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Geologic activities in the 90s

Southwest Section of AAPG 1994, Ruidoso, New Mexico, hosted by the Roswell Geological Society

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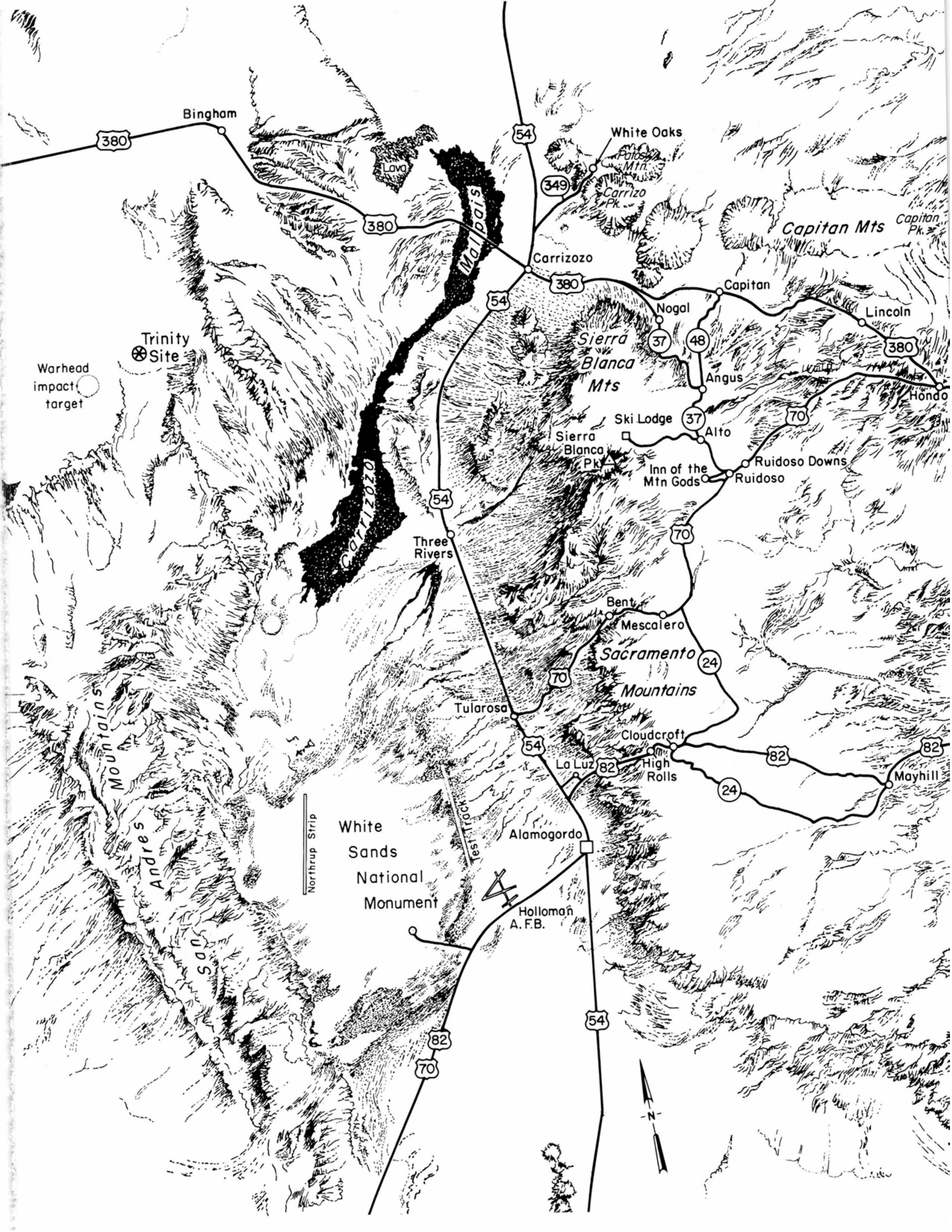
Contents

Articles

Abstracts of talks



Bingham
380
Lava
Malpais
54
White Oaks
Patos Mtn.
349
Carrizo Pk.
Capitan Mts
Capitan Pk.
380
Carrizozo
380
54
Capitan
Nogal
Lincoln
Trinity Site
Warhead impact target
Sierra Blanca Mts
37
48
380
Angus
Hondo
Ski Lodge
37
Alto
70
Sierra Blanca Pk
Ruidoso Downs
Inn of the Mtn Gods
Ruidoso
Carrizozo
54
Three Rivers
70
Bent
Mescalero
Sacramento Mountains
24
70
Tularosa
Cloudcroft
54
82
La Luz
82
High Rolls
82
24
Mayhill
San Andres Mountains
Northrup Strip
White Sands National Monument
Test Track
Alamogordo
Holloman A.F.B.
54
82
70
N

Editors' acknowledgments

We would like to congratulate and thank all the people who have contributed to this volume, from the authors, typists and reviewers to the editors, typesetter and publisher. It is not possible to publish a symposium volume such as this without the willing cooperation of all those who contribute the blood, sweat and tears. We are fortunate to have a dedicated group of authors willing to spend many hours of effort for our benefit.

You will note the great range of subjects on this year's program as our influence is required in new fields of geology. The editors are pleased to note the interest of many geologists in the environmental field. It is hoped that the highly politicized environmental concerns can be mitigated using sound geological research.

This is a period of continued change in the profession of petroleum geology in the Southwest. Many properties are being sold or offered for sale. Drilling dollars are scarce for many projects due to low product prices. It is again a time which requires a great deal of tenacity to remain active in our profession.

Progress in oil exploration will require innovative techniques, trends and transitions to carry us into the twenty-first century. New approaches include three-D seismic, horizontal drilling, CO_2 foam flooding, and borehole imaging.

We are indebted to Jiri Zidek, our Managing Editor, who has guided our efforts to produce each item in this volume. His supervision of the project and his many suggestions to authors yielded a polished publication.

Jack Ahlen
John Peterson
Arthur L. Bowsher

On behalf of the Roswell Geological Society, it is a pleasure to welcome the Southwest Section of the American Association of Petroleum Geologists to the 1994 Convention.

The convention committees have worked hard to organize the sessions and present an outstanding technical program. Our thanks are extended to the speakers, donors, exhibitors and officers of the Southwest Section who have made the convention possible. We also greatly appreciate the support extended by the New Mexico Bureau of Mines & Mineral Resources in publishing the papers presented in the technical sessions.

Gerald E. Harrington, President, SW Section AAPG
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History of Bravo Dome CO_2—discovery and early development

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Abstract—American Producing Corporation drilled a small surface structure with their No. 1 Bueyeros well (sec. 32, T31N, R31E, Harding County, New Mexico) in 1916. The Tubb Sandstone (Permian, Leonardian) contained CO_2, but the well was never completed.

Southern Dry Ice and Kummbach Oil and Gas tested another small structure nearby in 1931. This well, the No. 1 Kerun, discovered CO_2 in the Triassic Santa Rosa Sandstone and was completed as the initial CO_2 well in northeastern New Mexico.

Bueyeros Field supplied the CO_2 necessary for a dry ice business during the following several decades.

Athough the above facts relate to discovery of the first CO_2 in northeastern New Mexico, the dry ice industry, and Bueyeros Field, this history played a minor role as regards Bravo Dome CO_2 Field.

The economic need for CO_2 in the petroleum industry realized initially in the late 1960s, and Amoco's reaction to their needs in this regard led to the discovery and development of Bravo Dome CO_2 Field. Using original documentation, this report traces Amoco's discovery, acreage acquisition, unitization, and early development of Bravo Dome CO_2 Field.

Introduction

Engineers in several major company research centers were studying possible use of CO_2 enhancement of oil recovery in the late 1960s. Amoco Production's Research Center reported results of their study to Production Department management in several Amoco operational offices, including the Fort Worth office. Amoco's Fort Worth Production Department informed the Exploration Department relative to the need for CO_2 in a November 1969 letter. Quoting from that letter, "Our interest is in localizing large CO_2 reserves at shallow depths and as near to production in the Slaughter and Levelland Areas as possible. Large investment decisions are associated with our overall study and since competition for CO_2 supplies could adversely affect the economics, it is vital that this appraisal be held confidential."

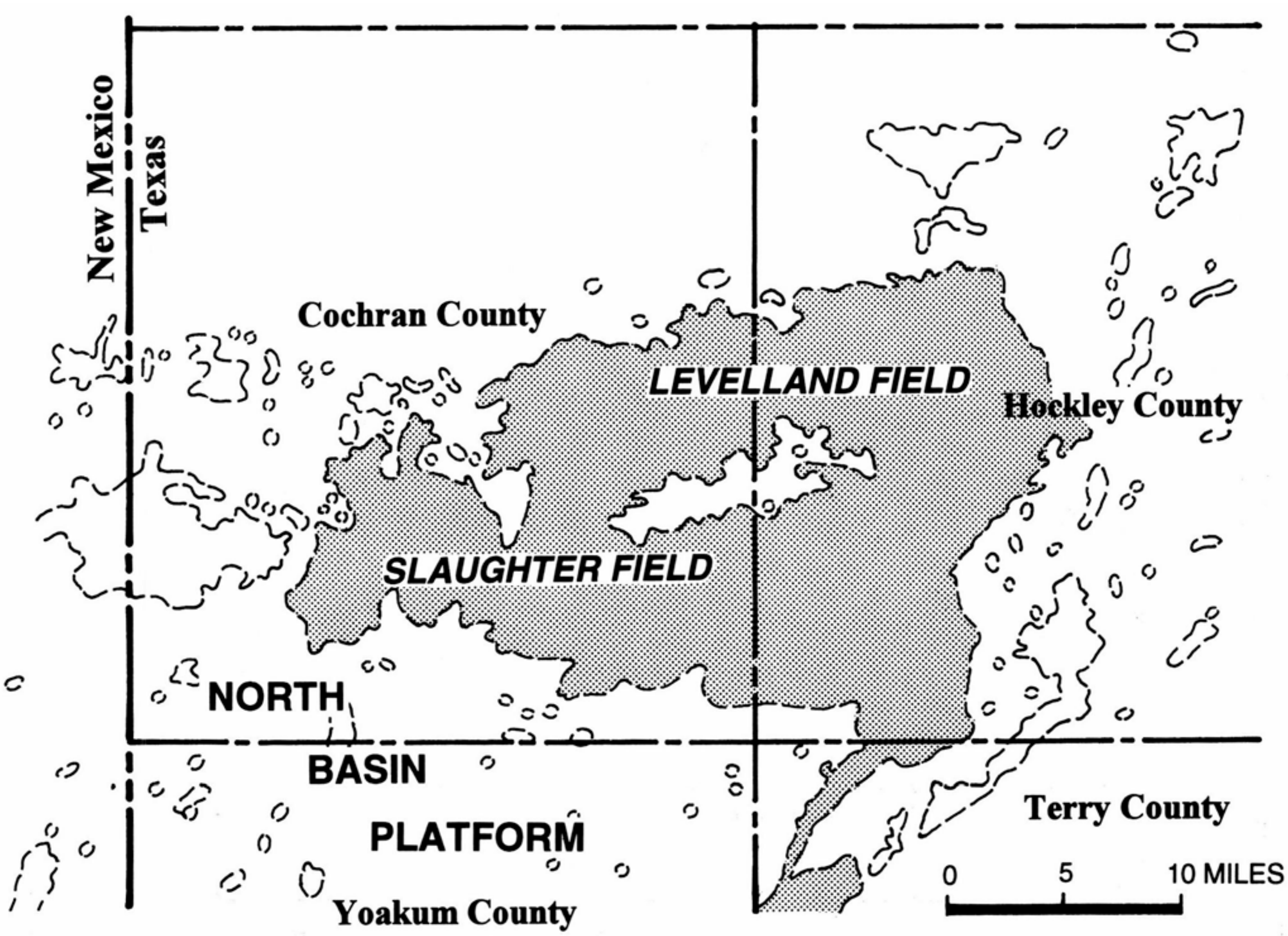

FIGURE 1—Map of North Midland Basin showing two of Amoco's core properties, Levelland and Slaughter Fields.

History

Amoco's Fort Worth Exploration Department moved rapidly. On January 26, 1970, only two months after awareness of Research findings relative to CO_2, an Exploration Department report was submitted to Fort Worth office management. This report, *Carbon Dioxide in Northeastern New Mexico,* focused on the location of a potentially large CO_2 reserve. Based on all data, including surface drainage patterns, magnetics, and subsurface relationships, a large structurally anomalous area situated in eastern Harding, southern Union, and northern Quay Counties, New Mexico, appeared to offer the best potential for a large and shallow CO_2 reserve. The presence of CO_2 in the Tubb Sandstone of the Bueyeros area had been known since 1916. These wells, other scattered well control, apparent continuity of the Tubb Sandstone, and the current structural interpretation indicated the potential for a huge CO_2 reserve. Structure over a large area was a certainty.

When referring to the Bravo Dome as originally defined, most writers restricted its position to an area immediately east of that described above and placed the crestal portion in Hartley and Oldham Counties, Texas. The significant interpretational difference made in Amoco's 1970 report was that if the structure actually crested in New Mexico, then the related oil and gas potential had not as yet been evaluated by the drill. Amoco explorationists favored the latter interpretation, that is a much larger structural complex that crested in New Mexico. The name Bravo Dome was derived from Bravo, a railroad siding in southwestern Hartley County and the Bravo subdivision in northwestern Oldham County, Texas. Although then (1970) conceived as possibly a much larger structural complex and largely in New Mexico rather than in Texas, the name Bravo Dome was retained. The possibility of enough CO_2 at shallow depth to satisfy Production Department needs in the Levelland and Slaughter areas (Fig. 1), coupled with the outside

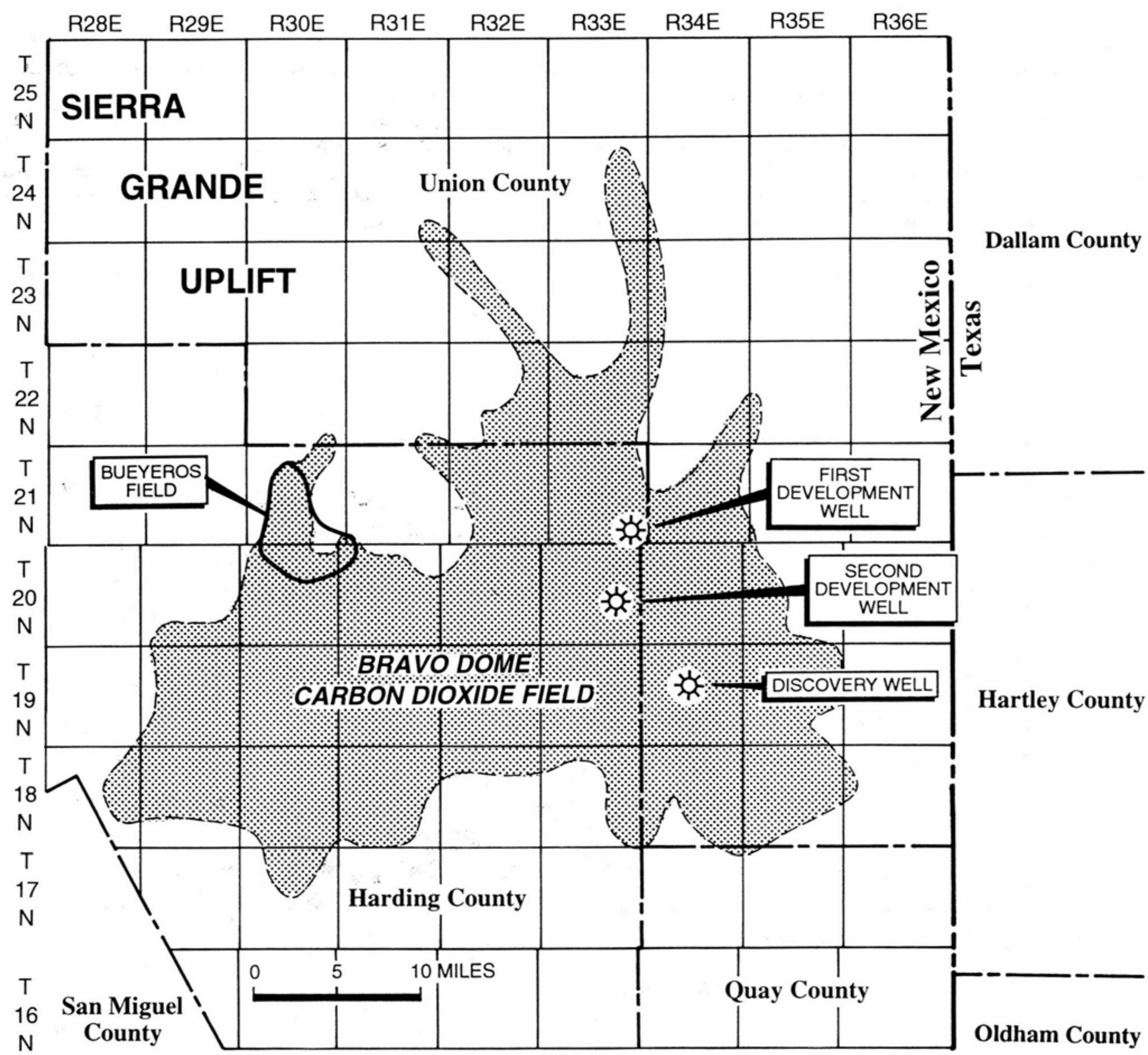

FIGURE 2—Map of Bravo Dome CO_2 Field. Note that the discovery well is approximately 22 mi southeast of the old Bueyeros CO_2 Field.

chance to corner the CO_2 market in the area for only about $1,000,000.00 up-front monies, comprised the incentives Amoco management needed to proceed as described below.

