. In those years we were lucky to be Bill´s graduate students because he asked for our opinions on his project. When I finished my PhD I went back to Mexico with the commitment to Bill to find out what persons, universities, or government offices would participate in this major project. Bill visited several offices in Mexico City and, to my surprise, the response was poor and they didn't show much interest in the project. Because of that, I decided to take responsibility; I invited several of my graduate and undergraduate students and started to compile the Mexican part, a task that took us several years.

In the early 1980's in Mexico, we had a fair understanding of the Mesozoic and younger rocks, but then we attributed most of the deformation of folded and thrusted belts of the eastern part of the country to the Laramide Orogeny. However, some things didn't make sense, because in Mexico the Laramide (Hidalgoan) Orogeny occurred during the Paleogene, while in the United States it was earlier (Late Cretaceous). Our knowledge of the pre-Mesozoic rocks of the basement was poor because outcrops were scarce and subsurface data from wells were very difficult to obtain.

Our major challenge today is to publish modern, dynamic maps that depict the proper rock sequences and that show tectonic, as well as genetic, geologic features cropping out at the Earth's surface. Bill had been interested in wrench tectonics areas since his PhD work in Cal Tech studying the Garlock fault, and he shared his preferred interpretations with several Mexican graduate students like me. Bill's enthusiasm for the themes of our graduate research obligated us to do better daily.

The influence of Bill on the development of our knowledge of the tectonics of Mexico was very significant, because he chose precisely the places that were meaningful for understanding how the structures of eastern Mexico, for example, were results of a combination of sinistral simple shear and gravitational sliding. We didn't know structures like "release" or "weld" faults, nor such mechanisms as trishear fault-propagation folding, In fact, we used very fundamental terms for our structures, but we worked quite hard to understand their origin and evolution; now it is easy to call them by modern names.

The tremendous enhancement in resolution of 3-D seismic images has contributed to a better understanding of tectonic features, as well as to quantification of what we suspected was below but could not prove. In the 1980's, we made many assumptions about the depth to the basement; today we can look at it directly in seismic images, and we can measure the depth.

In those years we couldn't interpret the complex geometry of large salt bodies because we couldn't image them. Also, we ignored the sedimentary patterns below large salt canopies; today we still ignore them, but we are closer to answers. We knew that salt favored the detachment of rocks in contact with it but didn't understand the magnitude of the process.

Computers have replaced physical modeling with many advantages. In the 1980's I remember how difficult it was to change scales precisely, for example, or to manipulate the contrast of a paper copy of a satellite image to try to see linear features (lineaments). Today, via the Internet GIS maps, satellite images, software to simulate almost anything, animations and movies are available to reproduce geological processes. These are an enormous advantage for fully understanding such processes as the movement of salt or shale masses, or the rapid deposition of deep-water sands. But something that was more frequent then, and very fruitful, is becoming less common now: fieldwork. The analysis in the field of rocks and structures was very productive but unfortunately today's geology -- and geologists – have become more "virtual", and this is a worldwide malpractice. I'm sure that today that it is easier to make a more precise and meaningful map than before.

Using Space Shuttle Photographs and the Tectonic Map of North America as Educational Tools to Teach Tectonics

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In the early to mid 1990's, Space Shuttle photographs became readily available to us. A digital library of photos was developed and made accessible from the NASA Earth Sciences and Image Analysis website (URL: http://eol.jsc.nasa.gov). During this time, the Tectonic Map of North America compiled by Bill Muehlberger (1992, 1996) was also published. These two resources emerged as two highly effective visual media to assist students in demarcating tectonic provinces, identifying large-scale tectonic features, and learning global plate-tectonic processes (Reese and others, 1997; Reese and Dickerson, 1999a). Shuttle photographs provide large-scale, true-color views of landforms and show processes – tectonic or otherwise – operating on the surface, spectacularly revealing Earth's dynamic nature (Muehlberger, 1991, and *many* references; Reilly and others, 1998). These photographs show Earth's spheres on enormous spatial scales and document earth-system processes and interactions and natural and human-induced environmental changes (for example, see Reese, 2003). They can be used in a variety of capacities. In my case, following Bill's lead, I use Shuttle photographs to delineate tectonic provinces, portray large-scale tectonic features, and clarify tectonic processes. The Tectonic Map of North America clearly displays spatially and temporally the major tectonic elements of the North American continent. I use the map to familiarize students with the location, map pattern, time of formation, and origin of significant tectonic features throughout North America. Taken together, separately, or with other resources, Shuttle photographs and the Tectonic Map are powerful and stimulating educational tools.

I teach elements of plate tectonics by using educational methodologies structured around Shuttle photographs and the Tectonic Map of North America. For example, western North America provides excellent examples of the products and processes of plate tectonics, many of which are documented vividly on the map and in photos. Several tectonic provinces, each with distinctive characteristics, are readily distinguished. Boundaries separating tectonic provinces also are shown to be remarkably sharp and distinct. Shuttle photos showing the Canadian foreland fold-and-thrust belt illustrate "Sevier-style" tectonics, whereas other photos show the fault-bounded, basement-cored uplifts and intermontane basins of the Rocky Mountains that are typical of "Laramide-style" tectonics.

The Tectonic Map shows the distribution and time of formation of these and related tectonic elements. The Colorado Plateau is shown to be moderately deformed by orogenesis and spectacularly dissected by river systems. Its sedimentary cover consists primarily of continental deposits, which imparts a distinctive warm hue to Shuttle photos of the region. Adjacent, more deformed tectonic provinces bound the Plateau. To the west, topography and structures of the extensional Basin and Range Province are well displayed in photos and on the map. The Wasatch Front and related normal faults along the fairly abrupt eastern margin of the province are easily observed on Shuttle photos, as are the more diffuse structural elements of the transtensional Walker Lane corridor along the western margin.

In north-central New Mexico, the Rio Grande Rift, High Plains, Rocky Mountains, Jemez Mountains, and Colorado Plateau lie in close proximity. Shuttle photos, the Tectonic Map, and field inspection distinguish these distinctive provinces across sharp boundaries (Reese and Dickerson, 1999b). To the west, Shuttle photos reveal clearly and impressively structures of the San Andreas transform plate boundary from the Salton Sea northward to the Bay Area. The Tectonic Map shows these features as well and allows students to reconstruct the plate margin through time. Students can also contrast the San Andreas transform margin with the Cascadia subduction zone margin to the north. The on-shore manifestations of the Cascadia subduction zone are obvious, with stunning views of Cascade arc volcanoes illustrating the explosive nature of volcanism here. To the east, volcanic products of the Snake River Plain-Yellowstone Plateau hotspot track are easily seen on the map and in photos. Using the Tectonic Map and Shuttle photos together, an educator is able to place the fascinating Yellowstone area, like many areas, into its regional tectonic framework. Both map and photos illuminate to an awe-inspiring degree and demonstrate with remarkable clarity the products and processes of plate tectonics and the large-scale Earth system. Each evokes in students a sense of wonder and curiosity about the Earth.

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Geologic Observations from Skylab, America's First Space Station

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The crews of Skylab were the first to make long-term, directed Earth observations by humans in orbit. When the last three Apollo manned moon missions were canceled in a time of declining budgets and growing public ennui, NASA used some of the remaining hardware to create the United States' first space station: Skylab. The Skylab 1 mission was the launch into low earth orbit (435 km) of a modified third stage of a Saturn V rocket on May 14, 1973. The Skylab module was heavily damaged during its launch. Skylab 2, the first manned mission, was launched on a Saturn IB rocket on May 25, 1973 and was devoted to the repair of the module. The following manned missions, Skylab 3, launched July 28, 1973 and Skylab 4, launched November 16, 1973, were devoted to scientific and engineering experiments. The three manned missions lasted 28, 59, and 84 days, respectively, and each set a record for the amount of time astronauts spent in space. Skylab reentered the Earth's atmosphere on July 1, 1979.