Amoco soon requested that the state of New Mexico put up about two million acres for oral bid, a request honored on April 20, 1971. During this sale, Amoco obtained more than one million acres at an average cost of about $0.43/acre with a 10-year lease term.

To test their block as well as acreage held by Humble, Amoco joined Humble in a six-well exploration effort. Both companies were interested in San Andres (Permian, Guadalupian) oil potential. However, Amoco's prinicpal interest was in the potentially large size of the CO_2 reserve in this area. Mr. Dan Yarbrough, an Amoco geologist and log analyst, sat on the wells. Dry in the San Andres, the sixth well tested a minor show of CO_2 in the Santa Rosa from the 1120-1210 ft interval utilizing a straddle packer test, with the original TD at 2100 ft. From the wellsite, Yarbrough gained permission for Amoco to assume operation of this well and deepen the original Humble No. 1 State "CN" to the Tubb Sandstone. Consequently, the well was deepened from 2100 to 2536 ft as the Amoco No. 1 State "EL" (sec. 16, T19N, R34E, Union County, New Mexico), the discovery well for Bravo Dome CO_2 Field completed in October 1971 (Figs. 2, 3, 4). Perforations in the Tubb Sandstone from 2260-2485 ft yielded nearly pure carbon-dioxide gas with a C.O.F. of 1.3 MMCF/day. This well is located about 22 mi ESE of Bueyeros Field.

The magnitude of the CO_2 reserve was extended with additional development wells. The confirmation well for Bravo Dome CO_2 Field was drilled about 10 mi to the NNW in December 1971 at a location in sec. 36, T21N, R33E. Again, in January 1972, a second development well was drilled at a location in sec. 23, T2ON, R33E (Figs. 2, 3).

Application was filed for unit formation in late 1979 and was approved by the New Mexico Conservation

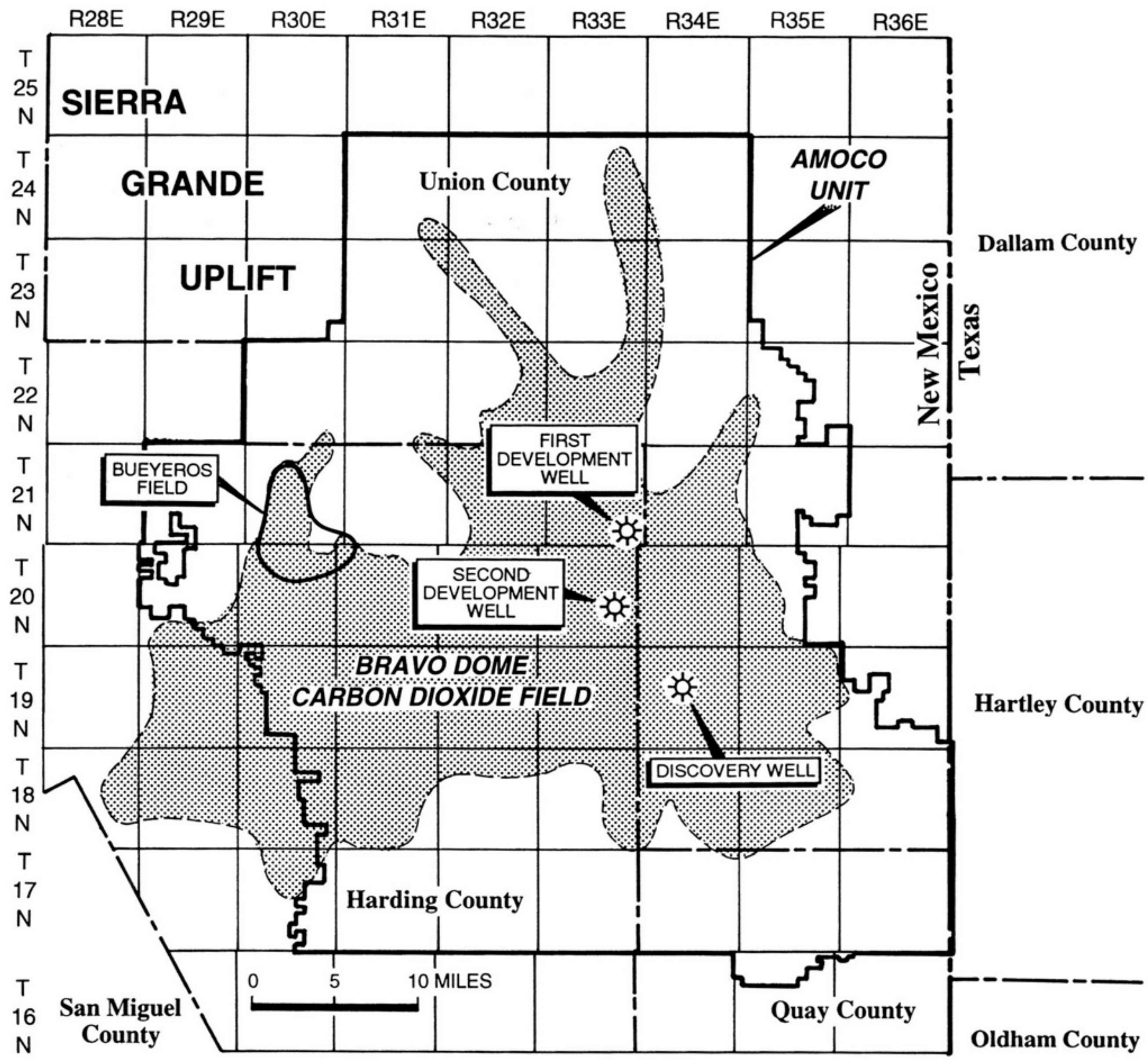

FIGURE 3—Map showing outline of Amoco's Bravo Dome CO_2 Field. The unit embraces approximately one million acres.

COUNTY UNION, NEW MEXICO WILDCAT (TUBB) FIELD
OPR AMOCO PRODUCTION COMPANY
LSE N. M. "EL" STATE WELL NO. 1
LOC Sec. 16, T-19-N, R-34-E (L)
1650' FSL & 450' FWL of Section
Orig. 1st rptd. as Humble #1 N.M. (CN) State
UNIQUE NO 30-059-20009
MAPS CO-ORD
F. R. 8-18-71 OBJ 2000' RT SPUD 10-17-71
CTR Vice LAHEE CLASS ELEV DF DF 4871'
TD 2536' PBD 2496'

PAY ZONE	PROD INTERVAL	IP BO W HRS CHK	TEST BASIS
Tubb	2260-2484	COF 3,700,000 CF CO2/Day	

GOR	GTY	CP	TP	BHP	POT DATE	TREATMENT
					1-15-72	A/1500

CSG 7 5/8 - 306 - 300
4 1/2 - 2524 - 300

UNION, NEW MEXICO WILDCAT (TUBB)
AMOCO #1 N.M. "EL" STATE

WELL RECORD REACHED TD	SPL (LOG) MARKERS
TD 2536' PB 2496'	U/Santa Rosa (530)
DST 1591-1616, Op. 75", Rec. 280' WCM	L/Santa Rosa (1040)
60" ISIP/143, FP 124-159, 120" FSIP 159 #	SA (1397)
DST 1702-18, Op. 65", Rec. 340' WCM	Glor (1720)
30" ISIP/194, FP 187-194, 30" FSIP 194 #	Yeso (1810)
TD 2100', Ran Logs	Tubb (2200)

SP-DST 1120-1210, Op. 90", GTS 10", TSTM Sample/Granite (2506)
(CO2) Rec. 50' GCM, 60" ISIP 51#,
FP 51-69, 120" FSIP 69 #
DST 2212-2296, Op. 70", CO2/TS 1"
FARO 550 MCFGPD 1/2" Ck, SFP 210#
FARO 770 MCFGPD 18/64" Ck.
SFP 169#, Rec. 10' MCW, 60" ISIP 375#
FP 292-313, 120" FSIP 375#
Perf. 8/2466-70, 2@2477, 2484
A/500, Flowed 50 BL, CO2 @ 782,000 CFGPD,
2 1/2', 34/64" Ck. FTP 120#
Perf. 2 @ 2319, 2325, 8/2328-32, 4/2336-38,
2 @ 2355, 10/2372-77, 2 @ 2386, 2394, 2404
A/500, Flowed 49 BL, CO2 @ 600,000 CFGPD
24/64" Ck, FTP 120#
Flowed 910,000 CFGPD (CO2), 15'
34/64" Ck., FTP 190#
Perf. 8/2260-64, 10/2268-73, 2 @ 2291,
10/2295-2300, A/500
Flowed 45 BL, CO2 @ 1,030,000 CFGPD, 2 1/2'
40/64" Ck., FTP 185#
FOUR POINT: (CO2)
F/777,000 CFGPD 8' FBHP 338
F/1,212,000 CFGPD 45" FBHP 324
F/1,317,000 CFGPD 30" FBHP 315
F/1,504,000 CFGPD 30" FBHP 308

(2-23-72)

FIGURE 4—Facsimile of scout ticket for the discovery well of Bravo Dome CO_2 Field.

Commission in November 1980 (Fig. 3). Time involved in forming a unit approximating 1,000,000 acres in size and pipeline construction dictated a 10-year lag in the development boom of 1981-1984. During this four-year span, about 63% of all wells begun as of year's end (1990) were completed. Cumulative production from Bravo Dome Field has recently surpassed 1 TCF of CO_2, about one-eighth of estimated ultimate recovery.

Summary

The Bravo Dome CO_2 Field was discovered in 1971 with the drilling of the Amoco 1 State "EL" (sec. 16, T19N, R34E, Union County, New Mexico). The field was unitized in 1979 and includes over one-million acres. Cumulative production has surpassed 1 TCF of CO_2, with an estimated ultimate rate of recovery of 8 TCF of CO_2.

Acknowledgments

The authors' understanding of the history and chronology of Amoco's aggressive, pre-emptive land acquisition that led to the discovery and development stages of the Bravo Dome Field was enhanced by discussions with Stanton and David Ball of Ball Exploration Inc., Fort Worth. Thanks are due to Dan Yarbrough and Herb Wacker of Amoco Production Company for advice and consultation, and Jim Darnell of Darnell Graphics and Reproduction, Fort Worth, for producing the illustrations.

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A great opportunity for geoscientists

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Abstract—If basic mineralogy had been used to define asbestos, billions of dollars could have been saved on the cleanup because 95% of asbestos is harmless to mankind. Only 5% causes pulmonary problems.

Scientific research has revealed that the ozone "layer" is a naturally occurring event. The chlorine released from chlorofluorocarbons (CFSs) is insignificant when compared to oceans and volcanoes.

Carbon dioxide has been named as the major cause of global warming. Scientific data show that all of the air-pollution materials produced by man since the beginning of the Industrial Revolution do not begin to equal the quantities of materials spewed into the atmosphere by just three volcanoes, Krakatoa in 1883, Mt. Katmai in 1912, and Hekla in 1947. Carbon dioxide is essential for plant growth.

It cost 600 million dollars for the 10-year study by the National Acid Precipitation Assessment Program. The study concluded: "There is no evidence of widespread forest damage from current levels of acidic rains in the U.S." The acidity of the soil, not precipitation, determines the acidity in watershed.

We cannot reach zero pollution. A baseline must be established by calculating the amount from naturally occurring pollution and adding what mankind is contributing, so reasonable scientific limits can be achieved for mankind's survival. We must also have economic-impact statements along with environmental-impact statements. This rational approach is the only realistic way to address the problem.

The notion of climate disasters has been widely propagated by those who want to impose controls—"to be effective these wildly expensive constraints must apply globally, condemning most of the world's population to a life of continued poverty."

Let us study scientific data and move prudently so we do not destroy the industries on which we so much depend. Nature is tough, humans are ingenious, and both are resilient.

Introduction

Take a minute and scrutinize your surroundings. Nowhere is there anything not related to oil. Oil is the world's life blood. Yet the domestic oil industry is having problems because of the increasing cost to be in compliance with environmental regulations and concerns. People must be reminded of the importance of hydrocarbons. Derivatives of this product are used in the clothes we wear, the food we eat, and the transportation system we enjoy. Science must be used to assess our so-called environmental problems.

Geologists have to be concerned about environmental issues if they are going to continue to explore and produce oil and gas in the United States. Involvement in environmental issues is necessary and vital to function in the oil and gas industry.

The environmental groups are excellent communicators because they have the ability to capture a person's imagination and prey on the fear of the unknown. The oil industry people do not seem to have much impact because statements made by scientists are rational analytical arguments and the audience is generally uninformed and already fearful.

Geologists need to educate the public in an imaginative manner. Statements must be made to illustrate the issues. This way everyone can understand and remember what is said.

Who should we believe? There are respected scientists on both sides of this issue. Many scientists say we simply do not understand climate phenomena well enough to take drastic action. When there is such a difference of opinion among experts, the conclusions must be: no one really knows, and when no one really knows the best solution is to withhold judgment and avoid precipitous action. No strong scientific issue can be resolved by a stongly held belief. Opinion polls are useless. Only evidence counts. Facts, measured and described, and independently verified, constitute the only basis for drawing conclusions in science.

Science and using it to help solve our problems

Oil fields

An oil spill contains a high concentration of material that is readily recognized, unpleasant, and does have toxic content, but industry tries to make every effort to prevent this occurrence. Oil is a biodegradable substance and is of organic origin. It is part of the natural planet Earth. The Earth releases a million barrels of oil every year on its surface. The U.S. Geological Survey has calculated that 10 billion barrels of oil have been naturally leaking and continue to do so on the ocean floor off the coast of Santa Barbara, California. An estimated three trillion barrels of oil-saturated tar sand are exposed on the surface in Venezuela. A huge quantity of tar sand is also exposed on the surface in Alberta, Canada. These naturally occurring oil seeps are found throughout the world. This equates 10 or more super-tanker loads of oil every year that are coming to the Earth's surface naturally and our planet is not bothered. It all gets consumed and is quickly and efficiently broken down by natural processes. All of the naturally seeping oil is by definition part of the clean, pristine environment that we strive to preserve. Clearly then, pristine environment is a somewhat subjective concept.

Asbestos

Asbestos has been listed as a hazardous material. However, 95% of asbestos does not have fibers which are the cause of pulmonary problems (Malcine, 1984). The remaining 5% is the very toxic, fibrous asbestos. Yet, the courts have ruled that all asbestos is hazardous material.

If the environmental regulatory agency had used science and basic mineralogy, 100 billion dollars of taxpayers' money could have been saved in the so-called "cleanup" of asbestos. With the implementation of the cleanup additional fibers were put in the air to further expose people. Simply painting over the material would have sufficed to remedy the situation.

If 95% of asbestos is white asbestos, what is the actual risk? Melvin Benarde (1990) outlined life-time risk values (chances of death per 100,000) on a number of examples. If you smoke, which is the highest, your chances of dying are 21,900/100,000; driving a car is 1600; lightning has a value of three; and the chance of dying from non-occupational exposure to asbestos is one. So the chance of dying from asbestos exposure is one-third of the danger of lightning.

The latest environmental concern is lead (Baker, 1993). "Lead is a bigger issue than asbestos ever was" claims the director of Environmental Quality Institute at the University of North Carolina. OSHA has repeatedly reduced what it considered to be an acceptable level of lead in the blood. EPA has set a maximum contaminant-level goal for lead in drinking water of zero ppb. Can mankind survive and pay the costs of zero levels? Is lead in small quantities really that toxic? Science must be used to assess these problems.

Instrumentation can now read in parts per million, billion, and trillion. Do people know what one part per billion equates? With a world population of 5 billion people this means five people. To express this another way, one part per billion equals a drop of vermouth in five train carloads of vodka or gin—that's a dry martini (Ray and Guzzo, 1990).

The scientific approach was not used to assess dioxin, PCBs or radon. It will ultimately take 100 billion dollars to bring radon levels to EPA recommended levels. Opening windows will solve the radon problem in houses. Our government has the mental attitude of passing legislation first and perform the science later.

The scientific assessment of chlorofluorocarbons or CFCs

In 1974 California scientists claimed that chlorofluorocarbons combine with the ozone, after being broken down by solar energy, destroy the ozone layer, thereby bringing catastrophe upon the Earth (Lee, 1992). Naturally, the media and those environmentalists with bureaucracies to build, latched onto the issue and in 1978 the United States became the first nation to ban CFCs from spray cans. Atmospheric physicists S. Fred Seiger and Candace G. Crandall stated in the July 1989 issue of *Consumer's Research Magazine* (the Rowland–Molina theory, the originators of the CFSs... caused ozone destruction theory): "the CFC concern has yet to be verified in detail because the mathematical models involve more than 100 chemical reactions." The much touted ozone "hole" has also been shown to be a naturally occurring event over the Antarctic (Ray and Guzzo, 1990).

If ozone was declining as the proponents would have the population believe, then there would be an increase in ultraviolet radiation reaching the Earth's surface. John Delouise and Shaw Liu of the National Oceanic and Atmospheric Administration see no increase in ultraviolet radiation, in fact these scientists see a decrease between 5 and 18% during this century. This is due to an increase in carbon dioxide (Ray and Guzzo, 1990).

The Environmental Protection Agency claims that an estimated 12 million Americans will develop skin cancer and 200,000 will die due to ozone thinning. How can this happen when ultraviolet radiation is diminishing? Skin cancer caused by ultraviolet radiation is readily treatable and is not related to the more deadly melanoma type.