While earth observations had long been part of NASA orbital missions, with the exception of photographic experiments on Apollo 7 and 9, the observations and photographs made had been left to the discretion of the individual crewmember. The crew of the second manned Skylab mission observed and photographed 35 land, ocean, and atmosphere sites under the direction of the mission support team at the NASA Johnson Space Center (JSC). The objective of this mission was to determine what kinds of features the crew were able to see and to determine what onboard data and materials were needed to perform these observations. From the results of this mission, a formal visual observation experiment was designed for Skylab 4. From the experience of Skylab 3, it was determined that additional preflight training was necessary to accomplish a multidisciplinary visual observation project. Due to time limitations, the Skylab 4 crew received only 20 hours of briefings by 19 scientists. In this short time, the crew was briefed on such diverse topics as tectonics, hurricanes, volcanoes, ocean phenomena, and weather features among many others. During the mission, the crew received daily recommendations from the support team at JSC. The crew verbally described more than 850 features and took approximately 2000 photographs. Following the mission, the Skylab 4 crew was debriefed by the science team. The preliminary results of the visual observation project were published in Kaltenbach, *et al*., 1974. Interpretations of these data were published in NASA SP 380 (1977) which includes Muehlberger's contribution (Muehlberger, *et al*., 1977). The majority of the content of this paper was extracted from the latter document.

Muehlberger's participation in the Skylab visual observation experiment included briefing the crew, providing support during the mission, and analyzing the data gathered. His area of interest was global tectonics features observed and photographed by the crews of Skylab 3 and 4. He was assisted by the cheap labor provided by graduate students P. R. Gucwa, A. W. Ritchie, and E. R. Swanson. The crews were directed to observe deformation features, principally faults represented by photolinears, in spreading zones, transform faults, and subduction zones. The specific areas observed were the East African Rift, the Afar region, and the Red Sea-Dead Sea Rift; the Alpine Fault of New Zealand and the Atacama Fault of Chile; the complex boundary between the North American and Caribbean Plates in Central America; and the Sierra Madre Occidental in Mexico. The crew were usually able to see the features studied, aided by repeated observations made during multiple passes under differing points of view, sun angles, and atmospheric conditions. In addition, they observed and commented on major fault zones and anomalous features that had not been addressed in the pre-flight briefings. The utility of the photographs taken during the visual observations project in the analysis of regional geology was very well demonstrated. The large-scale, synoptic view provided by hand-held photographs was proven to be of great value in regional geologic studies. Oblique views from many directions can reveal large-scale features not visible on conventional vertical photographs or images from aircraft or from orbit. The photographs also show the relationship of small, better-known areas within a larger, poorly studied area, much to the benefit of the field geologist.

From the perspective of having more than 30 years of geologic data obtained from orbit, these conclusions may seem primitive. However, the observations made from Skylab are the first directed Earth observations made by man on the first true space station. This project is one small example of Muehlberger's inventiveness, use of cutting-edge technology, and breadth of interest.

Skylab Crews
Skylab 1: Unmanned
Skylab 2: Conrad, Kerwin, Weitz
Skylab 3: Bean, Garriott, Lousma
Skylab 4: Carr, Gibson, Pogue

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Basal Stratigraphy of a NW-Trending Jurassic Rift in Honduras (Chortis Block)

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North of Danli in SW Honduras 1300-1500 meters of Jurassic nonmarine and 1300 meters of marine clastic strata exposed on limbs of large NW-verging asymmetric folds reveal a depositional architecture consistent with continental rifting.

The lowest member (Unit 1) consists of 200-300 meters of fluvial overbank shale, siltstone and coal unconformably above basement gneiss. Above the shale (Unit 2) are about 250 meters of alternating very coarse pebble-cobble quartz and metamorphic clast conglomerates with scoured bases and overbank shale facies containing plant fragments. This unit contains at least one 20-meter thick silicic ash-fall tuff. The coarse conglomerate and shale unit grades upward into Unit 3, comprised of a 200-meters-thick fine quartz pebble conglomerate and medium-grained quartz sandstone with unidirectional crossbeds, channels with scoured bases and shale from the overbank environments. This is overlain by Unit 4, approximately 400 meters of fine grained well-sorted and rounded quartz sandstone in 20-40 meter-thick units displaying lateral accretion surfaces of a mixed-load fluvial system. Sand bodies are embedded in shale sequences representing overbank deposition. Within this unit the steeply dipping north limb of the Cerro San Cristobal anticline is comprised of an amalgamated sand body at least 350 to 400 meters thick that represents the location of the axis of the valley in the Jurassic. This individual sand body was tracked 30 km to NW through a series of folds. Above (Unit 5) is an abrupt transition to dark dominantly shale section at least 1300 meters thick and containing ammonites. There are a number of beds that coarsen upward to fine-grained sandstone in the shale. A marine transgressive surface at the top of the fluvial sandstone is interpreted between Units 4 and 5. Deposition of Unit 5 appears to have been dominated by marine shelf conditions, and several lower shoreface sand bodies are recognized.

The depositional architecture, thickness and geographic positions of the strata are consistent with deposition on a south- or southeast-facing passive margin that resulted from the breakup of North and South America. The NW trend of the axial fluvial facies (Unit 4) indicates a large river system draining from the NW and is consistent with a rift extending into North America that subsequently failed as the proto-Caribbean seaway opened between the Americas. This NW-trending rift intersects the larger NNE-trending Agua Fria rift of eastern Honduras near Danli. Deposition along this and other NW-trending depocenters in central Honduras continued through the Cretaceous before being inverted in the Late Cretaceous.

Apollo 17 Lunar Exploration and Its Implications

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In December 1972, the Apollo 17 Mission became the most recent field trip to the Moon by human explorers. This 13-day adventure in space took Gene Cernan and Harrison Schmitt to the Valley of Taurus-Littrow in the southeastern rim of the 740 km. diameter basin filled by Mare Serenitatis. After 72 hours on the lunar surface, including 22 hours outside the lunar module *Challenger,* the astronauts returned over 250 pounds of samples to Earth, based in large part on an exploration plan overseen by William R. Muehlberger. The story of this mission captures all the adventure, excitement, beauty, and human drama of the exploration of space.

The samples, and the visual observation, photography, and geophysical data related to them, completed the documentation of the first human exploration of the Moon. Apollo activities on the Moon, and the international scientific studies related to them, have given us a first order understanding of the evolution of the Moon as a small planet. Our understanding of the early history of the Earth has been greatly enhanced as a consequence. In particular, it now seems unlikely that the Moon formed as a result of a giant asteroid impact on the Earth but rather was captured after forming independently as a small planet in the same part of the solar system.

Proximity to the Earth, lack of atmosphere, gravity only one-sixth that of the Earth, planetary position as the smallest of the terrestrial planets, and potential life-sustaining resources almost certainly assure a role for the Moon in future lunar activities in support of human exploration, utilization, and settlement of space. The Moon can be considered as a stepping stone towards Mars and beyond and also as the low cost supply depot for deep space exploration and settlement. A privately financed approach to the return of humans to the Moon and deep space appears to be the most likely means of being successful in such an endeavor. The first milestone in such an approach would be the development of helium-3 fusion power fueled by lunar helium-3.