Sources of atmospheric chlorine other than CFCs

If atmospheric chlorine is indeed "polluting" the ozone layer, from where could it be coming other than from man-made CFCs? Nature, it appears is contributing more than humans. It has been estimated that each year volcanoes pump 12 million tons of hydrochloric acid into the atmosphere, to which must be added the salt, NaCl, and the release of chlorine from ocean spray that diffuses upwards in storms, hurricanes, and typhoons (Ray and Guzzo, 1990).

Thirty-eight years ago I mapped for Humble Oil & Refining Company the surface geology on the Alaska Peninsula, where Mt. St. Augustine was a dormant volcano in the Gulf of Alaska. In 1976 the eruption of Mt. St. Augustine put over 300 million tons of hydrochloric acid directly into the stratosphere. This was 570 times as much as the entire world production of chlorine and fluorocarbons in 1975 (Ray and Guzzo, 1990).

In the Antarctic, only 15 miles from the McMurdo Sound scientific base, Mt. Erebus has pumped over 1000 tons of chlorine into the air every day for over 100 years (Ray and Guzzo, 1990). Sea water puts 600 million tons of chlorine into the air every year (Ray and Guzzo, 1990). *The peak world production of CFCs was equal to 750,000 tons of chlorine and only a portion was released into the air* (Pitts, 1992).

Volcanoes have been erupting on Earth for millions of years. The eruption of Mt. Pinatubo in the Philippines was expected by scientists to increase worldwide chemical reactions which would result in ozone thinning, and the increase was found as expected. It had nothing, or very little to do with chlorofluorocarbons leaking from the world's refrigerators.

The National Oceanic and Atmospheric Administration shows that 60,000 ozone molecules are created for every one destroyed by chlorine from a chlorofluorocarbon molecule (Pitts, 1992).

The Earth's magnetic field, interacting with solar wind, destroys ozone. We are currently in a cycle of high sunspot activity which creates the solar winds (Maxey, 1985).

A network of recording instruments set up in 1974 by the National Bureau of Standards to measure ultraviolet radiation reaching the Earth's surface has shown a continous decrease of penetrations ranging from 0.5 to 1.1% each year (Ray and Guzzo, 1990). If the ozone-depletion scare talk was accurate, the radiation should be increasing instead of decreasing.

Many of the reported measurements have never been made before and cannot be compared to any standard. It is possible that thinning of the ozone layer has been a normal occurrence for thousands of years.

Questions about supposed "global warming" also arose recently, when the National Weather Service (NWS) discovered that 300 of its fancy new electronic thermometers purchased at $5000 each have been reading one-half to two degrees Fahrenheit too high. This constitutes a monumental error when plugged into "global warming computer models" (Scott, 1993).

Consider the United States economy alone: CFCs, mainly freon, are used in 100 million refrigerators, 90 million cars and trucks, 40,000 supermarket market cases, and 100,000 building air-conditioners. It is estimated that banning CFCs would mean changing or replacing capital equipment valued at 135 billion dollars and the United States taxpayer would be paying this bill. All of the proposed substitutes have problems; none are in production, most are toxic, and many are flammable. It is possible to return to using toxic ammonia and sulfur dioxide!

One of the biggest users of freon is refrigeration, and the most important reason for refrigeration is food preservation. If the proponents of banning CFCs are anxious to reduce their use, why aren't they out campaigning for irradiating food as a substitute for refrigeration? Food irradiation is an available technology used by our astronauts and in hospitals for patients requiring sterile environment (Maxey, 1985).

Carbon dioxide

Recently, there has been considerable discussion about global warming and why humans are causing this phenomenon by burning fossil fuels and releasing large amounts of carbon dioxide into the atmosphere. The hypothesis is that the increasing carbon-dioxide content keeps the Sun's energy from escaping the Earth's atmosphere, thus warming the Earth. The Earth with its enveloping atmosphere constitutes a "greenhouse." The atmosphere is a porous blanket. This happens when heat, light, and other radiation from the Sun, and remember it all starts from the Sun, reach the upper atmosphere.

All of the deposits of hydrocarbons buried under the ground are seeping back to the surface. In time they will all return and be oxidized to carbon dioxide. This is the carbon cycle. This is what we learned during our early school days. Today's focus is on trees and leaves, and people do not make the connection between this process and the release of carbon dioxide from fossil fuels by natural processes. Man's production of fossil fuel is just speeding up the natural planetary process, and production of oil is just speeding up one part of this cycle. In order to stabilize or reduce carbon dioxide in the atmosphere an increase is needed to speed up its removal. Probably the permanent way to achieve this goal is to speed up the formation of limestone in the oceans. This is what the planet has been doing for 500 million years.

Although carbon dioxide and the burning of fossil fuel are the buzzwords today and getting all the attention, it is really water vapor in the atmosphere and droplets in the clouds that account for much of greenhouse gas. Water is responsible for 98% of all greenhouse warming and 600 million tons of water vapor are produced each year from the oceans. The other gases, including carbon dioxide, do absorb infrared and contribute to warming, but this is minor (2%) in comparison to water.

The greenhouse effect is real. We could not exist without it. Carbon dioxide is a greenhouse gas and the carbon-dioxide concentration has increased from 280 ppm prior to the industrial revolution to 360 ppm today. Part of the greenhouse effect is due to the Sun, and our current cycle indicates a high sunspot activity that creates solar winds. The burning of fossil fuels is not the main contributor to the greenhouse effect. Climate-wise, the planet has been very unstable for the past two million years and changes have been dramatic and rapid. In the past 1000 years the Earth has cooled down significantly, and it is now in a warming-up cycle. This has nothing to do with carbon dioxide in the atmosphere. The carbon-dioxide content did not change for 900 of the last 1000 years, but the climate certainly did. Four hundred years ago it was much colder than it is now. The subsequent warming has nothing to do with carbon dioxide but is related to changes in the Earth's orbit and Sun's radiation. There is no evidence that the rate of warming has been increasing in response to the increase in atmospheric carbon dioxide for the past 100 years. Carbon dioxide is absolutely essential for plant growth. There are many external factors in nature over which mankind has no control, and to date the process is not completely understood. The possibility of increasing carbon dioxide might help counteract a forthcoming 21st-century cooling episode and can help to enhance the 400-year warming episode. No matter what steps are taken, the climate cannot be stabilized. It is as unstable today as it has ever been over billions of years of the Earth's history.

The effects of man's contributions to the atmosphere have been minimized by several scientists. Ray and Guzzo (1990) noted that based on all the available data "all of the air polluting materials produced by man since the beginning of the Industrial Revolution do not begin to equal the quantities of toxic materials, aerosols, and particulates spewed into the air from just three volcanoes; Krakatoa in Indonesia in 1883, Mt. Katmai in Alaska in 1912, and Hekla in Iceland in 1947." Mother Nature's contributions to the atmosphere:

Mt. St. Augustine, 1976	300 million tons of hydrochloric acid
Mt. St. Helens, 1980	1 million tons of carbon dioxide
El Chicon, 1982	100 million tons of sulfur gases
Mt. Erebus	1000 tons of chlorine a day for 100 years plus 200 tons of sulfur dioxide a day
Mt. Pinatubo, 1991	30 million tons of material

Mt. St. Helens in Washington state erupted with a force of more than 500 atomic bombs and pumped out 1,000,000 tons of carbon dioxide, 242,000 tons of sulfur dioxide, and unkown amounts of aerosols. These gases were propelled 80,000 feet into the stratosphere and were deposited above the ozone layer (Ray and Guzzo, 1990). El Chicon in Mexico sent more than 100 million tons of sulfur gases into the stratosphere, and Mt. Pinatubo in the Philippines hurled upwards of 30 million tons of material into the stratosphere (Lee, 1992).

Many environmentalists attributed the 1988 drought in the United States to global warming, but researchers with the National Center for Atmospheric Research in Boulder, Colorado, reported that the freakish weather was actually due to a natural phenomenon, the interaction of El Nino and La Nina, two massive currents in the tropical Pacific Ocean (National Center for Atmospheric Research, 1988). Present data suggest that no significant, if any, warming has taken place over the past 100 years.

Weather stations are not evenly distributed around the globe and land represents only 30% of the planet's surface. Most weather stations are located around airports in large cities, where local asphalt or black-top warming commonly can be documented.

Animals also contribute their share to environmental degradation. An international team of researchers reported that "the amount of carbon dioxide produced by termites was more than twice the net global input from fossil fuel combustion" (Science Digest, 1983). "Termites are a potentially important source of atmospheric methane that could account for the large fraction of global emissions. These wood-eating pests have bacteria that enables them to digest carbon so efficiently that some 90% is converted to carbon dioxide, methane, and other gases they belch into the atmosphere" (Zimmerman et. al., 1982).

Carbon dioxide is absolutely essential for nearly all life on Earth; the more of it there is in the air, the more productive is the entire planet. In the case of agriculture, a 300 ppm carbon dioxide content in the air increases crop yields by one-third. Higher carbon-dioxide concentrations reduce the pores in plant leaves which carbon dioxide enters and water vapor exits. This effect lowers the rate of water loss by evaporation to the atmosphere, thereby allowing crops to conserve one-third of their water. It also doubles the efficiency with which plants utilize water to produce organic matter (Krug, 1993).

The U.S. Water Conservation laboratory in Phoenix, Arizona, conducted tests of plant growth in a controlled environment. The plants subjected to an increase in carbon dioxide grew faster and produced more fruit than those growing in normal air (The Greenhouse Conspiracy, 1990). Thus, fertilizer is not the sole factor in growing abundant crops. Carbon dioxide is a major contributor to this enhanced growth.

It has been suggested that planting a billion trees is a way to absorb carbon dioxide from autos and industries. It should be pointed out that as trees die, their rotting remains put as much carbon dioxide in the air as they absorbed during their life while producing oxygen. This reflects a no-net gain.

It is indeed unfortunate that while many scientists urge a "let's take another look" attitude about global warming, some politicians and environmental activists are plunging ahead with plans to limit energy usage. Dr. Fred Singer, professor of environmental sciences at the University of Virginia concludes: "The notion of climate disaster has been widely propagated by those who want to impose controls...to be effective, these wildly expensive constraints must be applied globally, condemning most of the world's population to a life of continued poverty" (Ray and Guzzo, 1993).

Conclusions

The environmental community cites "scientific evidence," but growing numbers of scientists say the evidence is not only weak to nonexistent, but actually suggests exactly the opposite.

All of man's activities, including forest burning in Brazil, industrial plants, and automobiles, provide approximately 5% of the world's carbon dioxide. The other 95% comes from nature, which at times has produced *five to ten times* as much carbon dioxide as today's levels (Ray and Guzzo, 1993). Obvious facts are ignored by extremists and the threat of global warming is still the environmental centerpiece for panic.

Science and technology have moved us forward with the amenities that make life rather enjoyable. In order for mankind to survive on Earth, scientists must establish a baseline that takes into account the contributions which Mother Nature makes daily to the atmosphere. It has been calculated that man adds seven billion tons of carbon dioxide annually to the atmosphere, whereas Mother Nature contributes 200 billion tons (Ray and Guzzo, 1993). We can maintain a realistic baseline figure based on these data and still continue to exist on the Earth. In the capitalistic free-market west, technology is actively improving the environment and environmentally sensitive products are being produced to meet consumer demand.

If we as scientists do not take advantage of our training and knowledge and forcefully address scientific conclusions to environmental problems, then we are indeed derelict in our duties. The geoscience community can accept these challenges to address environmental issues. We must start an education program and make it available to the public. The data and delivery procedure used must be such that everyone can understand the purposes and reasons for concern if any are present, otherwise people will disregard what the scientist said.

A rational approach must be used to address environmental concerns. We must use *Economic Impact Statements* as well as *Environmental Impact Statements* for mankind to exist. Nature is tough, humans are ingenious. Both are resilient.

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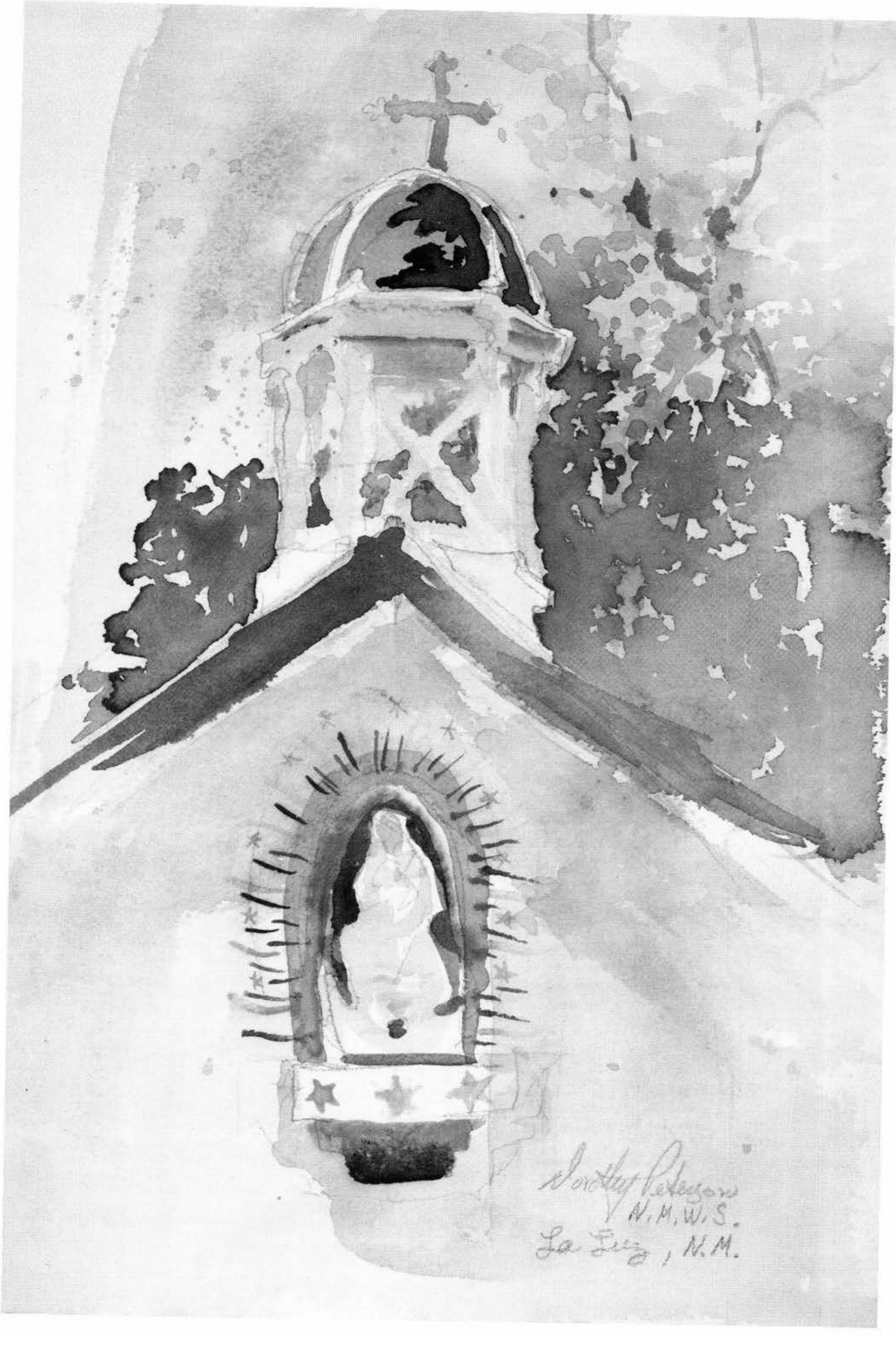
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Surface reclamation in the Big Lake Field, Reagan County, Texas

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Abstract—Since the discovery of Santa Rita #1 in 1923, millions of barrels of salt water have been produced along with 135 million barrels of oil from the Big Lake Field in Reagan County, Texas. Until the early 1960s, the accepted disposal method for the produced water was surface discharge to large evaporation ponds north of the field. Produced water was allowed to flow from wells to the ponds via natural topographic drainage. This practice resulted in 7000 acres of eroded, barren landscape characterized by highly saline soils incapable of supporting vegetation.

In 1989 the University of Texas System, the U.S.D.A. Soil Conservation Service, and Marathon Oil Company, which acquired Big Lake Field in 1962, initiated an experimental project to reclaim the affected land and restore it to rangeland productivity. An underground drainage system, consisting of 125,000 ft of buried drainage conduit and eight collection sumps, was installed over nearly 300 acres of the affected area. Earthen terraces were constructed to capture and hold rainwater to facilitate downward percolation and leaching of salts from the soil profile. Salts leached from the soil are captured by the drainage system and pumped to injection wells for disposal.

The excellent revegetation that has occurred over the test area after three years of operations is encouraging and shows the need for expanding and enhancing the existing system with supplemental water from fresh-water wells, application of soil amending agents, additional terracing, and selective planting of salt-tolerant species.

For four decades after the 1923 discovery of oil in the Big Lake Field near the town of Texon, Texas, the salt water produced in conjunction with oil from this multi-pay field was discharged onto the surface. Natural drainage ditches and erosional gullies transported the produced water, by gravity flow, to evaporation ponds several miles to the north and northeast of the field. The salt water was allowed to evaporate, leaving behind the salt as an evaporite, which was mined and sold for use as a livestock supplement. Over the nearly 40 years in which this disposal method was used, millions of barrels of salt water were produced and discharged from the Big Lake Field. As the salt water meandered to the ponds via the natural topographic drainage, areas hundreds of feet wide were often inundated. This resulted in soils with sodium-chloride contents too high to support plant life. Approximately 7000 acres of landscape became denuded and eroded. Over the past 30 years some of the rangeland was reclaimed naturally, leaving a current "U"-shaped scar of approximately 3800 acres.

In the area known as the Texon Scar (Fig. 1), the upper few feet of the soil profile have been stripped away as a result of water and wind erosion. The Texon Scar is named after the town of Texon, which is located near the southwestern edge of the Big Lake Field. Within the scar area, hundreds of mesquite *(Prosopis glandulosa)* stumps with up to 3 ft of upper root zone exposed dramatically reveal the amount of soil that has been lost since the field was discovered in 1923. In areas of severe erosional damage more than 4 ft of soil have been removed because of the lack of vegetation to hold it in place.

The A and B soil horizons originally present in the scar area prior to erosion were silty-clay loam soils with a blocky, subangular structure. This soil profile was typical of the area and readily supported indigenous plant life. The clay subsoil, now on the surface, has been changed from its original state to a soil that has lost its ability to form clumps or clods. The present soil has little structure and no organic material in the upper few inches. Due to the sodium absorbed onto the exchange complex of the fine-textured soil the surface soils have deflocculated, thereby destroying the original soil structure and fabric, which in turn has restricted water infiltration due to puddling. Puddling occurs when the deflocculated clay particles, after initially becoming wet, position themselves in a tightly packed, platy orientation parallel to the surface, thereby restricting further rainwater infiltration. Due to these and other factors, such as the presence of a salt-water-contaminated perched water table, limited, annual rainfall, and hot summer temperatures, the establishment of permanent vegetation on the soil currently found within the Texon Scar is extremely difficult.

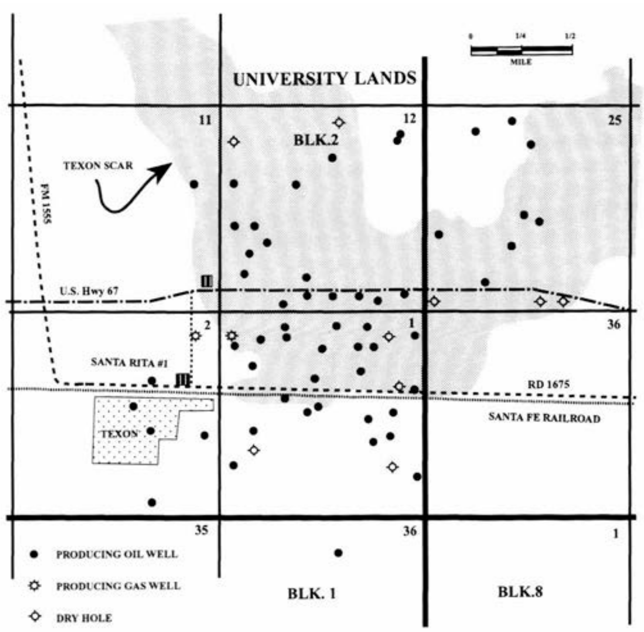

FIGURE 1—Current-production map of the Big Lake Field showing the generalized outline of the southernmost part of the Texon Scar.

In August 1989 an experimental project was initiated in the Big Lake Field by the West Texas Operations Office of the University of Texas System, Marathon Oil Company, and the U.S.D.A. Soil Conservation Service. The primary goal of the project was to reestablish vegetation in a selected area of the Texon Scar along the north and south sides of Texas State Highway 67 (Fig. 2) and to restore it to resemble the surrounding natural landscape. The approximately 300 acre area was selected for a number of reasons. It is near the southern edge of the scar, where a network of lease roads, county roads, and state roads made the project area easily accessible. Since work was done on both sides of a state highway running through the area, the evolution of the entire project could be easily viewed by the public. This area was also chosen to improve highway safety. High winds are common in west Texas; as this area contains very little vegetative cover, blinding dust storms blowing across the highway are a common traffic hazard.

One of the major problems encountered in restoring the land to productivity was the presence of a perched water table beneath the area. Perched water tables are created when unconfined ground water is separated from an underlying main body of ground water by a permeability barrier. This permeability barrier precludes the downward movement of water and traps it above the barrier. In the Big Lake Field area the major source of ground water is the Cretaceous Trinity sands which occur locally at depths of 200 to 300 ft. However, the presence of an impermeable bed of caliche at a depth of approximately 8 ft contributes to the formation of a local perched water table. This perched water table beneath the Texon Scar was probably formed, and certainly contaminated, during the 40 years that produced water was being disposed of on the surface. As the produced salt water from the Big Lake Field was flowing to the evaporation ponds, an undetermined amount of it soaked into the ground and was trapped by the impermeable bed. The large volumes of produced salt water that percolated downward and were subsequently trapped by the barrier created a perched water table with an extremely high sodium-chloride content. The water level in this perched water table varies from about 2 to 6 ft below the ground surface. This fluctuation is primarily due to rainfall, temperature variations, and local changes in topography. In times of drought the water level may drop 3-4 ft due to evaporation from the upper part of the saturated soil profile. This evaporation leaves behind high concentrations of salt in the soil. Some samples taken within the scar had electrical-conductivity readings as high as 200 mmhos/cm, which is four times higher than ocean water. In addition, capillary action causes the salts to move upward in the soil as the water evaporates. In periods of wet weather, as rain falls and percolates down through the unsaturated, salt-contaminated soil, some of the salts are dissolved by the rainwater. Since the downward flow of the water is restricted by the impermeable layer only a few feet beneath the surface, once the soil becomes saturated, the rainwater with the salts in solution has no place to go but upward. The water level may rise 3-4 ft, until the usually hot and dry west Texas climate causes the water nearest the surface to evaporate, once again leaving behind salt-contaminated soil.

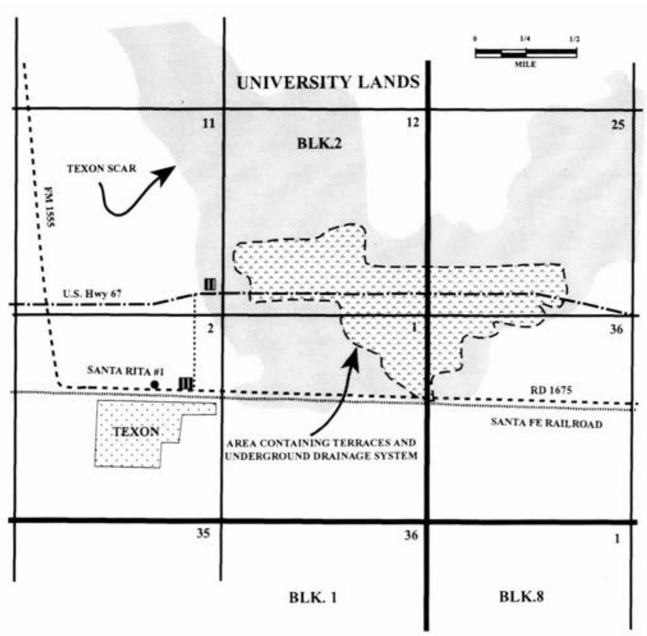

FIGURE 2—Project-area map showing the generalized outline of the area which contains the underground drainage system and is covered by earthen terraces.

This cycle of salts being dissolved, percolating downward during rainfalls, and then moving back upward in the soil by capillary action as the water evaporates during dry, hot weather has repeated itself for many years. With the low annual rainfall in the Texon area (14-inch average), and the downward movement of any available rainwater being restricted by the impermeable layer several feet below the surface, the contaminating salts have not been flushed out. After steadily increasing in concentration for the first 40 years during surface disposal, the salt contamination has remained localized for approximately the past 30 years. Although produced water is no longer being discharged onto the surface and is being disposed of by the use of salt-water disposal wells, the soil and any water found within the perched water table still contain salt concentrations at levels too high to support native vegetation. In addition, as previously noted, much of the fabric in the upper part of the soil has been destroyed. The soils in this area, which are very fine-textured, have lost much of their ability to clump up or form clods. This soil deflocculation adversely affects hydraulic conductivity by restricting the downward percolation of meteoric water. This further prevents flushing out contaminants.

The U.S.D.A. Soil Conservation Service attempted to establish vegetative growth in the area in the 1970s. This effort mainly involved planting of different species of salt-tolerant grasses, which resulted in the reestablishment of some vegetation on the outer perimeter of the project site. In addition, some minor "syrup pan" terracing was done, but only on a small part of the project area. This previous work produced no significant and lasting results.

In order to restore the area to productivity, several factors would have to be addressed. The level of the water in the perched water table would have to be lowered sufficiently to reduce the damaging effects caused by the presence of salts and salt water in the soil and to prevent these contaminants from moving upward by capillary action in times of hot, dry weather. Leaching of the salts in the upper few feet of the present soil profile by the downward percolation of rainwater and the disposing of the resulting salt water solution would also be necessary to re-establish an acceptable root zone for revegetation. In addition, lowering of the salt content in the upper few inches of soil would be necessary to provide proper conditions for seed germination and plant growth. By establishing plant growth erosion would decrease and organic material would be added to the soil, helping to re-establish structure to the deflocculated soil fabric present on the surface of much of the scar. This in turn would promote more infiltration of surface water.

To lower the perched water table and encourage the downward flushing out of contaminants, the Big Lake Field surface reclamation project utilized underground drainage technology commonly used in agriculture. Similar drainage systems are used in agricultural operations to drain or lower water levels in shallow water tables that have been contaminated by an accumulation of salts due to heavy irrigation. However, these techniques have not been used extensively in remediating salt-water spills normally found associated with oil and gas production.

The drainage system designed for use in the Big Lake Field consisted of approximately 125,000 ft of underground drainage conduit, sumps, and sump pumps. The drainage system included a series of 13 mains, five sub-mains, and 160 related laterals connected with the mains and sub-mains. The mains and sub-mains ranged in length from 270 to 2580 ft. The lengths of the laterals were 210 to 1270 ft. The locations of the laterals, mains and sub-mains, and sumps were influenced by the overall direction of drainage, the presence of roads, and the location and depth of surface drainage ditches, gullies, flowlines, and pipelines. Where possible, the lateral lines were oriented perpendicular to the estimated direction of groundwater flow. Four-inch diameter, corrugated, slotted, plastic pipe was used for all of the laterals. This flexible pipe was covered with a nylon-sock filter to prevent debris from clogging the perforation slots.

The drainage pipe used for the mains was similar to the laterals except the diameter of the mains ranged from 4 to 6 inches. The mains were designed to drain as much area as possible without having to increase the diameter of the drainage pipe. Larger diameter pipe would require hand-laying and bracing of the trench walls. This would be much more dangerous and more expensive.

The depths of the laterals were between 2 and 8 ft, with an average depth of about 5 ft below the surface. Based on factors such as soil type, soil permeability, topography, and annual rainfall, a 100 ft spacing between the lateral drainage lines was determined to be best. The 100 ft spacing and 5 ft average depths of the laterals should allow for the development of a 4 ft root zone, estimated by the U.S.D.A. Soil Conservation Service to be needed for the establishment of permanent vegetation. The entire drainage system was installed using laser technology to position the mains and laterals on a calculated grade of 0.10 ft per 100 ft. This grade was determined best to prevent having to increase the size of the main lines or the depths of the sumps. Eight sumps were installed to collect the salt water and pump it to one of the four wells used for disposal. The entire system has a maximum disposal capacity of 55,000 barrels of water per day and is installed under approximately 290 acres of the project area.

Due to water-infiltration restrictions created by the deflocculation of the clay soil, most of the small amounts of rain that falls in the Texon area runs off before it can percolate downward through the soil. There is, therefore, insufficient rainfall available to dissolve and transport the salt contamination found in the soil to the drainage system for disposal. Consequently, it was necessary to create a way to reduce the surface runoff of rainfall.

Beginning in August 1990, nearly 92,000 ft of level earthen terraces were constructed over approximately 280 acres of the project area. The terraces were designed to trap and contain, in the interval between the terraces, up to 1 ft of rainfall and subsequent surface runoff. Altogether 66 terraces were built, with the distance between them averaging about 110 ft. Lengths of the terraces are 350 to 3000 ft; they have an approximate height of 1.5 ft with a 3:1 slope. The end blocks of the terraces were constructed 1.2 ft high so that during heavy rainfall and surface runoff, as the area between the terraces filled up, the water would run around the end of the block into the next terrace instead of flooding over and eroding the terraces. Where feasible, the terraces were constructed perpendicular to the direction of surface-water runoff.

The drainage system was installed and the construction of terraces completed by March 1991. After construction, areas between the terraces were ripped or plowed to a depth of about 12 inches. As previously discussed, deflocculation of the soil within the scar area has caused the clay particles to orient and compact themselves in such a way as to restrict surface-water infiltration into the ground. Ripping, tilling, discing, or plowing temporarily breaks up this puddling effect and enables the water to percolate downward with fewer restrictions and begin the process of leaching of the salts in the soil.

In addition to providing for downward infiltration of surface water, the ripping also provided a bed for seed germination. In November 1991 the areas between terraces were packed with a suface roller and seeded with barley, which is an annual, salt-tolerant plant. Several months of above-average rainfall coupled with a mild winter helped produce a fair to good stand of barley by the spring of 1992. As anticipated, this reduced the effect of wind erosion and added organic matter to the soil. Although no more barley has been planted to date, the soil has become more stable and receptive to plant growth. Kochia *(Kochia scoparia)*, a warm-season annual herb, has become established over much of the project area, especially where ripping has occurred. The unusually high precipitation also positively affected the establishment of Kochia. The succession of this plant into the project area, although unplanned, has also added stability and much needed organic material to the soil. Kochia is a salt-tolerant species and has been present in areas adjacent to the affected area for many years.

Since the project was initiated in August 1989, the reclamation effort has resulted in the establishment of rangeland plants in areas previously devoid of or deficient in vegetation. In adjacent untreated areas there was little or no establishment of rangeland plants during the same time period. The success in the project area is due to a number of variables. While there is insufficient information to suggest which variable was the most important, certainly all of them had a positive effect on the project. The underground drainage system provided a mechanism to lower the contaminated perched water table and transport the salt water to the disposal wells. Without the drainage system the contaminants would have remained in place indefinitely. However, without the earthen terraces to trap and hold surface-water runoff, the drainage system would have been much less effective. Breaking up the top foot of soil by ripping was also a vital factor in the success of the project. This ripping temporarily alleviated the puddling caused by de-flocculation of the soil. The ripping enhanced water infiltration and provided a bed for seed germination and new plant growth. The plants added stability as well as organic material to the soil, which was needed to restore soil structure. The fact that the area received heavier than normal rainfall over the previous two years cannot be discounted. In fact, the amounts of water available to the area may be one of the most important variables. Certainly the salt cannot be leached from the soil without large amounts of available fresh water.

In conclusion, the establishment of vegetation in the project area has been encouraging. The success of the project, however, has shown the need for additional enhancements of the existing system such as supplemental water, soil-amending chemicals, or ganic mulching, and the planting of additional halophytic plants.

Due to the limited precipitation in the area, supplemental water from local fresh-water wells could be used. Additional fresh water introduced into the terraced area will intensify and speed up leaching of the salt from the soil and the subsequent flushing out of the contaminants.

As the salinity of the soil decreases, soil-amending agents such as gypsum or other commercially available products may be added to aid in the removal of sodium ions that attach themselves to the clay particles, especially in the upper few feet of the soil profile where plant growth occurs. The sodium sulfate formed as a result of the ion exchange between the sodium ions and supplemental gypsum is highly water-soluble. This method may be used to further reduce contamination in the Texon Scar.

As salt-contamination levels continue to decrease, salt-tolerant grasses such as Alkali Sacaton *(Sporobolus airoides)* or Inland Saltgrass *(Distichlis spicata stricta)* should be planted. In addition, heartier salt-tolerant perennials such as Fourwing Saltbush *(Atriplex canescens)* or Salt Cedar *(Tamarix* sp.) should be introduced into the area.

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Cimarron Superfund site, Carrizozo, New Mexico: An update

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Abstract—The Cimarron Mill in Carrizozo, New Mexico, was operated by Southwest Minerals Company under the name of Cimarron Mining Company (CMC) as a cyanide mill for gold recovery from 1979 until 1982. In 1980 the New Mexico Environmental Improvement Division (NMEID, now called the New Mexico Environment Department, NMED) received a report of improper use and dumping of cyanide at the *site.* A certified notice of violations was sent to CMC in 1982 by NMEID for discharging into a non-permitted discharge pit. CMC filed for bankruptcy in 1983 so no action on the violations was taken by the state. A Site Inspection Follow-Up Report was done by NMEID in 1984; in 1988 the mill site was listed as a Superfund site by the U.S. Environmental Protection Agency (USEPA). A feasibility study to determine the method of remediation was completed by USEPA contractors in June 1990 and a remediation method was chosen in September 1990. Clean-up by a USEPA-supervised contractor was expected to begin in the spring of 1991 and to be completed in 1992. However, the clean-up did not begin until late fall of 1991 and is not yet complete to USEPA standards, and probably never will be.

History

The Cimarron Mill site, located approximately at the intersection of U.S. Highways 54 and 380 in Carrizozo, New Mexico (Fig. 1), is an inactive milling facility built in the late 1960s and originally operated for the purpose of concentrating iron ore. The mill changed ownership six times between 1977 and 1979 and was finally purchased and operated by Southwest Minerals Company (SMC) under the name of Cimarron Mining Company (CMC). This company became convinced that the iron ore which the mill had previously been processing contained large amounts of gold. In order to recover this gold, the iron-ore concentration process was changed to a cyanide process. The cyanide process was evidently not recovering sufficient gold, so it was modified further to use a combination of a cyanide salt and a metal stripper of the type used to recover gold from electronic parts.