Resources on the Moon, verified by Apollo 17 and other mission samples, in addition to their potential use in space, could become an essential part of future Helium-3 fusion or solar energy alternatives to the use of environmentally unacceptable hydrocarbons as fuels on Earth. The vision of a proposed Interlune-Intermars Initiative encompasses commercial enterprises related to resources from space which support the preservation of the human species and our home planet. A commercially instigated return of human activities to the Moon will be required as an alternative to government sponsored efforts due to the increasing limitations on discretionary spending of tax resources.

Attaining a level of sustaining operations for the core fusion power and lunar resource business of the proposed Interlune-Intermars Initiative requires about 15 years and $10 to 15 billion of private investment capital as well as the successful marketing and profitable sales of a variety of applied fusion technologies. This level of private investment lies within the spectrum of similar private financing of modern projects such as the TransAlaska Pipeline and the Eurotunnel.

Tectonics of the Western Indian Ocean

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The tectonic province of the Western Indian Ocean is defined by: 1) the East African Rift Zone to the west, 2) the Ninety-East Ridge to the east, 3) the Arabian peninsula to the north, and 4) the southern Indian Ocean spreading center to the south. Mantle plume extrusions mark the migrating plates.

Significant thicknesses of sediment accumulated in various rift basins, in front of advancing thrust plates, in deepwater fan deposits, in deltaic areas along the coastal margins, and in the deep water environment off the developing shelf margins.

MAJOR GEOLOGICAL EVENTS

MYBP	ERA/SYSTEM	EVENT
1,000	Proterozoic	A mosaic of Precambrian terrains was separated by orogenic belts.
600-450	Late Proterozoic-Early Paleozoic	Thermal rejuvenation marked the beginning of the formation of Gondwana.
600-360	Precambrian Ediacaran into Devonian	Formation of the Proto-Tethys Ocean.
390	Early Devonian	Gondwana formed.
356	Early Carboniferous	Pangea began to form and the Paleo-Tethys began to replace the Proto-Tethys.
306	Late Carboniferous	North America/Europe joined Gondwana forming western half of Pangea.
249	Permian-Triassic Boundary	Cimmerian plate (Turkey/Iran/Tibet/parts SE Asia) broke away from Gondwana (now Pangea) with Tethys Ocean beginning to replace the Paleo-Tethys Ocean.
237	Early Triassic	Pangea assembled, except for SE Asia.
195	Early Jurassic	Pangea assembled with addition of SE Asia. Laurasia (North America/Europe/SE Asia) now complete.
152	Middle Jurassic	East Gondwana began separation from West Gondwana; Africa began separating from South America.

127-121	Middle Cretaceous Earliest Barremian	Spreading between Africa and Madagascar ceased. Spreading and separation developed between India to the north and Antarctica/Australia to the south. A transform fault developed between Madagascar and India/Sri Lanka/Seychelles/Laxmi
121-98.9	Middle Cretaceous Barremian/Aptian/ Albian	Spreading continued between India to the north and Antarctica/Australia to the south as a north-dipping subduction zone developed along India's north coast. The Rajmahal Traps (117-110 Ma) appeared in eastern India. The left-lateral transform between Madagascar and India/Sri Lanka/Seychelles/Laxmi evolved into an oblique spread center as a triple junction formed in the ancestral Indian Ocean.
98.9-65	Late Cretaceous Cenomanian-Maastrichtian	India rotated counter-clockwise as it continued its northward movement; the Rajmahal Traps evolved into the Ninety-East Ridge; the Deccan Traps appeared in western India. The north-dipping subduction zone north of India continued active. A secondary spread center separated the Seychelles/ Laxmi microcontinent from western India.
65-54.8	Paleocene	The Laccadives/Maldives Ridges developed along the Reunion hotspot basalt ridge
54.8-33.7	Eocene	The Mascarene/Saya de Malha and Chagos Banks developed east of the Seychelles microcontinent; a continuation of the Reunion hotspot activity.
34	Eocene/Oligocene Boundary	India collided with Asia. The Bengal Fan/Delta began forming.
33.7-23.8	Oligocene	The northwestern Indian Ocean spread center cut through the Reunion hotspot volcanic ridge. The East African rift system was initiated..
23.8-5.0	Miocene	The Arabian plate began separating from Africa; spreading began in the Red Sea and in the Gulf of Aden. The Miocene salt basin developed in the Red Sea. The Indus Fan/Delta began developing.
18-16.5.1	Miocene Burdigalian	The marine connection between the eastern Mediterranean and the western Indian Ocean closed. The Mediterranean became isolated.
11-6.5	Miocene Tortonian	The western Mediterranean opened to the Atlantic.
6.5-0	Plio-Pleistocene Last Glacial Maximum (22,000-18,000 BP)	Glacial ice covered Fenno-Scandinavia and parts of the Alps and British islands

Gravity and Magnetometer Survey, Culberson and Hudspeth Counties, Trans-Pecos Texas – from Texas Lineament to Rio Grande Rift

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Between summer 1966 and summer 1969, I performed a gravity and magnetometer survey covering about 1,200 sq. mi. in southern Culberson and Hudspeth Counties, Texas, to test the viability of the Texas Lineament as part of the world-wide wrench fault system proposed by Moody and Hill in 1955. Previous work in the region resulted in excellent surface geologic maps but virtually no subsurface information. Although some gravity and vertical magnetometer work had been performed in the region, these data were proprietary to various companies and unavailable for academic research. The chief objective was to search for geophysical evidence of through-going structures oriented about N. 60° W. (the Texas Direction of wrench faulting) beneath the prevalent intermontane bolson fill in the region.

The survey comprised 1,566 gravity and 1,703 magnetic control points (“stations”). Geographic locations and elevations of most stations were established by reference to 1:24,000 scale preliminary USGS topographic maps. Some stations were established by plane table surveying. All gravity stations were corrected for nearby topographic irregularities through zone J of Nettleton’s 1940 terrain correction charts, or 6,652 m from the station.

Contour maps of Bouguer gravity anomaly and vertical magnetic intensity were produced and profiles prepared from them. In order to numerically interpret the geophysical profiles, estimates of sub-regional to regional rock density and magnetic susceptibility were made using any available data because no direct measurements were available. The most significant gravity anomalies strongly suggest mostly down-to-the-south high angle dip-slip faults which resulted in denser Precambrian and Paleozoic rocks being juxtaposed against thick, less dense bolson fill of Eagle Flat.

Using simple block fault models, vertical to near vertical displacements up to 1,400 meters along the north side of Eagle Flat were calculated. A fault zone extending from the south end of the Carrizo Mountains about N. 60° W. can be drawn following the inflection points of the profiles. The maximum displacement occurs south of the Carrizo Mountains and decreases to about 600 meters 32 km west near Sierra Blanca, Texas. The direction of this fault zone is roughly parallel to the Texas Direction of wrench faulting. However, instead of continuing southeastward (S. 60° E.) from the southern tip of the Carrizo Mountains, the fault zone turns southward (S. 20° E) following the surface trace of the Rim Rock fault which extends about 125 km to the Chinati Mountains near Presidio, Texas. In the Van Horn Mountains, the Rim Rock fault zone has a dip-slip displacement similar to the displacement interpreted south of the Carrizo Mountains. There is no geophysical evidence for continuation of the fault zone, or any other significant structure, east of the Carrizo Mountains.