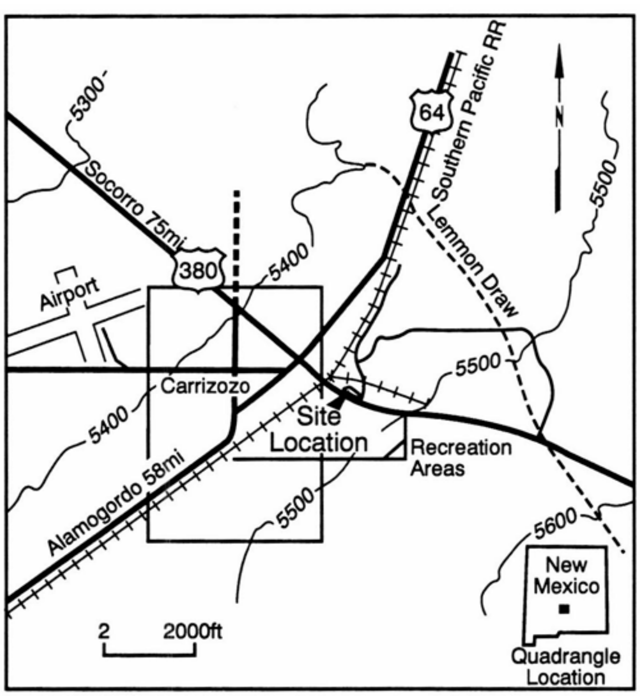

FIGURE 1—Cimarron Mining Company Superfund site.

In February 1980 the New Mexico Environmental Improvement Division (NMEID) received a report of improper use and dumping of cyanide at the site (Swickard, 1980). Until then NMEID was unaware that the mill was operating as a cyanide mill and as such did not have the permits necessary for conducting cyanide milling and processing. NMEID sent a certified notice of violations to CMC on June 22, 1982 (letter from Russell Rhodes, NMEID Director, to Robert Watson, CMC Production Manager). There was no response to the letter. Operations at the site ceased in July 1982, and the company filed for bankruptcy in July 1983 (Malone and Roblin, 1988).

NMEID field inspections in May and June 1984 (Anonymous, unpubl. report for NMEID, 1984) revealed cyanide in shallow ground water, soil, and mill tailings. Mercury, selenium, arsenic, lead, and copper were also reported in potentially hazardous concentrations in ground water, soil, and tailings. Site facilities (Fig. 2) included two concrete-lined cyanide-solution tanks, an unlined discharge pit, an unlined tailings impoundment, and several tailings piles. Stored in various places on the site were ten 55 gallon drums of cyanide salts, 26 containers of metal-stripper compounds, and approximately one hundred 55 gallon unlabeled drums believed to be "concentrates." According to a local source (R. Forsythe, pers. comm. 1988) these drums were shipped to the Asarco Smelter in El Paso for sale as gold concentrates. Asarco, after assaying the "concentrates," refused to buy them and the drums of "concentrates" were shipped back to CMC at the owner's expense.

In autumn 1984 NMEID requested that USEPA authorize a Resource Conservation and Recovery Act (RCRA) 3012 Site Inspection Follow-Up (SIF) action. Based on the results of the above mentioned site-inspection report, NMEID performed a trial ranking of the site to determine if it scored high enough (at least 28.5 points) to be nominated for the Superfund National Priorities List (NPL). The results indicated that the site was within three to five points of the cutoff score of 28.5. NMEID proposed additional work to obtain the information necessary to document reliably a higher score.

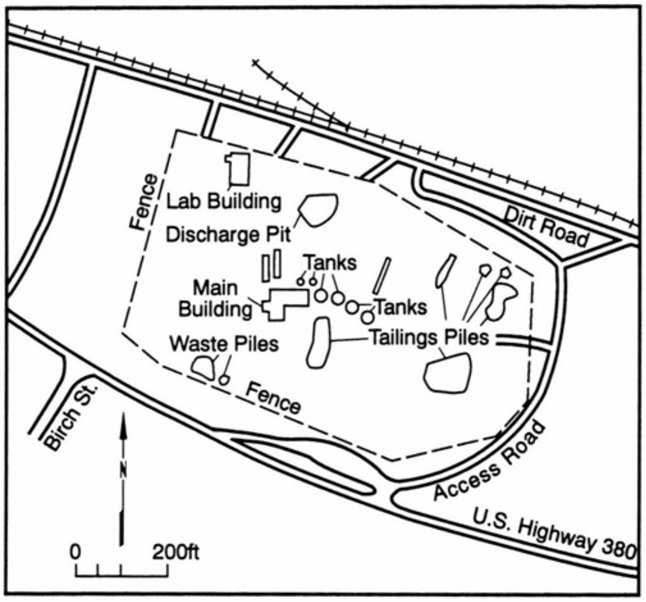

FIGURE 2—Aerial view of Cimarron site.

The SIF involved a detailed survey of the volumes of mill tailings, ore pits, and drums of materials at the site. Using the data generated by the SIF, which involved analysis of the above mentioned materials for heavy metals and cyanide, USEPA and NMEID prepared a final-ranking package for the site. The final score of 38.93 exceeded the 28.5 minimum and the site was nominated for the NPL (Federal Register, 53 FR 23988, June 24, 1988). Thus the Cimarron Mill became an official Superfund site. This meant that USEPA had determined the site to be a possible major, longterm threat to human health and the environment.

Ecology and Environment Inc. of Dallas, Texas, was hired by USEPA to conduct an Expanded Site Inspection (ESI) which included surface and subsurface sampling, installation of monitoring wells and sampling ground water in the wells, sampling municipal drinking-water wells and irrigation wells near the site, and identifying adjacent land uses. The final report (Malone and Roblin, 1988) listed the following conclusions:

1. Both the surface and subsurface soils are contaminated with cyanide (0.88-21 ppm), arsenic (15 ppm), chromium (11-19.6 ppm), mercury (0.11-0.18 ppm), and cobalt (6.8-209 ppm).
2. The first water-bearing unit is contaminated with cyanide (21.3-1970 ppb), lead (81-150 ppb), manganese (796-10,400 ppb), chromium (0.55-384 ppb), cobalt (125-246 ppb), and mercury (0.25-0.62 ppb).
3. The process bathing tanks contain hazardous materials, confirming that cyanide and metal-stripping agents were used on site. These materials were disposed into an unlined, non-permitted discharge pit and solid wastes were placed directly on the ground at the tailings waste-pile area. The solid and fluid discharges have contaminated ground water and surface and subsurface soils at the site.
4. Ground-water contamination in the first water-bearing unit appears fairly widespread in relation to the site. Water-flow direction in the unit appears to be to the northwest, but seasonal variations in water levels and massive pumping of the lower aquifer by irrigation wells at the recreation area may cause a reversal of flow direction.
5. The tailings waste piles are sources of subsurface contamination, but their primary release mechanism would be windblown erosion and dust. Although air sampling was not conducted, contaminant release through windblown erosion of the piles is considered likely under the arid conditions of south-central New Mexico.

On September 29, 1988, USEPA held a briefing about the investigation in Carrizozo. Townspeople contacted the New Mexico Bureau of Mines & Mineral Resources (NMBM&MR) and two representatives from the NMBM&MR attended the meeting. This briefing gave the public the first official information about the site. The previously mentioned reports had been circulated only at NMEID and EPA. Yet the EPA officials at this meeting could give no specific information about the site to the interested parties. One individual (Cherry, 1988) stated at the meeting that the manner in which the amount of possible hazardous waste was presented by EPA was terrorizing as well as incorrect. This individual, a former manager of the mill, stated that at no time was a 50/50 solution of cyanide salt and metal stripper used (as USEPA had stated in a fact sheet handed out at the meeting); only very dilute solutions of each were used. EPA later corrected their statement to reflect these dilute-solution concentrations in subsequent Superfund Fact Sheets. NMBM&MR personnel pointed out that "free" cyanide breaks down in a very short time (months to several years) to non-hazardous substances. Because operations at the site ceased in 1982, sufficient time had passed for all the "free" cyanide exposed to air to break down. Furthermore, any cyanide in the tailings piles and tank sediments would be complexed as unreactive iron-cyanide complexes. Because the earlier mentioned reports on the site were not available to the public, it was impossible to comment further.

EPA hired a contractor (Camp Dresser & McKee Inc.) to perform the Remedial Investigation (RI) and Feasibility Study (FS). An RI assesses the type of contaminants present, identifies the degree of contamination, and characterizes potential risks to the community. An FS examines the feasibility of various alternative remedies.

An "open house" was held in March 1989 in Carrizozo by EPA and the contractor to inform interested parties about the work to be done at the site. NMBM&MR representatives at the meeting attempted to convince EPA and their contractor that, on the basis of the study by Ecology and Environment Inc. of the geology of the site and cyanide chemistry, the cyanide contamination would be confined to the shallow ground water and, therefore, it would not be necessary to drill more monitoring wells. However, more monitoring wells were drilled on and off site, bringing the total to 17 wells! Still more surface-soil samples and more ground-water samples were taken.

Mitigation

In March 1990 USEPA held a workshop in Carrizozo, which NMBM&MR representatives attended, to present the preliminary results of the field sampling done the previous October. USEPA representatives announced that on-site monitoring wells in the shallow ground water were heavily contaminated (up to 4330 ppb), although off-site wells were not impacted (Harrold, 1990). Soil and surface-water runoff and air were not contaminated at levels above health-based criteria. Questioning brought out that the well (MW-4) that was reported to contain 4330 ppb total cyanide had been analyzed repeatedly and had yielded the following levels of cyanide (as total cyanide): 101, 360, 1970, 3000, and 4330 ppb. Yet EPA was using only the 4330 ppb value as an example of the heavily contaminated well at the site. The variable values obtained were probably a function of how the well was flushed and how much sediment was collected. EPA estimated that at that time approximately $531,000 had been spent at the site. The final conclusion was that one shallow well at the site had been contaminated with cyanide. The amount of ground water impacted was thought to be about 3 million gallons.

The FS was completed in June 1990 and in July EPA held a public meeting to solicit comments on the various proposed remedies. Six alternatives for remediation were discussed:

1. No action.
2. Institutional controls.
3. Pump and evaporate ground water.
4. Pump and discharge ground water to a POTW (publicly owned treatment works).
5. Pump, treat, and discharge ground water to POTW.
6. Pump, treat, and recharge ground water.

Alternative #4 was USEPA's preferred remedy. Mention was made by USEPA representatives at the meeting that, regardless of the selected remedy, materials at the site which contained hazardous substances would be removed and equipment would be cleaned to remove hazardous substances.

In September USEPA announced the selected remedy, alternative #4. This remedy consisted of using extraction wells to pump contaminated ground water to the surface and then to discharge it to the public sewage system where it would be treated by the local sewage treatment plant. The remediation was expected to take approximately 13 months and cost approximately $95,000. Work was expected to begin on the site in early 1991.

Remediation

A USEPA contractor arrived at the site in the summer of 1991 and dismantled the I-beam supports, electric motors, shafts, and agitators from the tanks and used a torch to cut up the tanks, reducing the mill equipment to junk. The equipment was placed on plastic sheets and rinsed with high-power hoses. Then the contractor left and the sediments removed from the equipment were allowed to dry out and blow around (R. Forsythe, pers. comm. 1993).

The U.S. Bureau of Reclamation was named by USEPA as the contractor for the remediation of the ground water. In the fall of 1991 they arrived to begin the drilling of seven wells from which the contaminated water would be pumped and discharged into the town sewer. The seven wells (Fig. 3) were to be drilled northwest of monitoring well MW-4 which had yielded the high total-cyanide values (from 101 to 4330 ppb). The discharges from these new wells were to be mixed on site and tested for soluble cyanide before being discharged to the sewer system. When the Bureau of Reclamation personnel arrived on site, Carrizozo Mayor Cecilia Kuhnel talked with the foreman and discovered that there were no permits from the New Mexico State Engineer Office to do the drilling (Cherry, 1991). The Mayor contacted the State Engineer Office and was told that USEPA took the position that Superfund projects supersede state law and they do not need any permits. The Mayor insisted that they did need permits; eventually, the Mayor prevailed and the Bureau of Reclamation filed the necessary permits. Before the contaminated water could be pumped into the sewer, USEPA also had to obtain the approval of the Mayor and Board of Trustees. But they had done such a good job of convincing the townspeople of the dangers at the site that the Mayor and Board of Trustees were afraid USEPA would put that "hazardous" material into their sewer system. USEPA as well as NMEID and NMBM&MR personnel attempted to reassure the town officials that any cyanide in the water would be destroyed by aeration and bacterial action in the sewage treatment plant. The town officials were concerned that at some later date they might incur liability by allowing the water into their system, so they asked USEPA to accept any liability or give them some sort of written assurance that the town would not be held liable. USEPA refused and threatened to issue an administrative order to hook up and/or assess financial penalties of $25,000 a day (Stallings, March 1992). The town officials stood their ground and eventually USEPA agreed to most of their terms (testing at the site and only pumping into the sewage system if the cyanide concentration is at an acceptable level, paying the town $1500 a month for use of the treatment plant) with the exception of the third-party indemnity (Stallings, April 1992). Seven shallow (approx. 50 ft) recovery wells were drilled down-gradient from the "hot" well (MW-4). Two of the seven were dry holes, the other five (Fig. 3) produced about $7^1/2$ GPM (Steve Hansen, Bureau of Reclamation, pers. comm.). The water was pumped into the holding tank, also shown in Fig. 3, before being discharged to the city sewer system. When pumping began in September 1992, the highest free cyanide found in the recovery wells was 0.027 ppm and the "hot" well contained 0.100 ppm (drinking-water standard is 0.200 ppm). Pumping continued until the summer of 1993 when the wells went dry. When the pumps were pulled from the wells it was discovered that the pumps were all badly corroded, and it thus could not be known for sure whether the wells were dry or not.

Remarks

There were some major problems with the SIF report which were never addressed by USEPA or NMEID.

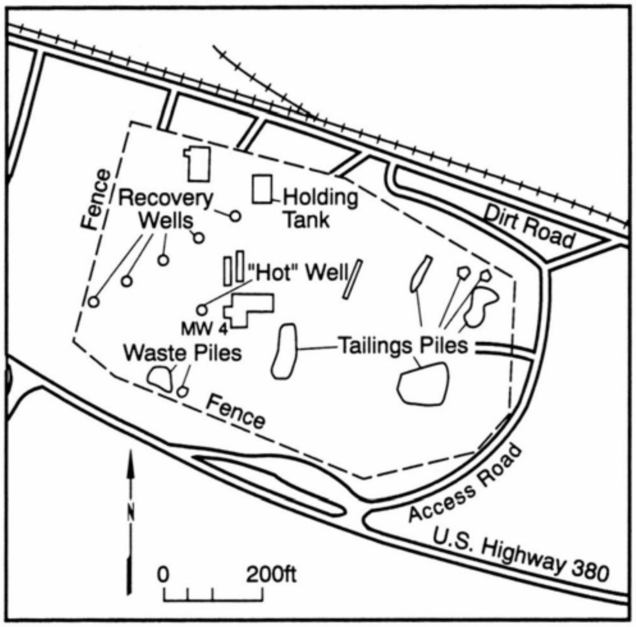

FIGURE 3—Cimarron site recovery wells and holding tank.

If they had been, I doubt the site could have ever qualified for listing as a Superfund site. This site is on alluvial fans fed in part by debris from local mining districts (Griswold, 1959). Elevated levels of heavy metals are not unusual in this type of situation. The values of heavy metals, as listed in this report, in surface and subsurface soils are in the range of what would normally be expected. Furthermore the ore, high-grade magnetite, was brought to the site for the very reason that it contained elevated levels of heavy metals. The one hundred 55 gallon drums of material stockpiled along the west fence were magnetite concetrate.

Water samples taken from monitoring wells were acidified but not filtered in the field and then acid-digested in the laboratory before analysis. Under these conditions the values obtained reflect heavy metals in any sediment brought up with the water, and/or sediment which might have been carried into the well from the surface by the drill bit and then brought up with the water. Furthermore, these heavy metals would not be soluble in the ground water under the existing pH conditions, nor would they move through the ground water. Thus the results are not an accurate measure of heavy metals in the ground water.

Cyanide determinations were done for "total" cyanide and not for "free" cyanide, the form which is considered hazardous. Iron-cyanide complexes, the form of cyanide most likely to be present at this site, are very stable and non-hazardous. The antidote for ingesting cyanide is to drink a solution of iron salts! USEPA's definition of hazardous substances is based on total amounts present and does not take into consideration solubility, biological availability, or chemical form. Water samples were preserved for cyanide analysis but again were not filtered. Differences in how the well was flushed and how much sediment was collected no doubt explain the wide range of cyanide values (100-4330 ppb) reported for MW-4.

In 1988 NMBM&MR personnel contacted the two manufacturers of the 26 cardboard drums of metal-stripper compounds, many of which were stored outside exposed to the elements, who said they would be glad to accept them back for reuse. One manufacturer said they would send their own hazardous waste personnel to pick up the chemicals at no cost (I. Gundiler, pers. comm. 1989). This information was passed on to the USEPA site manager. In 1992 USEPA had them taken to an approved disposal facility, an expensive waste of material.

The representative of the court handling the CMC bankruptcy was approached by individuals who wished to purchase equipment and materials from the site. These individuals were referred to USEPA because nothing could be removed from the site without their permission (everything on a Superfund site is considered to be hazardous material). The New Mexico State Highway Department was building a new highway west of Carrizozo and was interested in buying the unprocessed ore (which was environmentally non-hazardous) from the site for highway fill. USEPA refused to consider this offer until after the RI and FS had been completed, which was estimated to be late 1990 (letter from William Rowe, EPA Enforcement Section, to Ralph Forsythe, March 22, 1989). One individual (letter from William Rose to Barry Allen, April 5, 1989) inquired about buying the property, cleaning it up, and operating a cyanide mill at the site. He was told that if he purchased the property he would become a "Potentially Responsible Party" under CERCLA and would be responsible for some or all of the costs associated with the clean-up of the site, which would have to be done under EPA's oversight. Another individual (letter from William Rowe to Richard A. Benner, Jr., April 5, 1989) inquired about buying the equipment and moving it to another site for use in a cyanide mill. He was told that any equipment which had cyanide residuals on it (ball mill, vats, piping, tanks, etc.) would have to be decontaminated before leaving the site. A decontamination plan would have to be submitted to EPA for approval and would have to include: dismantling the equipment, hauling equipment by crane to a cleaning area (a child's wading pool to collect rinse solutions), steam-cleaning equipment, testing to determine disposal options for rinse solutions, and chemicals to be used in steam cleaning. The cleaning would have to be done under EPA supervision and EPA personnel would have to be compensated for their time plus travel and per diem. All this for equipment which would then be used in a similar cyanide process at a different site. Meanwhile, the cyanide salts contained in cardboard drums were sitting outside exposed to the elements. These were potentially the most hazardous materials at the site, yet no effort was made to remove them or even move them inside. Finally the drums were removed without USEPA participation by a local person at a cost of $100 per barrel and donated to a cyanide mining operation in the state (Harrold, 1989).

Thus, a small mill with equipment estimated to be worth a million dollars when new (I. Gundiler, pers. comm. 1988) has been destroyed, USEPA has spent at least $968,171 (USEPA Financial Status Report, Carrizozo, Cimarron Mines, 11/18/92), and the site has not been declared cleaned up and will have to be monitored for 10 years following cleanup. All this for a site where it is questionable if it should have ever been declared a Superfund site in the first place.

Acknowledgments

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Ochoan (Late Permian) stratigraphy and chronology, southeastern New Mexico and west Texas

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Abstract—The "Ochoan Series" of southeastern New Mexico and west Texas consists of (ascending) Castile, Salado, Rustler and Quartermaster Formations. The Castile Formation is at least 700 m thick and is mostly anhydrite. It conformably overlies Guadalupian strata, and examination of depositional cycles suggests the Castile was deposited during about 200-300,000 years of Late(?) Permian time. The overlying Salado Formation interfingers with the Castile and is mostly halite with a maximum thickness of 725 m. No age constraints other than stratigraphic position are available for the Salado Formation. The overlying Rustler Formation is a marine transgressive sequence of dolomite, anhydrite, sandstone and shale as much as 150 m thick. Five Rustler members can be recognized (ascending): Virginia Draw (introduced here), Culebra, Tamarisk, Magenta and Forty-Niner. Late Permian invertebrate fossils (mostly brachiopods and bivalves) and conodonts are known from the Virginia Draw and Culebra Members. The Quartermaster Formation (= Dewey Lake Formation or Pierce Canyon Redbeds) is a red-bed sequence of sandstone, siltstone and anhydrite as much as 115 m thick. Magnetostratigraphy and fossils indicate a Late Permian age for the Quartermaster, which is consistent with K–Ar ages obtained from Quartermaster ash beds. The Upper Triassic (upper Carnian) Chinle Group disconformably overlies the Quartermaster Formation. General lack of age indicators makes Ochoan strata ill-suited for the stratotype of a stage, and Ochoa is better regarded as a lithostratigraphic unit (Ochoan Group) than as a series or stage.

Introduction

Upper Permian (Ochoan) strata, mostly evaporites capped by a relatively thin sequence of nonmarine red beds, are exposed intermittently and have an extensive subsurface distribution across the southern High Plains of west Texas and eastern New Mexico (Fig. 1). These strata were the basis of the Ochoan Series (Stage) of Adams et al. (1939; also see Adams, 1944). Our purpose here is to briefly review the stratigraphy and chronology of the Ochoan rocks and to discuss the utility of the Ochoan as a Late Permian stage.

Ochoan stratigraphy

Ochoan rocks are assigned to (ascending) the Castile, Salado, Rustler and Quartermaster Formations (Fig. 2). The potash resources of these strata and their use in the burial of low-level radioactive waste have led to an extensive stratigraphic data base which is briefly reviewed here.

Castile Formation

Richardson (1904, p. 43) named the Castile Gypsum for Castile Spring, which is in "outcrops in a belt between the Delaware Mountains and Rustler Hills." This definition included all strata between the Delaware Mountain and Rustler Formations, so the strata now included in the Salado Formation would have been in Richardson's (1904) Castile Gypsum (Fig. 3).

Subsurface data from the Delaware basin demonstrated that Richardson's type Castile consists of two distinct lithostratigraphic units (Fig. 3; Cartwright, 1930). Lang (1935) named the upper unit the Salado Halite and defined it as all pre-Rustler evaporites that contain >0.5% potash (K_20).

The main outcrop area of the Castile Formation is the gypsum plain which extends from south of Carlsbad, New Mexico, to Culberson County, Texas, and includes the western part of the Delaware basin (Fig. 1). Other than a thin wedge that overlaps the basinward margin of the Capitan reef system (Figs. 2, 4), the Castile Formation is confined to the Delaware basin where it conformably overlies the uppermost Bell Canyon Formation (Jones, 1954). Maximum reported thickness of the Castile Formation is more than 700 m near the center of the Delaware basin (Adams, 1944).

The Castile Formation consists of anhydrite, calcite-banded anhydrite, halite, limestone and minor amounts of other evaporites (but no potash) and clastics (Ad-

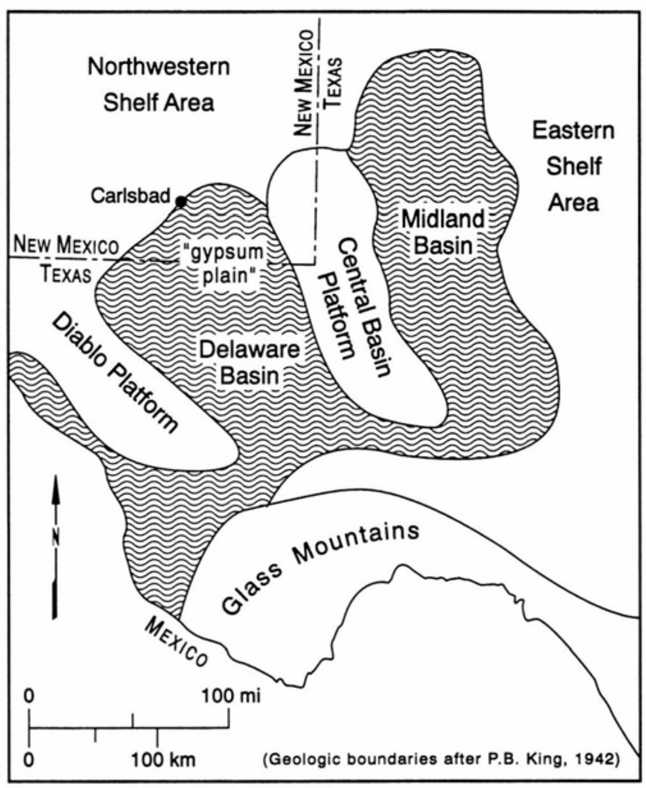

FIGURE 1—Index map of location of Delaware and Midland basins and adjacent shelf and platform areas.

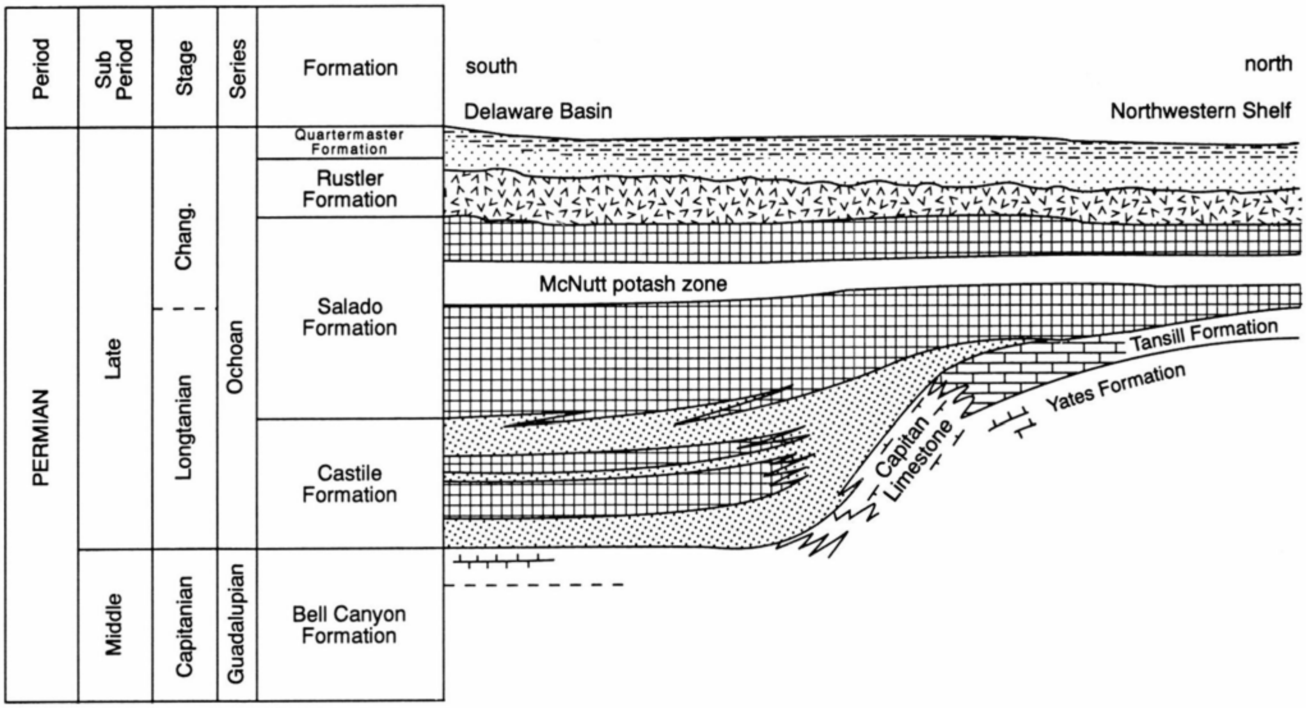

FIGURE 2—Generalized stratigraphy and age relationships of Ochoan strata in southeastern New Mexico and west Texas.

Lithology	Richardson 1904	Lang 1935, 1937, 1938, 1939	Adams 1944		Lucas and Anderson 1994	
	(not considered)	Pierce Canyon Redbeds	Dewey Lake Formation	Ochoan Series	Quartermaster Formation	Ochoan Group
	Rustler Formation	Rustler Formation	Rustler Formation		Rustler Formation	
	Castile Gypsum	Salado Formation	Salado Formation		Salado Formation	
		Castile Gypsum	Castile Formation		Castile Formation	

FIGURE 3—Development of Ochoan stratigraphic nomenclature.

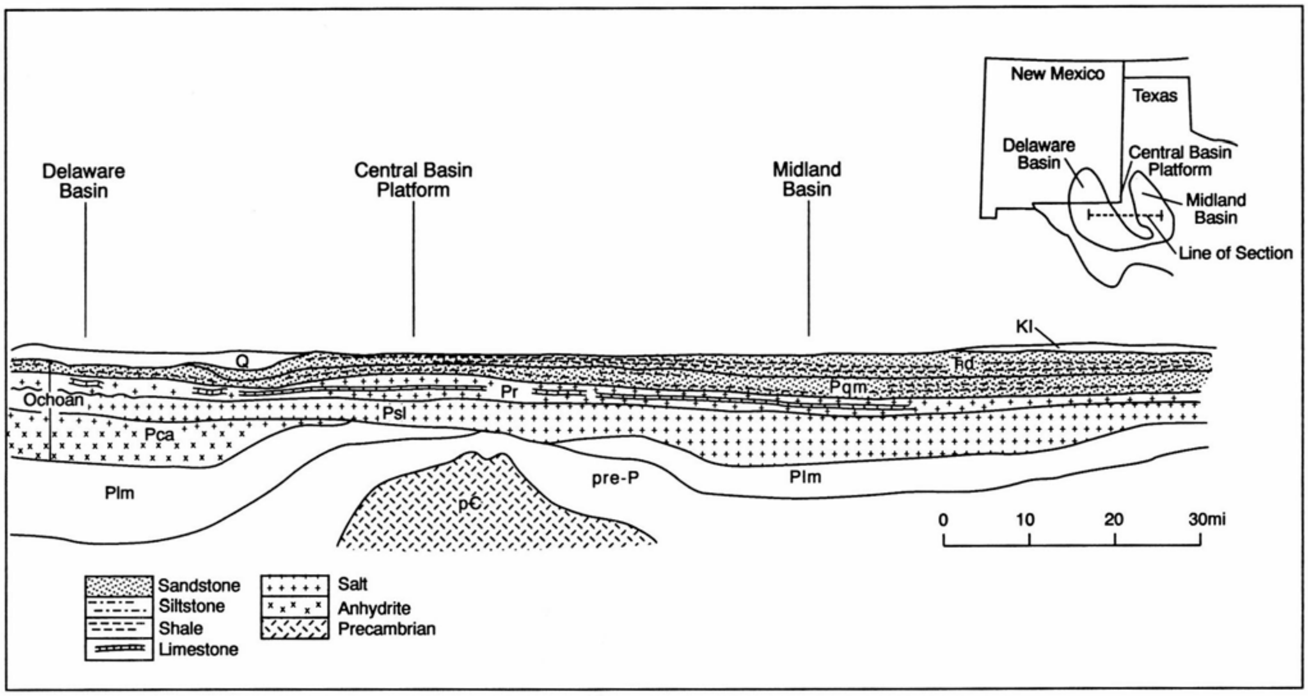

FIGURE 4—Generalized cross section through Delaware and Midland basins showing regional extent of Ochoan strata. Pe = Precambrian, pre-P = pre-Permian rocks, Plm = Lower and Middle Permian rocks, Pcz = Castile Formation, Psl = Salado Formation, Pr = Rustler Formation, Pqm = Quartermaster Formation, Trd = Dockum Formation, Kl = Lower Cretaceous rocks, Q = Quaternary deposits. Modified from King (1942).

ams, 1944). Alternating laminae of anhydrite and calcite are characteristic of the formation, and these laminae are commonly microfolded (e.g. Kirkland and Evans, 1980). Dissolution features are also common, due to removal of underlying salt. The Castile Formation is most noted for the limestone masses which stand out in bold relief on the gypsum plain to form "castiles." The Castile Formation has a conformable and intertonguing upper contact with the overlying Salado Formation throughout the Delaware basin (Fig. 2).

Salado Formation

As noted above, Lang (1935) coined the name Salado Halite for the upper part of Richardson's (1904) Castile Gypsum (Fig. 3). The stratotype of the Salado is a subsurface section in a well in Loving County, Texas, and the unit takes its name from Salado Spring in the northern part of that county (Lang, 1935, 1939). Lang's (1939) redefinition of the Salado lowered its base to include an anhydrite (the Fletcher Anhydrite Member of Lang, 1942) that he had previously included in the Castile. However, we see little value in recognizing a separate Fletcher Anhydrite Member and including it in the Salado Formation, and recommend that these strata be returned to the Castile Formation (Figs. 2, 3).

The Salado Formation is mostly halite with thin beds of anhydrite, polyhalite, shale and potash-bearing salts (Lowenstein, 1987), although in northwestern Pecos and southern Reeves Counties, Texas, the Salado grades into massive anhydrite (Lang, 1939). Adams (1969) reported that the Salado Formation is nearly 84% halite or argillaceous halite and only 12% sulfate. Maximum reported thickness of the Salado Formation is about 725 m (Lang, 1939). There are no known outcrops of the unit, but it is present in the subsurface throughout the Delaware basin and the northwestern shelf area of southeastern New Mexico (Fig. 1).

In Lea County, New Mexico, a distinctive fine-grained, orangish-red sandstone approximately 3 m thick occurs in the upper part of the Salado Formation. This is the Vaca Triste Sandstone Member of Adams (1944). Never more than 3 m thick, the Vaca Triste Member occurs above the McNutt potash zone and can be traced in the subsurface throughout much of the northwestern shelf area into the Delaware basin (Adams, 1944; Jones, 1954).

The Salado Formation has a conformable and intertonguing contact with the underlying Castile Formation throughout the Delaware basin, but beyond the basin to the north—northwest it rests unconformably on Guadalupian-age strata (Fig. 2). The Rustler Formation conformably overlies the Salado in the central part of the Delaware basin, but along the basin's northern and western margins it truncates the Salado. Indeed, in the western Delaware basin the Rustler lies on the basal part of the Castile Formation and reportedly rests on Guadalupian limestones in the Apache Mountains (Adams, 1944).