Although the north boundary of Eagle Flat follows a major geologic discontinuity active in both Precambrian (*ca*. 1 Ga) and as a mid to late Mesozoic basin margin hinge line, geologic evidence for continuation of these boundaries further east is lacking. The gravity, magnetic, and geologic evidence begs an interpretation different from the Texas direction of wrench faulting. Subsequent work by Muehlberger and other workers shows that the Rim Rock fault, as extended across Eagle Flat, is part of the northern boundary of Texas-Chihuahua Border Corridor intracontinental transform zone of the Rio Grande rift.

Engineering Geologic Problems near the Mt. Bonnell Fault — Homage to W.R. Muehlberger and Richard H. Jahns

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Having benefited from wisdom passed along the pathways of “academic genealogy” (Jahns to Muehlberger to the multitudes), I present examples of “geologic jeopardy” in the Austin area that relate to spatial coincidence of the Balcones Fault Zone, the Colorado River, and the Edwards aquifer. Case studies include Tom Miller Dam (TMD) and Ullrich Water-Transmission Tunnel (UWT) and involve problems at the interface between geology and civil engineering. These problems stem from flawed “states of knowledge,” unappreciated levels of uncertainty with respect to local geologic conditions, and break-downs in communication between the disciplines.

TMD (originally named Austin Dam) was completed in 1893 without a single geotechnical test boring into its foundation in the Edwards Limestone, which was assumed to be a “stable” rock unit. Moreover, knowledge of variations in river discharge was apocryphal, because the first stream gage in Austin was not established until 1892. The dam failed in 1900 and again in 1915; it remained in a derelict condition until the establishment of the LCRA following the flood of record in 1935. Initially, the failures were presumed to have been caused by a fault beneath the structure, but recent studies indicate that the foundation was compromised by sapping of the aquifer-host strata beneath the dam, although fault-related fracture porosity abetted dissolution of the carbonate bedrock.

UWT is approximately 4,300 ft long, roughly 10 ft in diameter, and extends about 95 ft beneath the surface of Lake Lady Bird, about 1,000 ft downstream from TMD. Host rock is Edwards Limestone, and groundwater discharge into the excavation posed problems that were expected and managed during construction. However, at about 400 ft from the project’s northern terminus, the excavation intersected an unexpected karst cavity that extended across the working face of the tunnel and that was filled with highly plastic, red clay. This feature was not disclosed in geotechnical borings and has no surface expression. Excavation of the tunnel was discontinued at this location; a shaft was dug, and the final project extent was completed as a surface excavation.

Both case studies illustrate that interactions among hydrologic processes acting on variable rock sections in (even) an inactive fault zone pose untoward surprises to engineers and geologists alike.

Richard H. Jahns presents a charge to Earth scientists near the end of his paper, “Geologic jeopardy” in *Limitations of the Earth: A compelling focus for geology* (symposium proceedings for dedication of geology building, UT-Austin, 1967). He exhorts geologists to better predict, avert, and abate natural hazards (and other geologic urban- environmental problems) by means of “coordination of empirical and basic data and of observation, experiment, and theoretical analysis.” This charge is all the more important today, and it provides standards and guidance for all of us, but especially for disciples and academic descendents of Professors Muehlberger and Jahns.

The Great Muehlberger – Folk Debate of 1955-1956:
Did the Moon Come Out of the Pacific Ocean?*

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Over the past five decades, whenever a group of geologists of our vintage would gather, nearly always someone would mention the event that has become known as The Great Debate. We would reminisce, laugh and enjoy it all over again. It was an event which will not, and should not, fade into oblivion. I will do my best to record the elements of it that remain alive in my memory as accurately as I can. It is difficult to avoid embellishing the story; on the other hand, it needs none.

The principals in The Great Debate were Professors William Muehlberger and Robert Folk. If you do not know these men, I must say that is unfortunate. They are two remarkable people who will enrich anyone crossing their paths. I will try to introduce them to you.

Bill Muehlberger is a big man who looks even bigger. He has a strong square jaw, a prominent chin and the perfect posture of a drill sergeant. It would be a mistake to equate his demeanor with this physical description. He is a gentle man. He seems always predisposed to teach, as all good teachers are. I did not have courses under Muehlberger, but I had the great pleasure of visiting the Solitario with him a few years ago. Over a bowl of chili at a remote camp house, there is no better company. He is a structural geologist but he is probably best known for his pioneering and lengthy role in training astronauts.

Bob Folk is a smaller man with a youthful face and boundless exuberance in everything he does. He is, beyond a doubt, a certifiable genius. I had him for sedimentation, his specialty then. I also had him for structural geology, which he was called upon to teach before Muehlberger's arrival. (To illustrate rock mechanics, he would roll silly putty into a ball and bounce it off the back wall of the classroom, a pretty good arm. Then he would stick it to the blackboard and have us notice how it slowly deformed toward the floor. How could a student ever forget that?) I was taking photogeology when, a few weeks into the semester, the instructor quit. Guess who stepped in to teach photogeology? Folk taught the first-ever-in-the-world carbonate petrography course. The heart of the course was his developing scheme of classification of carbonate rocks. (Folk's AAPG article, *Classification of Carbonate Rocks,* won Best Paper for 1961.). In later years Folk would discover nannobacteria (perhaps simultaneously with another scientist) and I suspect that we have not heard the last from these little guys. Did I mention he is a genius?

Folk had an affinity for colored chalk in his lecturing. He also had an affinity for knit ties, popular at the time. Knit ties are wrinkle-free but the fabric is heavy and of low tensile strength such that, as the day wears on, they get longer and longer. By the end of one of Folk's energetic late-morning lectures, the end of the tie would be down around the bottom of the zipper and he, the tie and the blackboard would be covered with colored chalk dust. Unforgettable.

In the 1950's "plate tectonics" was not yet in the jargon. Continental drift (the forerunning term) was viewed with disdain if not derision. Sea-floor spreading, the magnetic patterns, and several other determining factors were not as yet discovered.

It leaked out that Folk was a closet continental drifter. The fact was that he had a smoothly integrated theory which held, in part, that a nearby passing star plucked Earth material from what is now the Pacific Ocean basin. The vacancy began to close by the separation and drifting apart of North-South America from Eurasia-Africa. The former "other side" of the Earth reached orbital velocity, and there it sits as our Moon.

My dim recollection is this: we thought a talk on continental drift would be great for a UT Geological Society meeting because it was controversial. Then the idea of a talk evolved into the idea of a debate. The question would be "Did the Moon Come Out of the Pacific Ocean?". The real enabler of the debate was Bill Ward, who was able to persuade Folk to present and defend his unpopular theory. Bill also solicited Muehlberger to take the other side of the question. And it was Ward, again, who made wonderful posters to advertise the event. The stage was set.

I wish I could remember exactly where the debate was held. It may have been the auditorium of the physics building. Someone told me that they thought it was the journalism building. The room as I picture it was bigger than the geology auditorium, a capacity of maybe 300 people, and it was very close to full.

It fell to me to introduce the speakers and to state the rules: Folk first, with 20 minutes for the "pro", Muehlberger with 20 minutes for the "con". Then Folk with 5 minutes for rebuttal and Muehlberger with 5 minutes for rebuttal. It was all very proper and I would be time-keeper.

I turned it to Folk and he went to the blackboard and went to work, knit tie flailing and colored chalk dust flying. He laid out, as I recall, his convincing story of floating continents. He took the pressure off me by finishing right on time.