Rustler Formation

Richardson (1904, p. 44) coined the term Rustler Formation for strata above his Castile Formation (Castile + Salado Formations of later workers, see Fig. 3). He took the name from the Rustler Hills in Culberson County, Texas, but did not designate a specific type locality. Lang (1938) and Adams (1944) subsequently described the Rustler Formation in some detail. It is present in both the Delaware and Midland basins, though it is thinner in the latter. A maximum reported thickness is 150 m in the subsurface (Lang, 1938; Cox et al., 1954) and 114 m on outcrop in the Rustler Hills (Adams, 1944).

Lithologically, the subsurface Rustler can be divided into two parts, a lower portion of dolomite, anhydrite, sandstone and shale and an upper 45-53 m thick bed of anhydrite or gypsum (Adams, 1944). Rustler dolomites are generally less than 9 m thick, but are porous and locally form good aquifers (Adams, 1935).

Several subdivisions of the Rustler Formation have been proposed. Lang (1938) named two persistent dolomite intervals the Culebra Dolomite and Magenta Dolomite Members. Vine (1963) named the Tamarisk and Forty-Niner Members. The unnamed basal member of the Rustler Formation (strata between the Salado or Castile Formations and Culebra Member) is herein named the Virginia Draw Member. The type section of the Virginia Draw Member (Figs. 5, 6) is at Walter's (1953) locality 2, which is the NE[1]/4 sec. 2 of block 42 of the P.S.L. Survey (Walter, 1953, fig. 1). This locality is approximately 3 km south of Rustler Spring and near the drainage of Virginia Draw, from which the unit takes its name.

At its type section, the Virginia Draw Member is 20 m thick and consists of interbedded sandstone, limestone and dolomite (Figs. 5, 6A). These beds weather buff, orangish-brown and gray. The sandstones are fine-grained and quartzose, display flaser beds and indistinct crossbeds, and locally are bioturbated. Kaolinite and gypsum inclusions are present locally. The base of the Virginia Draw Member is a sandstone bed disconformably overlying gypsum of the Castile Formation (Fig. 6B).

Virginia Draw Member limestones are silty and massively bedded. They typically weather medium gray and pale brown and contain kaolinitic and gypsiferous specks. The dolomite beds are similar and locally contain macrofossils such as crinoid columnals (Fig. 6C). The thick (10 m +) Culebra Member is a

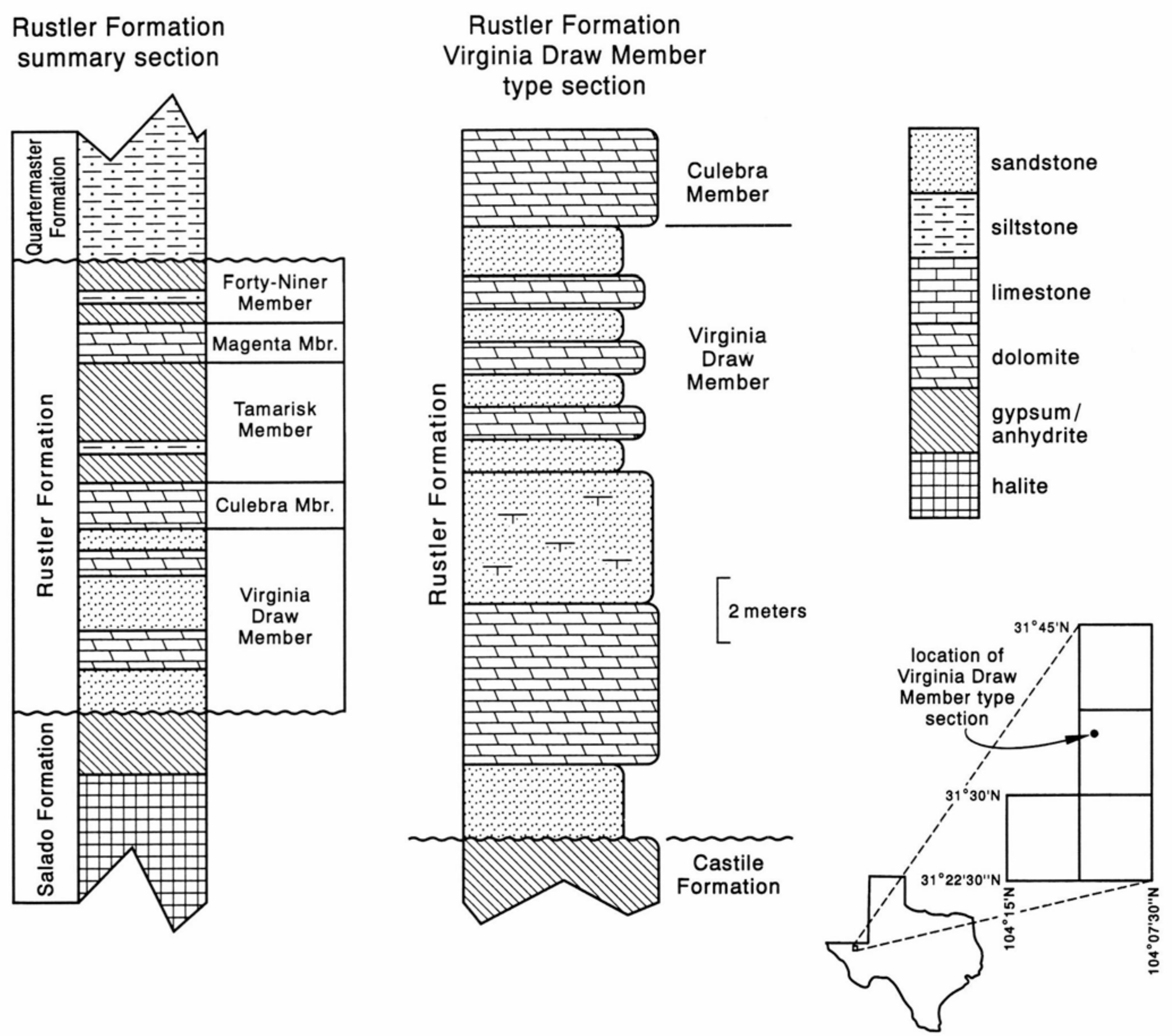

FIGURE 5—Generalized section of Rustler Formation and type section of Virginia Draw Member.

pale gray to tan bench-forming dolomite that overlies the Virginia Draw Member at its type section (Figs. 5, 6A, D).

The Virginia Draw Member of the Rustler Formation is exposed throughout much of the Rustler Hills, where it is as much as 30 m thick. In New Mexico its best studied subsurface sections are in the Nash Draw area of eastern Eddy County (Vine, 1963). Here the Virginia Draw Member consists of as much as 40 m of siltstone, sandstone and gypsum, and was identified as the "unnamed part" of the Rustler Formation by Vine (1963).

The (conformable—unconformable) contact of the Rustler Formation with the underlying Salado was described above. The Rustler—Quartermaster contact has generally been described as conformable (Adams, 1944). This strikes us as improbable, however, and we suggest that the red-bed clastics of the Quartermaster Formation disconformably overlie Rustler carbonates and evaporites.

Quartermaster Formation

The final stage of Ochoan depositional history is represented by a relatively thin sequence of red to reddish-orange fine-grained sandstone, siltstone and shale similar to that of the much older (Guadalupian) Artesia Group. These strata were named (Lang, 1935) the "Pierce Canyon Redbeds" after exposures in Pierce Canyon southeast of Loving in Eddy County, New Mexico, but the exposures were very limited and the type section was described from well cuttings in a test hole in Loving County, Texas, 56 km to the southeast. The subsurface thickness of 106 m was established from this well. Adams (1935) discounted correlation of the Pierce Canyon Redbeds with the youngest Permian strata in Oklahoma and the Texas Panhandle, which had been designated the Quartermaster by Gould (1902). Adams recognized the Quartermaster throughout the Panhandle, but southward into the northern Midland basin he incorrectly correlated it with the Yates Sand of the Whitehorse (Artesia) Group. Adams thus considered the Quartermaster to be much older than the youngest Permian rocks of the southern basins, for which he preferred to use the name Pierce Canyon Redbeds.

In their discussion of Permian stratigraphy in the Midland Basin, Page and Adams (1940) introduced the name Dewey Lake Formation for the youngest strata of the Ochoan Series (Fig. 3). They discarded the name Pierce Canyon because it had been established to their satisfaction that the red beds exposed in Pierce Canyon belonged to the Gatuña Formation of Plio-Pleistocene age (Hawley et a1.,1993). The Dewey Lake Formation was then named from a subsurface section, the Penn-Hanbenstreit No. 1, a cable-tool well (dry hole) in Glasscock County, Texas; Dewey Lake is a nearby alkali lake.

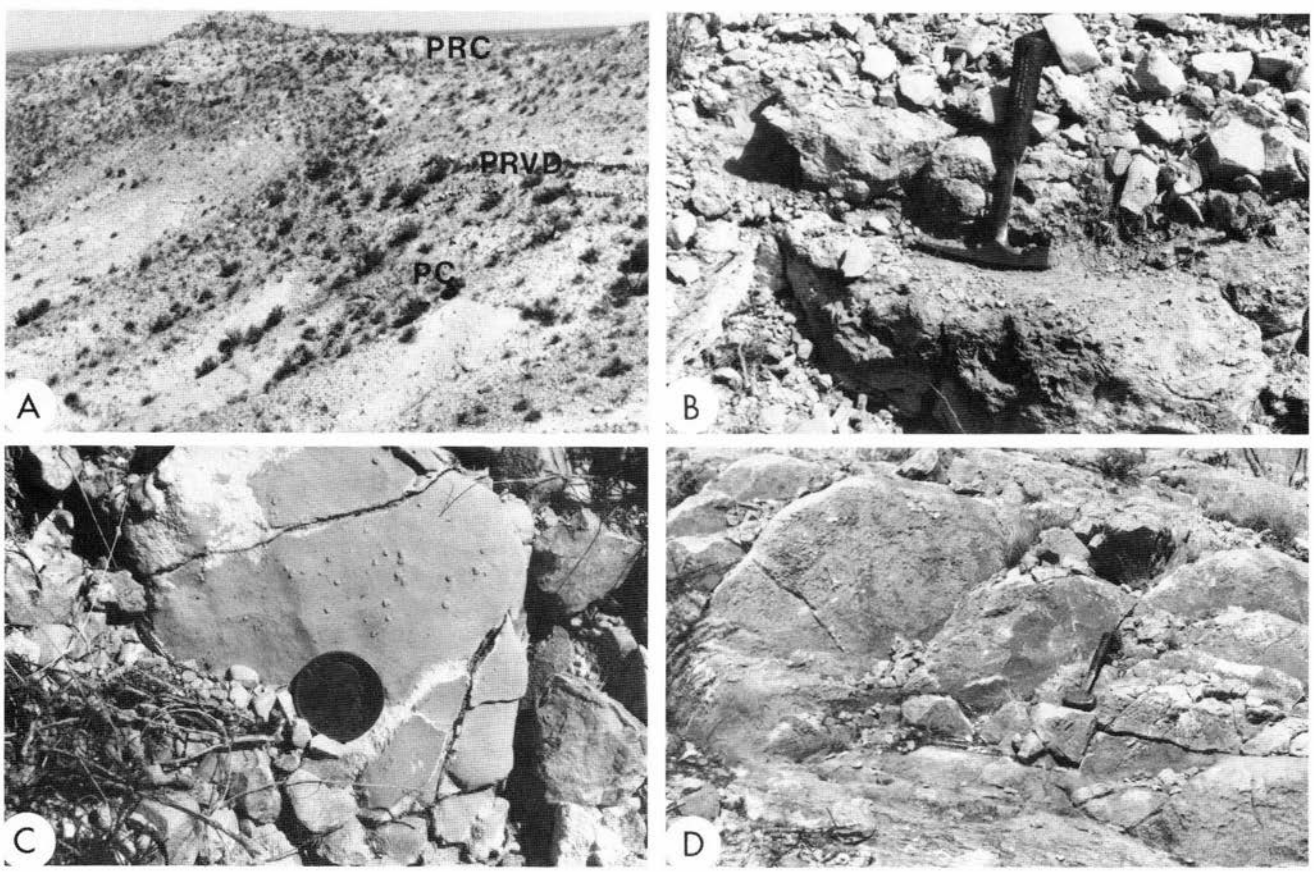

FIGURE 6—Type section of Virginia Draw Member, Rustler Formation, south of Rustler Spring in Rustler Hills, Culberson County, Texas. **A**, Virginia Draw Member (PRVD) overlain by Culebra Member (PRC) above Castile Formation (PC). **B**, Close-up of Rustler–Castile contact (hammer head). **C**, Close-up of lowest dolomite bed of Virginia Draw Member with isolated crinoid columnals. **D**, Close-up of Culebra Member.

Aside from the revelation that the Pierce Canyor outcrop was in reality that of the Gatuña Formation the unit had also been included with the overlying Upper Triassic Dockum Group (Formation). Lang (1937 implied in his discussion of the Pecos Valley that the top of the Permian was the top of the Rustler. Morgar (1942) presented a cross section in which he includec the Pierce Canyon Formation in the Dockum. Sub sequent work, however, beginning with that of Bate! (1942), used the name Dewey Lake for these strati and correctly included them in the Permian Ochoar series. The overlying Dockum has a conglomerate a or near the base, resting unconformably on Permiar strata (Lucas and Anderson, 1992, 1993a, b, c). The(Dockum also has a much less mature lithology, both texturally and mineralogically.

The U.S. Geological Survey eventually recommended that the name Pierce Canyon be abandoned (Keroher, 1966) and that Dewey Lake be used instead across the Permian basin. Most published accounts followed that recommendation, but both names would subsequently appear informally. One of the most recent usages of Pierce Canyon Formation was by Fracasso and Kolker (1985), who described and dated volcanic-ash beds in the Quartermaster (= Dewey Lake) Formation (see below).

With the name Pierce Canyon abandoned, the nomenclature for latest Ochoan rocks now consisted of Dewey Lake in the Permian basin (both Delaware and Midland basins) and the Quartermaster to the north in the Texas Panhandle and into Oklahoma. Millei (1966) recognized that the Quartermaster and Dewey Lake had "essentially identical mineral assemblages" and occupied the same stratigraphic position (also see Roth, 1945). Based on our own observations of these units, both in the field and in the laboratory, we agree with Miller's conclusions. In an effort to simplify the nomenclature and add to the understanding of regional correlations, we suggest that one name be used for these strata. The name Quartermaster (Gould, 1902) has precedence over Dewey Lake (Page and Adams, 1940), and we thus recommend that Dewey Lake be abandoned in favor of the name Quartermaster Formation.

The maximum reported thickness of the Quartermaster Formation is 115 m in the Delaware basin (Adams, 1944). The unit is red beds of fine- to medium-grained sandstones, siltstones and gypsum intercalated to give the appearance of cyclical deposition.

Ochoan chronology

Most of the Ochoan strata are evaporites devoid of fossils, making precise age assignments very difficult. Here we review the ages of the Ochoan strata, applying all available geochronological data.

Age of Castile Formation

The Castile Formation contains no fossils or other evidence such as volcanic-ash beds by which its age could be directly estimated. Since it overlies Capitanian strata (Lamar Limestone Member of the Bell Canyon Formation and its equivalents; Fig. 2), its late Guadalupian maximum age is established. King (1948) mapped several post-Lamar limestone beds in the basal Castile that may contain evidence of a Guadalupian age.

Preservation of thin laminae in the Castile, studied by Anderson and Kirkland (1966), suggests that deposition was in relatively deep water, well below wave base, and spanned approximately 200-300,000 years (Anderson, 1982). The end of the Capitanian is estimated to have preceded the end of the Permian by 5 million years on most numerical time scales (Forster and Warrington, 1985; Harland et al., 1990). This indicates that Castile deposition consumed approximately 5% of Late Permian time, if Anderson's (1982) cyclostratigraphic estimate is correct. Therefore, the entire Castile Formation is Permian, and it represents a tiny fraction of Permian time very close to the Middle–Late Permian boundary.

Age of Salado Formation

No fossils or other age indicators are known from the Salado Formation or are likely to be found. Its conformable and interfingering lower contact with the Castile Formation and position below Rustler Formation strata with Late Permian fossils indicate that the Salado must be of Late Permian age. However, the duration of Salado deposition is impossible to estimate.

Age of Rustler Formation

The Rustler Formation offers the best time contraints of the entire Ochoan section. An extensive marine invertebrate fauna from the Virginia Draw Member in the Rustler Hills is of Permian age (Donegan and DeFord, 1950; Walter, 1953). This fauna is dominated by brachiopods (especially *Derbya sulcata* Walter), with lesser numbers of bivalves and gastropods. It co-occurs with an extensive conodont fauna (Croft, 1978) that Wardlaw and Grant (1992) considered to be of Changxingian (Late Permian) age.

The post-Virginia Draw Member strata of the Rustler lack an invertebrate macrofauna, although in their lowest part (Culebra Dolomite Member, basal Tamarisk Member) they contain conodonts like those lower in the Rustler section (Croft, 1978). Therefore, it is probable that the entire Rustler Formation is of Late Permian age, though there is no direct age control for the upper part of the formation.

Age of Quartermaster Formation

Four lines of evidence bear directly on the age of the Quartermaster Formation:

1. Three molluscan taxa from Quartermaster outcrops in Briscoe County, *Texas—Naticopsis trans-versus* (Beede), *Schizodus oklahomensis* Beede and *Myalina acutirostratus* Newell and Burma—suggest a Permian age (Roth et al., 1941).
2. Magnetostratigraphy of the Quartermaster Formation in Palo Duro Canyon, Texas, suggests correlation with the Illawara magnetozone at the end of the Kiaman superchron (Molina-Garza et al., 1989). This indicates a Late Permian age.
3. Fracasso and Kolker (1985; also see Kolker and Fracasso, 1985) sampled and dated a volcanic-ash

bed in the Quartermaster Formation. The ash bed lies 4 to 20 m above the base of the formation in Caprock Canyon State Park, Texas. K—Ar dates of 251 ± 4 and 261 ± 9 Ma were obtained by Fracasso and Kolker. The Permian—Triassic boundary is very close to 251 Ma (Claoué-Long et al., 1991). The Quartermaster radiometric ages are thus either latest Permian or earliest Triassic.