Now Muehlberger. (Many of these recollections are foggy and uncertain. This is not one of them. It is as clear as if it happened this morning. Here is precisely how it went.) Muehlberger came, unhurriedly, to the long black lab table that served as the lectern. He spent what seemed like a long time looking downward at his notes and thoughtfully arranging them. Finally he raised his eyes to the audience and said exactly this: "I feel like the guy who inherited the harem. I know what to do. I just don't know where to start." The audience convulsed, and then convulsed some more. I think if you could visit that room late some night when the campus is quiet, you could still hear laughter reverberating off those walls. Muehlberger stated his argument, based mainly on strength of materials and rock mechanics, punctuated here and there with his remarkable humor. He too finished on time.

Folk had 5 minute for rebuttal. He attacked Muehlberger's work in a cloud of chalk dust. A couple of minutes of that and Muehlberger went to the board, took the chalk from Folk, and attacked Folk's work. Folk brought plenty of colored chalk. He grabbed another piece and the debate reached, as they say, a new level. The convulsions of the crowd are now continual. I am in a quandary. How do you time this? Finally I stood and announced that the time for rebuttal had expired. I have some faint recall of a scattering of boos.

The next may be imaginary: I think that the UTGS officers (Ellie Macha Hoover, Rex White, Bill Ward and I) huddled quickly and decided that – wouldn't you know it? – the debate was a tie! More boos.

I have a clear picture of people slowly leaving the room, some almost staggering with laughter or with exhaustion from laughter. The Great Debate was a learning experience that would remain in the minds of people for years. No one dozed off. No one's mind wandered. It was all things a college lecture should be. And a half century later it is still remembered and enjoyed.

EPILOGUE

Not many years after The Great Debate continental drift, rechristened "plate tectonics", shed its dubious reputation and became hailed as a major advance in the science of geology. It became a popular topic of technical talks. They always featured the symmetries of the Atlantic side of the globe. After such a talk, when I could do so discreetly, I would ask the speaker "What about the other side of the globe?" The answer was usually something like "Well, it is pretty complicated over there". I would think to myself, "Damn right it is. That's where the Moon came from."

A few years ago I saw Folk at an AAPG convention where he was receiving another honor. I asked him if he still believed that the Moon came out of the Pacific. He replied that he did not. He said that the lunar samples denied it. Isn't it interesting that the astronauts whom Muehlberger trained would bring back samples that would settle the debate. On the other hand, continental drift, under a pseudonym, is universally accepted. So the Great Debate was, in fact, a tie.

*****Excerpted from:

White, Leslie P., 2006-2007, The Great Debate and a few related recollections: Austin Geological Society Bulletin, volume 3, 7 pages.

Symposium Sponsors & Acknowledgments

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Acknowledgments

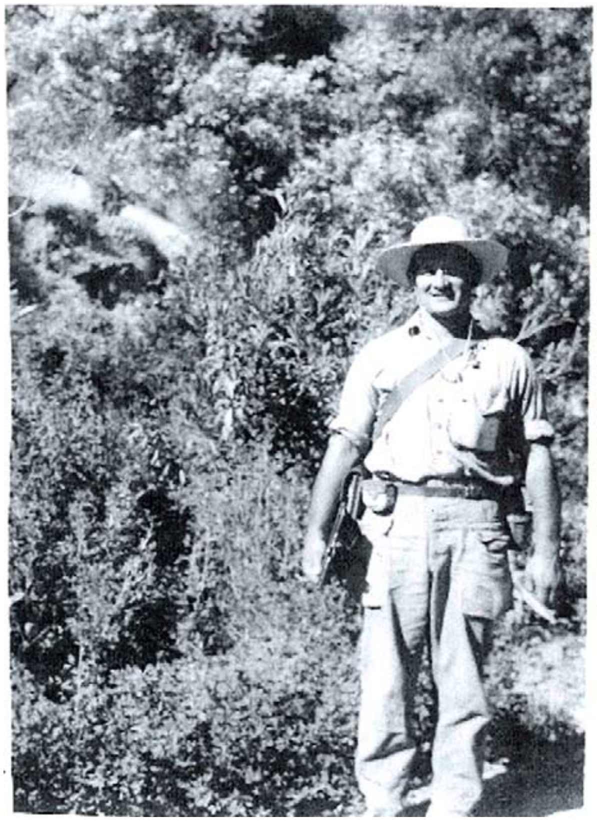
From the outset this salute has received unswerving support from Sharon Mosher, Dean of the Jackson School of Geosciences, whom we acknowledge with gratitude. The fact that we can announce the W. R. Muehlberger Graduate Fellowship in Structural Geology and Tectonics owes to the prodigious efforts of Lisa K. “Rusty” Goetz and Kimberly Kassor Rose (JSG). In addition, Rusty recruited corporate and individual underwriters (listed above) for Symposium functions. The placards acknowledging those contributions were created by Jeffrey Horowitz (JSG). Nicole Evans and Angela Obolsky of the Dean’s office graciously and capably handled the myriad hotel and catering arrangements.

The impressive presentation pieces for Bill – the NASA STS 132 Shuttle mission certificate and the Fellowship certificate – reflect the artistry and effort of both NASA-JSC and JSC people. At JSC, Duane Ross arranged to have the rock samples flown on STS 132 (May, 2010). Greg Thompson (JSG-DGS) finished the rock slices for mounting; and Sean Collins (JSC) created the handsome display. Kimberly Rose brought the Fellowship certificate from concept to elegant portfolio.

Photographs figure prominently in this celebration, which is being chronicled by David Stephens, Tommy Kile, and Jim Bones. For the opening reception Bill St. John, Bob Hatcher, Pat Bobeck, Diana Ritmire, Ric Finch, Peter Hennings, Ricardo Padilla y Sánchez, Chock Woodruff, Rusty Goetz, Dan Barker, Ernie Lundelius, and Marc Airhart furnished photos that Robert Reed (JSG-BEG) fashioned into an entertaining slide show. Diana Ritmire, Eric and Edie Muehlberger, and Marc Airhart provided photos for the abstract volume. Public distribution of the book has been arranged through the UT Digital Repository, thanks to the efforts of Dennis Trombatore (Walter Geology Library).

This abstract volume comprises scientific contributions of 53 authors – colleagues, students, friends and family of Bill Muehlberger; Bill himself is author or co-author of four. The most visible and vocal encomia, however, will have been the Symposium talks and posters that he inspired. Our profoundest thanks to all of you for making this a fitting tribute to a genuine giant of geology.

Patricia W. Dickerson
Mark Cloos



June 52
Geologists Field "apparatus"
On belt = canteen, compass,
notebook & pencil case
In hands = mapholder, hammer
In pocket = acid bottle, snake-bite
kit, toilet paper
Watch hanging from button hole
Magnifying glass hanging around
neck & in pocket
Bag on back for lunch, camera,
rocks
Clothing as appropriate

The well-dressed field geologist of 1952

Theses & Dissertations Supervised by W. R. Muehlberger

Adams, Gordon Edward, 1957, The Geology of Chama Area, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1957 Ad17

Balke, Bennie Kuno, 1958, Structural Geology Along Mount Bonnell Fault, South Central Travis County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1958 B199

Balkwill, Hugh Robert, 1969, Structural Analysis of the Western Ranges, Rocky Mountains, Near Golden, British Columbia. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1969 B199

Barrett, Michael E., 1979, Depositional Systems in the Rinconada Formation, Taos County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1979 B275

Barton, Gerald Stanley, 1971, Fortran Program for the Generation of Mean Gravity Anomalies by Least Squares. (Muehlberger, W. R.).
Degree: MA
Call Number: T1971 B287

Bennett, Richard Edwin, 1959, Geology of East Bourland and Simpson Springs Mountains, Brewster County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1959 B439

Berg, Edgar Lowndes, 1971, Geology of the Sierra de Samalayuca, Chihuahua, Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1971 B452

Berge, Timothy Bryan, 1981, Structural Evolution of the Malone Mountains, Hudspeth County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1981 B453

Bhatrakarn, Tanakarn, 1961, Correlation of Gravity Observation with the Geology of Parts of Burnet, Blanco, and Llano Counties, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1961 B469

Bingler, Edward Charles, 1964, Precambrian Geology of La Madera Quadrangle, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1964 B513

Bjorklund, Thomas Kieth, 1962, Structure of Horse Mountain Anticline (Southwest Extension), Brewster County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1962 B556

Bumgardner, John E., 1976, Geology of the Gabbro Sill Surrounding Mariscal Mountain, Big Bend National Park, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1976 B88

Byrd, William Martin, 1958, The Geology of a Portion of the Combs Ranch, Brewster County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1958 B996

Chapin, Thomas Scott, 1981, Geology of Fort Burgwin Ridge, Taos County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1981 C3653

Clabaugh, Patricia Sutton, 1962, Petrofabric Analysis of Salt Crystals from Grand Saline Salt Dome. (Muehlberger, W. R.).
Degree: MA
Call Number: T1962 C512

Clemons, Russell Edward, 1966, Geology of the Chiquimula Quadrangle, Guatemala, Central America. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1966 C592

Cobb, Robert C., 1980, Structural Geology of the Santiago Mountains Between Pine Mountain and Persimmon Gap, Trans-Pecos Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1980 C634

Coley, Katherine L., 1987, Structural Evolution of the Warwick Hills, Marathon Basin, West Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1987 C679

Connors, Harry E. III, 1977, Structure of the Heart Mountain-Tinaja Spring Area, Brewster County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1977 C762

Cooley, Beaumont Brewer, 1956, Areal Geology of Dry Cimarron Canyon, Union County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1956 C776

Davis, James Harrison, 1960, Geology of El Vado Area, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1960 D294

DeCamp, Dodd Werner, 1981, Structural Geology of Mesa de Anguila, Big Bend National Park, Trans-Pecos Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1981 D355

DeMis, William D., 1983, Geology of the Hell's Half Acre, Marathon Basin, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1983 D395

Denison, Roger Espy, 1966, Basement Rocks in adjoining Parts of Oklahoma, Kansas, Missouri, and Arkansas. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1966 D416

Dickerson, Patricia Wood, 1995, Tascotal Mesa Transfer Zone, Rio Grande Rift of West Texas (Presidio, Brewster Counties) -- A Structural, Mechanical, and Thermal Characterization. (Muehlberger, W. R.).
Degree: Phd
Call Number: Diss 1995 D558

Diggs, Timothy Neighbours, 1989, Sedimentology and Structural Geology of the Housetop Mountains/Castle Mountain Area, Marathon Basin, Trans-Pecos Texas. (McBride, E. F. and Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1989 D569

Doney, Hugh Holt, 1966, Geology of the Cebolla Quadrangle, Rio Arriba County, Northcentral New Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1966 D717

Dunaway, William Edmon, 1962, Structure of Cretaceous Rocks, Central Travis County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1962 D91

Duncan, Mary Anne, 1987, Geology of the West Bourland Mountain Area, Marathon Basin, West Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1987 D9124

Dunn, David Evan, 1964, Evolution of the Chama Basin and Archuleta Anticlinorium, Eastern Archuleta County, Colorado. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1964 D922

Dupre, William Roark, 1970, Geology of the Zambrano Quadrangle, Honduras, Central America. (Muehlberger, W. R.).
Degree: MA
Call Number: T1970 D928

Emmet, Peter A., 1983, Geology of the Agalteca Quadrangle, Honduras, Central America. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1983 Em64

Erdlac, Richard John, 1988, Structural Development of the Terlingua Uplift, Brewster and Presidio Counties, Texas. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1988 Er27

Everett, John Raymond, 1970, Geology of the Comayagua Quadrangle, Honduras, Central America. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1970 Ev26

Everett, John Raymond, 1964, Post-Cretaceous Structural Geology Near Del Norte Gap, Brewster County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1964 Ev26

Fakundiny, Robert Harry, 1967, Birrimian Metamorphic and Associated Granitic Rocks (Precambrian) South-Central Ghana, West Africa. (Muehlberger, W. R.).
Degree: MA
Call Number: T1967 F179

Fakundiny, Robert Harry, 1970, Geology of the El Rosario Quadrangle, Honduras, Central America. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1970 F179

Finch, Richard Carrington, 1972, Geology of the San Pedro Zacapa Quadrangle, Honduras, Central America. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1972 F491

Fish, Johnnie Edward, 1970, Crustal Structure of the Texas Gulf Coastal Plain. (Muehlberger, W. R.).
Degree: MA
Call Number: T1970 F52

Goetz, Lisa K., 1977, Quaternary Faulting in Salt Basin Graben, West Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1977 G555

Gordon, Mark Buchanan, 1990, Strike-Slip Faulting and Basin Formation at the Guayape Fault--Valle de Catacamas Intersection, Honduras, Central America. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1990 G657

Gries, John Charles, 1970, Geology of the Sierra de La Parra Area, Northeast Chihuahua, Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1970 G873

Haenggi, Walter Tiffany, 1966, Geology of El Cuervo Area, Northeastern Chihuahua, Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1966 H118

Harpster, Robert Eugene, 1957, Geological Application of Soil Mechanics to Del Rio Formation in Austin, Texas, Area. (Muehlberger, W. R.).
Degree: MA
Call Number: T1957 H234

Harris, William Howard, 1961, Geology of the Post Corners Area, Washington and Rensselaer Counties, New York. (Muehlberger, W. R.).
Degree: MA
Call Number: T1961 H244

Hennings, Peter Hill, 1991, Structural Studies of the Chihuahua Tectonic Belt. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1991 H393

Hightower, Maxwell Lee, 1958, Structural Geology of the Palestine Salt Dome, Anderson County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1958 H538

Houser, John Foster, 1967, Structural Geology of Threemile Hill Area Brewster County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1967 H817

Iranpanah, Assad, 1964, Structural Geology of Burnet Area, Burnet County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1964 Ir1

Kirschner, Carolyn E., 1979, Structural Evolution of a Precambrian Tidal Flat, Taos County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1979 K639

Kraft, Jennifer L., 1984, Structural Evolution of the Sunshine Springs Thrust Area, Marathon Basin, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1984 K855

Kurie, Andrew Edmund, 1956, Fractures in Austin Group, Southern Travis County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1956 K965

Leason, Jonathan O., 1983, Structural Geology of the Horse Mountain Area, Marathon Basin, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1983 L481

Leininger, Roland L., 1982, Cenozoic Evolution of the Southernmost Taos Plateau, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1982 L553

Leonard, Raymond C., 1977, An Analysis of Surface Fracturing in Val Verde County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1977 C553

Lindholm, Roy Charles, 1963, Structural Petrology of the Ortega Quartzite, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1963 L644

Longgood, Theodore Edward Jr., 1960, Geology of Chromo Peak Area, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1960 L861

Maler, Michael Otis, 1989, Structural Geology of the Southernmost Sierra del Caballo Muerto/Boquillas Canyon Area, Big Bend National Park, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1989 M293

Mankin, Charles John, 1958, Stratigraphy and Sedimentary Petrology of Jurassic and Pre-Graneros Cretaceous Rocks, Northeastern New Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1958 M374

Manley, Walker D., 1977, Central Peaks of Lunar and Martian Craters. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1977 M314

McGookey, Douglas A., 1986, The Queen Formation of the Ozona Arch Area of Crockett County, Texas: Structure and Depositional Systems. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1986 M177

McReynolds, J. Carroll, 1958, Structural Geology of Southwest Austin Area, Travis County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1958 M246

Meneses-Rocha, Javier, 1985, Tectonic Evolution of the Strike-Slip Fault Province of Chiapas, Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1985 M524

Meneses-Rocha, Javier de Jesus, 1991, Tectonic Development of the Ixtapa Graben, Chiapas, Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1991 M524

Moustafa, Adel R., 1983, Analysis of Laramide and Younger Deformation of a Segment of the Big Bend Region, Texas. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1983 M867

Nance, Hardie S., 1988, Facies Relations and Controls on Artesia Group Deposition in the Matador Arch Area, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1988 N153

Padilla y Sanchez, Ricardo J., 1982, Geologic Evolution of the Sierra Madre Oriental Between Linares, Concepcion del Oro, Saltillo, and Monterrey, Mexico. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1982 P1347

Peterson, Christine M., 1981, Late Cenozoic Stratigraphy and Structure of the Taos Plateau, Northern New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1981 P447

Pew, Elliott, 1982, Seismic Structural Analysis of Deformation in the Southern Mexican Ridges. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1982 P463

Poth, Stephen, 1979, Structural Transition Between the Santiago and Del Carmen Mountains in Northern Big Bend National Park, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1979 P848

Ritchie, Alexander W., 1975, Geology of the San Juan Sacatepequez Quadrangle, Guatemala, Central America. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1975 R511

Ritchie, Alexander Webb, 1969, Geology of Part of Las Tablas Quadrangle, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1969 R511

St. John, Billy Eugene, 1960, Geology of the Tecolote Point Area, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1960 Sa25

St. John, Billy Eugene, 1965, Structural Geology of Black Gap Area, Brewster County, Texas. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1965 Sa23

Strong, Walter Morrill, 1957, Structural Geology of Pilot Knob Area, Travis County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1957 St882

Tauvers, Peter Rolfs, 1988, Structure Sections through the Marathon Basin, Trans-Pecos Texas--Implications for Basement-Influenced Deformation. (Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1988 T196

Trice, Edwin Leslie Jr., 1957, Geology of Lagunitas Lakes Area, Rio Arriba County, New Mexico. (Muehlberger, W. R.).
Degree: MA
Call Number: T1957 T731

Tyburski, Stacey Ann, 1992, Deformational Mechanisms Along Active Strike-Slip Faults: SeaMARC II and Seismic Data from the North America-Caribbean Plate Boundary. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1992 T954

Warner, Ralph Hartwin, 1961, Structural Geology of Carboniferous Rocks Near Marble Falls, Burnet County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1961 W147

Watkins, Joel Smith Jr., 1961, Gravity and Magnetism of the Ouachita Structural Belt in Central Texas. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1961 W325

Wiley, Michael Alan, 1970, Correlation of Geology with Gravity and Magnetic Anomalies, Van Horn-Sierra Blanca Region, Trans-Pecos Texas. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1970 W648

Witebsky, Susan N., 1987, Paleontology and Sedimentology of the Haymond Boulder Beds (Martin Ranch), Marathon Basin, Trans-Pecos Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: Thesis 1987 W771

Yilmaz, Pinar O., 1981, Geology of the Antalya Complex , SW Turkey. (Maxwell, J. C. and Muehlberger, W. R.).
Degree: PhD
Call Number: Diss 1981 Y56

Youash, Younathan Yousif, 1961, Correlation of Gravity Observations With the Geology of Southern Burnet County, Texas. (Muehlberger, W. R.).
Degree: MA
Call Number: T1961 Y83

Youash, Younathan Yousif, 1965, Experimental Deformation of Layered Rocks. (Muehlberger, W. R.).
Degree: PhD
Call Number: TD1965 Y83

W. R. Muehlberger – A Biography

[1]Peter A. Emmet, [2]Paul Mann, [3]Mark B. Gordon, [4]Richard C. Finch & [5]Robert D. Rogers

[1]Brazos Valley GeoServices, Inc., Cypress, TX; [2]Jackson School of Geosciences, Institute for Geophysics, University of Texas at Austin; [3]Shell Oil, Houston, TX; [4]Tennessee Tech University, Cookeville, TN; [5]California State University – Stanislaus, Turlock, CA

Origins:

William Rudolf "Bill" Muehlberger was born in New York City on September 26, 1923, and moved to Hollywood, California, at the age of six. Bill's claim to have moved from Harlem to Hollywood is only a slight exaggeration (they lived on 124th Street in NYC) and his willingness to embellish the truth for a good story has enriched his fiends and colleagues throughout his long career. His father was a butcher. Boy Scout outings to the San Gabriel Mountains and a high school teacher of physical science (Geology, Astronomy and Meteorology), who happened to be a geology graduate from Cal Tech, were important early influences. Bill graduated from John Marshall High School in Hollywood in 1941 and began undergraduate studies in Geology at Cal Tech in the fall of 1941. Bill was determined to become a geologist, but two wars and the U.S. Marine Corps provided temporary distractions. In the wake of Pearl Harbor he volunteered for the Marine Corps. Bill always liked a challenge and he figured that, if he had to fight, they could teach him how to do it properly. He was sent to an officer training program at U.C. Berkeley to study civil engineering to be a combat engineer. He was called to active duty in June 1943, attended boot camp at Paris Island, and graduated from Engineering School at Camp Lejeune on VJ day in 1945. In the demobilization after the war Bill served in various capacities at Camp Pendleton, the USMC Recruit Depot in San Diego, and Camp Elliot before being released from service in May 1946. He then returned to Cal Tech as a junior in geology and was recruited to play football. Bill notes that Cal Tech's home field was the Rose Bowl, but he concedes that it was also the home field for Pasadena High School.

During the summers as an undergraduate Bill found his real vocation working on field mapping projects. He was summer field assistant for a mapping study of pegmatite deposits in New Mexico in 1947 for Dick Jahns, professor of geology at Caltech who later served as Bill's PhD advisor. Bill was touched by stardust several times in his career. Another field assistant that summer was the young Eugene Shoemaker who was to become a pioneer in planetary geology. The field area in New Mexico lacked a proper base map and a large part of the work that summer consisted in the compilation of a topographic base using air photos, a barometric altimeter and a transit. This was a seminal experience. Bill gravitated toward geologic frontiers and many of Bill's future study areas would also require the assembly of base maps from images and other remotely sensed data (Honduras, the Moon, etc). In 1948 and 1949 he again assisted Dick Jahns on glacial and bedrock mapping in New England for the USGS. Although he was essentially finished with his undergraduate studies in 1948 Bill's athletic eligibility was extended another year by a technicality, and he received Bachelors and Masters degrees from Cal Tech simultaneously in 1949.

Early career and family:

Bill met his sweetheart, Sally Provine, an English literature major at Scripps College, in 1948 and they married in 1949. They had two children: Karen, (born in 1952 in Pasadena, CA) and Eric (born in 1956 in Austin, TX). Bill began his PhD studies at Cal Tech in the fall of 1950 and elected to study the Garlock fault zone for his dissertation topic. Again, war and the Marine Corps interrupted his plans. Bill was recalled to active duty in December 1950 to an engineering battalion, but by some miracle of logic the Marine Corps recognized his value as a military geologist and in May 1951 he was transferred to Camp Pendleton where for the next year he studied the groundwater geology of the area and served as an expert witness for the US Government in litigation over water rights. Released again from the Marine Corps in May 1952 Bill returned to Cal Tech and to his dissertation. But by then his Garlock field area had been turned into a restricted military base (a rocket firing range! Bill's future career would involve rockets, but at this point they were a serious hindrance). Undaunted, he undertook an entirely new PhD study of the Transverse Ranges of Southern California and defended his dissertation "Geology of the Soledad Basin, California" in January 1954.

The University of Texas:

Bill began his teaching career in the spring semester of 1954. He was recruited by Sam Ellison who he had met at an AAPG meeting in Los Angeles during a recess in one of the water rights trials in which he was testifying. Bill was introduced to Sam by his Marine Corps colleague and fellow military geologist, H. Nelson "Web" Webernick, who had studied with R.K. Deford at Texas. At UT Bill was promoted from Assistant Professor to Professor in 1962 and served as Chairman from 1966 to 1970. In 1967, during Bill's tenure as Chairman, the Department of Geological Sciences moved into a new building on campus and Bill took pride in having shepherded the Department through this difficult process. Over his career Bill supervised 61 masters and 26 doctoral students (*see* list, this volume) and served on the committees of many others on topics that included tectonics, structural geology and petrology in Texas, New Mexico, Colorado, southern mid-continent basement, Vermont, Canadian Rockies, Gulf of Mexico, Mexico, Guatemala, Honduras, Turkey, and the Moon. Work on basement rocks produced the "Basement Rock Map of the United States" at a scale of 1:2,500,000 published by the USGS in 1968. Bill also edited an updated version of Phil King's "Tectonic Map of North America", a six-by-six foot wall map published by AAPG in 1988.

Lunar Geology and Remote Sensing:

Bill's early interest in astronomy eventually led him to an affiliation with NASA that began in 1964 when he led a group of astronauts on a geologic field trip to the Marathon basin, West Texas, to begin training them for lunar missions. In this and in subsequent training exercises he designed the astronaut's field excursions to simulate real missions, with realistic objectives and logistics, and with the very limited communications that would be available to them with Mission Control when on the Moon. Bill took a leave of absence from UT once he had completed his tenure as Chairman of the Department in order to work full-time for NASA from 1970 until 1972 during which time he was principal investigator for the Apollo 16-17 Field Geology Experiment Team which had the responsibility of planning all of the geological traverses for those missions. Later he was a co-investigator for the Earth Observations team of the Skylab and Apollo-Soyuz missions. In later years Bill was involved in briefing Shuttle astronauts on tectonic features that they would see and photograph from space and he still wears with pride a bolo tie of New Zealand jadeite that was taken into orbit by John Young, one of his Apollo geology trainees and Commander of the inaugural flight of the space shuttle in 1981. Bill's Hollywood credits include a cameo appearance in a documentary film on the Apollo program in which his beaming face can be seen among the jubilant staff at Mission Control just after the historic landing on the Moon by Apollo 11. Except that Bill wasn't at Mission Control for Apollo 11! But he certainly was there for Apollo 16 and 17, and Bill may smile to think that the editorial license taken by the producers of that film might serve to fuel conspiracy theories about NASA hoaxes and moon landings conducted in the back lots of, where else? Hollywood!

Central American Mapping Program at The University of Texas:

Several of the presentations at this symposium had their roots in the thesis work of Bill's students who participated in a unique program of geologic mapping and research during an intensive period from 1968 to 1975, and which continued intermittently during the 1980s and 1990s. The initial research was conducted with the close collaboration of Gabriel Dengo, who first suggested to Bill that he undertake a geological field program in Honduras which was essentially unmapped at that time. Dengo was affiliated with the Instituto Centro-Americano de Investigaciones Tecnológicos e Industriales (ICAITI) which was based in Guatemala but was active throughout Central America. Dengo and colleagues at ICAITI provided critical logistical, intellectual and moral support to the UT mapping program. Funding for the program was provided in part by The University of Texas and by NSF. ICAITI funding came, in part, from USAID. Additional funding was received from governmental agencies within the host countries of Guatemala and Honduras. Support for mapping efforts in later years in Mexico was provided by Pemex. There was some collaboration between the mapping efforts of The University of Texas and the Peace Corps in Honduras and some volunteers who performed geological mapping studies were mentored by UT faculty or students and one (Rob Rogers) elected to enter the graduate program at the University of Texas following his Peace Corps experience.

The early Honduran mapping, in particular, established a rigorous regional framework that included the basement geology, Mesozoic and Cenozoic stratigraphy and the complex Laramide wrench and Cenozoic extensional tectonics. The mapping program resulted in the first four geological quadrangles to be mapped in Honduras. At about the same time two important quadrangles were mapped in Guatemala. All were mapped at a scale of 1:50,000. Eventually Bill's students were credited with 14 quadrangles maps in

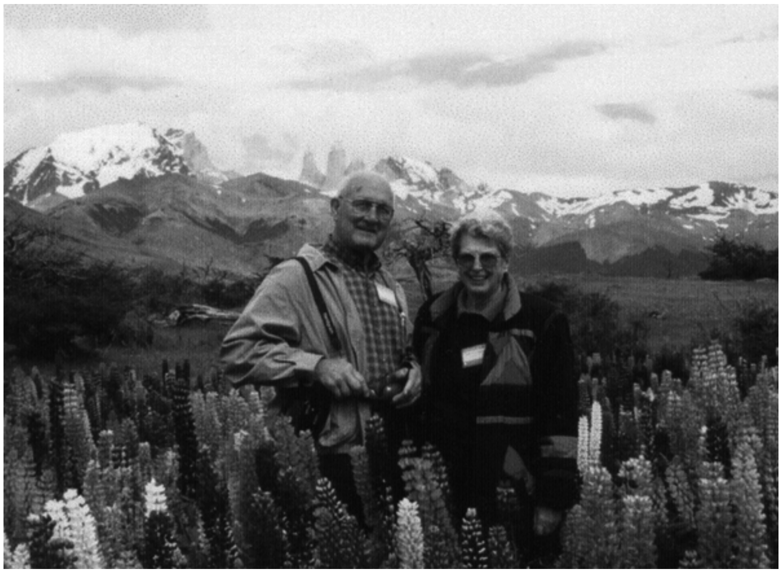
Honduras and Guatemala and with significant regional mapping in Chiapas, Mexico. These geologic maps remain in wide use for a variety of purposes including urban planning, mineral and oil exploration, and academic research.

Over the years the Central American mapping program required Bill to match the skills and interests of a variety of students to many different geological opportunities and logistical challenges. This wasn’t easy for anyone involved, but the results were worthy of the efforts.

Coda:

Bill Muehlberger has made a life and a career of field-based geological studies. He has participated in a meaningful way in some of the most spectacular field trips ever undertaken by mankind. He has attracted and motivated many people to study the things about which he was passionate. As a graduate advisor he allowed his students to take risks, he supported them without meddling in their creative affairs, and he gave them the stern editorial and administrative direction that they needed. As a scientist he has been rewarded with an enviable body of accomplishment and by the devotion of a large group of peers, colleagues and students, for whom it has been a privilege to have known and worked with him.

W. R. Muehlberger – Environment of Success



Bill and Sally Muehlberger, Patagonia, mid-2000's

Muehlberger Children & Grandchildren

Siblings –
Left, Diana, Bill, Roy, Eugene (front), 1936-ish
Right, Eugene, Bill, Diana and Roy, 2008

Most of Muehlberger Clan, 2008

Epilogue

Bill Muehlberger,
A geologist fully immersed in his field work…