4. Late Permian sequence stratigraphy is not well delineated, largely because most Upper Permian strata are either nonmarine or evaporite rocks, the Ochoan being a case in point (Ross and Ross, 1988). Clearly, deposition of the Rustler and overlying Quartermaster Formations represents a cycle. The Haq et al. (1988) global sea-level curve indicates a major Late Permian transgression—regression event at about 253-252 Ma, which might be that which produced the Rustler—Quartermaster sequence. Nevertheless, it should be stressed how poorly delineated and calibrated the global record of eustasy is (Ross and Ross, 1988).

All evidence either directly indicates, or is consistent with, a Late Permian age assignment for the Quartermaster Formation. None of these lines of evidence, however, is incontrovertible, and the possibility that some of the Quartermaster Formation is of Triassic age (Schiel, 1987, 1988) needs to be considered, though no evidence currently supports such an age assignment. Upper Triassic (upper Carnian) strata at the base of the Chinle Group or younger, Cretaceous or Cenozoic, rocks disconformably overlie the Quartermaster Formation (Lucas and Anderson, 1993b).

The Ochoa Group

Although originally proposed as a series, Ochoan has been treated as a stage equivalent to Late Permian time. As the stratotype of a stage, Ochoan strata have been well studied and described and are very accessible, thus meeting two of the key requirements of a stratotype for a chronostratigraphic unit (Hedberg, 1976). Nevertheless, the Ochoan strata fall far short of an ideal stratotype for a Late Permian stage because they generally lack fossils, radiometric-age data and geomagnetic-polarity data with which to correlate. Furthermore, estimates of the duration of early Ochoan evaporite deposition and intra-Ochoan unconformities suggest that Ochoan strata present only a very incomplete record of Late Permian time. It is even possible, though currently not demonstrable, that some of the youngest Ochoan strata are of Triassic age.

We thus conclude that the Ochoan strata do not provide a suitable stratotype for a stage in the SGCS (standard global chronostratigraphic scale). The use of Ochoan as a regional stage also is problematic because outside of the southern High Plains of eastern New Mexico, west Texas, Oklahoma and parts of Colorado and Kansas there are no known Late Permian rocks in North America. Thus, as a chronostratigraphic unit, Ochoan has very limited utility. Therefore, we recommend that it be dropped from the chronostratigraphic hierarchy and be redefined as a lithostratigraphic unit, the Ochoa Group. So redefined, the Ochoa Group consists of the Castile, Salado, Rustler and Quartermaster Formations, an evaporite-dominated sequence of mostly anhydrite and halite. Available data suggest that the Ochoa Group was deposited during the Late Permian in the southwestern United States. Strata of the Ochoa Group are largely unfossiliferous and do not provide a suitable basis for global correlation of Upper Permian strata.

Acknowledgments

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The saga of the Dockum Group and the case of the Texas/New Mexico boundary fault

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Abstract—The Upper Triassic Dockum Group consists of continental red beds exposed around the southern High Plains of western Texas and eastern New Mexico. Although these strata are contiguous between the two states, different stratigraphic nomenclature is used in Texas and New Mexico. New mapping of the type area in Texas and physical tracing into New Mexico allow recognition of five units in the Dockum Group. A distinctive quartzose conglomeratic sandstone, the Santa Rosa Sandstone, is recognized as the base of the Dockum Group in New Mexico. The informal name Camp Spring Conglomerate should not be used for this same unit in Texas. The Santa Rosa Sandstone is overlain by multicolored shale of the Tecovas Formation in Texas. The name Garita Creek Formation should not be used for these same strata in New Mexico. The Tecovas Formation is overlain by cliff-forming lithic sandstone of the Trujillo Sandstone. The same unit was later named the Cuervo Sandstone in New Mexico. Overlying the Tujillo Sandstone is a thick sequence of red shale called the Cooper Canyon Formation in Texas. These same strata were given the name Bull Canyon Formation in New Mexico. The Redonda Formation comprises the uppermost unit in the Dockum Group, and it is only present in New Mexico. Use of the name Chinle Formation or Chinle Group for part or all of these strata in eastern New Mexico is not appropriate and ignores the fact that formal names had previously been given to these strata in Texas.

"Stratigraphy can be defined as the complete triumph of terminology over facts and common sense" (attributed to P. D. Krynine by J. Ferm *in* Burton et al., 1987)

Introduction

Over the past several years, a number of major stratigraphic revisions have been proposed for the Upper Triassic Dockum Group of west Texas and eastern New Mexico. Red beds of the Dockum Group crop out almost continuously around the Caprock Escarpment of the southern High Plains in Texas, through the Canadian River valley in Texas and New Mexico, and along the Pecos River valley in New Mexico southward into Texas (Fig. 1). Furthermore, these strata are present throughout the subsurface of the southern High Plains between the two states. The Dockum Group, like the overlying Tertiary Ogallala Group, is a complex of largely fluvial strata that bind Texas and New Mexico together along that artificial boundary running near the 103° west line of longitude.

Much of the stratigraphic nomenclature of the Dockum Group extends back more than a century, originating in the early days of the Geological Survey of Texas and the U.S. Geological Survey. Many of the early works on the Dockum Group were published by now venerated stratigraphers such as W. F. Cummins, N. H. Darton and C. N. Gould, and renowned paleontologists such as E. D. Cope, E. C. Case, and J. T. Gregory.

The purpose of this paper is to argue that most of the recently proposed revisions in the stratigraphic nomenclature of the Dockum Group: 1) are unnecessary and confusing, 2) violate the letter and spirit of the code of stratigraphic nomenclature by ignoring priority of established names, 3) are not supported by mapping, and 4) should be rejected by stratigraphers involved with mapping of Triassic strata in Texas and New Mexico.

This paper portrays a case study in the problem of a perceived state boundary "fault" between Texas and New Mexico. This case study illustrates what happens when stratigraphers across state boundaries do not communicate or lack regard for one another, and when paleontologists apply formal names to strata without actually mapping them. This report gives the preliminary results from work in progress and justifies the stratigraphic nomenclature used in our mapping program in west Texas. I advocate the use of this simple nomenclature in New Mexico as well. Geologic maps of several key regions, including the type area of the Dockum Group, are given here for the first time (Figs. 1, 3, 4). No new stratigraphic names are proposed.

A wealth of history

Study of the Dockum Group has a rich history entwined with the early geologic exploration of the southern High Plains region. A full investigation of this history is a wonderful exercise, and readers are encouraged to pursue the complete accounts of the works cited herein. A brief summary of this history is provided here to impress upon the reader the weight of tradition behind the original nomenclature of the Dockum Group.

The Dockum beds were named by W. F. Cummins, working for the Geological Survey of Texas in 1890, in his study of strata exposed along the northern part of the Caprock Escarpment in Texas (Fig. 2). The type area and sections were located along Dockum Creek in Dickens and Crosby Counties (Fig. 3). **In** their reports of 1891 and 1892, Cummins and his assistant N. H. Drake recognized that the Dockum beds extended completely around the High Plains into New Mexico and were the same strata identified as the "Keuper" or "American Trias" by Marcou in his accounts of the Canadian River valley of New Mexico in the 1850s. Drake (a member of the field party headed by Cummins) suggested that the Dockum could be subdivided into lower, central and upper beds.

In his 1906 and 1907 studies of the geology and water resources of the Canadian River valley, C. N. Gould of the U.S. Geological Survey elevated the Dockum to group status and formally subdivided it

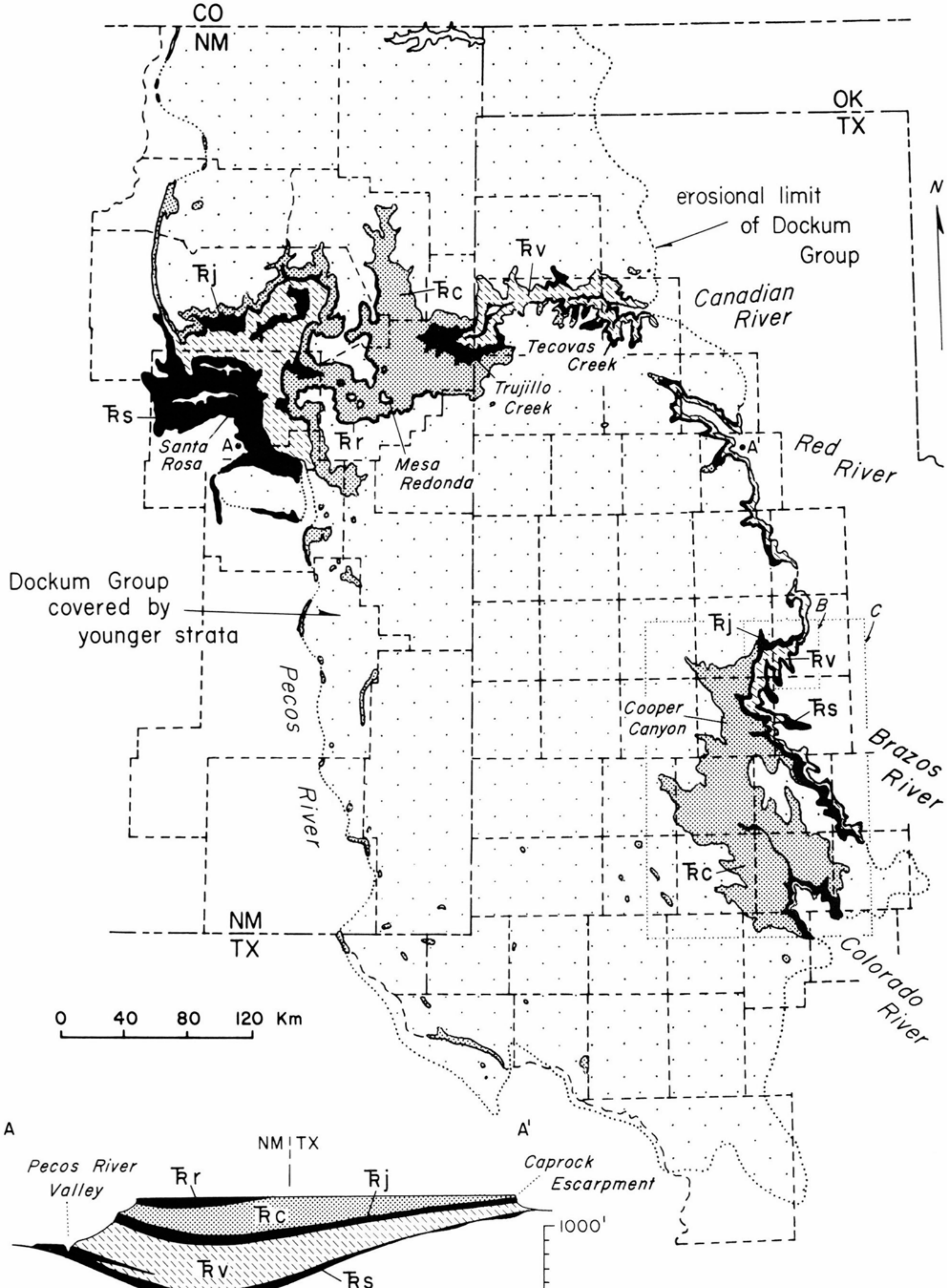


FIGURE 1—Generalized geologic map of the southern High Plains region of west Texas and eastern New Mexico, showing distribution of the Upper Triassic Dockum Group. Outcrops of major sandstone units (TRs = Santa Rosa Sandstone, TRj = Trujillo Sandstone, TRr = Redonda Formation) are shown in black; outcrops of shale units (TRv = Tecovas Formation, TRc = Cooper Canyon Formation) are stippled or cross-hatched. Type areas for the formations are indicated. Region where the Dockum Group is overlain by younger strata is shown in coarse stipple. Inset cross section (A–A′) shows general subsurface geometry of the Dockum Group beneath the High Plains. Locations of detailed geologic maps in Figure 3 (B) and Figure 4 (C) are indicated. Outcrop distribution in upper Pecos River valley is adapted from Kelley (1972), and in Canadian River valley in part from *Geologic Atlas of Texas* Amarillo and Tucumcari sheets (1969).

into the Tecovas and Trujillo Formations (Fig. 2). The Tecovas Formation corresponded generally with Drake's lower beds, the Trujillo with Drake's central and upper beds. Gould (1907), and later Patton (1923), gave detailed descriptions and showed the map distribution of these formations over much of the Canadian River valley in Texas up to the New Mexico border. By 1928 many workers (e.g. Case, Darton, Hoots) realized that outcrops of the Dockum Group extended completely around the High Plains of Texas and New Mexico. Darton (1922, 1928) found that the base of the Dockum Group in the Pecos River valley of New Mexico is marked by a thick distinctive sandstone unit which he named the Santa Rosa Sandstone (Fig. 2). He clearly recognized that this unit comprised the base of the Dockum Group. Gould, Patton, and others found similar quartzose conglomeratic sandstone beds that occupied the same stratigraphic position in the base of the Tecovas Formation throughout the Canadian River valley in Texas and, at least locally, along the eastern Caprock Escarpment. In 1946, Dobrovolny and Summerson recognized a distinctive, rhythmically bedded sandstone unit at the top of the Triassic section exposed along the Canadian Breaks in New Mexico, which they named the Redonda Member (later elevated to formation by Griggs and Read, 1959).

Hence, at least 50 years ago the basic components of the Dockum Group (Santa Rosa, Tecovas, Trujillo, and Redonda Formations) were recognized. Unfortunately, trouble began shortly thereafter.

Reconciling the stratigraphy of the Colorado Plateau with the High Plains

The state of New Mexico straddles the boundary between two spectacular geologic provinces. The axis of the Rocky Mountains and Rio Grande valley separates the Colorado Plateau and highlands of the western part of the state from the High Plains and Permian Basin to the east. Each of these regions has its own history of geological exploration and tradition. Problems arise when considering strata, such as those of the Triassic System, that cross over between these two regions. Traditionally, separate nomenclature has been adopted for many units on either side of the state because these were separate centers of investigation. Moreover, strata are, for the most part, no longer physically contiguous between these areas (owing to uplift of the Rocky Mountains), although they certainly are genetically related in many cases.

As early as the 1920s, stratigraphers began using the Colorado Plateau term Chinle Formation for that part of the Dockum Group which overlies the Santa Rosa Sandstone in eastern New Mexico (Darton, 1928; Adams, 1929; Gorman and Robeck, 1946). Despite objections to this practice (e.g. McKee *in* Reeside et al., 1957, p. 1476), on the New Mexico state geologic map of 1965 Dane and Bachman "officially" extended use of the name Chinle Formation from the Colorado Plateau country eastward into the Pecos and Canadian River valleys of New Mexico. They applied the name Chinle Formation to all Triassic strata above the Santa Rosa Sandstone (Fig. 2). Most of what had pre viously been considered part of the Dockum Group was now Chinle Formation. Kelley (1972b) continued this practice and subdivided the Chinle Formation in eastern New Mexico into several informal members (lower shale, Cuervo sandstone, upper shale). The Redonda was variously mapped as a separate formation, or included as the uppermost member of the Chinle Formation. Hence, by the 1970s the Dockum Group and its constituent formations (Tecovas and Trujillo) named in Texas were completely ignored in connection with the same Triassic strata in eastern New Mexico (Fig. 2).

In retrospect, we can now see that extension of the name Chinle into eastern New Mexico was a mistake, and that it constitutes a violation of the code of stratigraphic nomenclature. These identical strata had previously been given names just across the border in Texas—the Tecovas and Trujillo Formations. No real attempt had been made to trace the strata identified as Chinle in eastern New Mexico into Texas to determine whether or not they were physically contiguous with the Tecovas or Trujillo. Moreover, the Dockum, named in 1890, has priority over the Chinle, named in 1915. In the 1972 New Mexico Geological Society Guidebook, Z. Spiegel (1972, p. 81) summed up this dilemma stating, "due to unfortunate provincialism, Gould's terminology of Tecovas and Trujillo for the complete Triassic section in Texas was not followed in New Mexico."

Maps produced in the 1970s and early 1980s as part of the *Geologic Atlas of Texas* series, which commendably overlap the Texas/New Mexico border, indicate the Tecovas and Trujillo as extending into New Mexico and equate only the uppermost shale of the Trujillo Formation (the upper beds of Drake) with the Chinle Formation of eastern New Mexico. This solution had also been advocated by Spiegel (1972). In several unpublished open-file reports, Finch et al. (1976) and Finch and Wright (1983) reached similar conclusions and showed how the Tecovas and Trujillo of Texas correlated with the Santa Rosa and Chinle in New Mexico. The Santa Rosa Sandstone is the basal sandstone of the Tecovas Formation in Texas, and the Trujillo Sandstone of Texas is the Cuervo Sandstone Member of the Chinle Formation in eastern New Mexico. Reviewing the Chinle/Dockum problem, Chatterjee (1986) concluded that use of the name Chinle in eastern New Mexico and Texas should be suppressed, and proposed the name Cooper Member for what had formerly been the upper shale interval of the Trujillo Formation (the upper beds of Drake, shown as Chinle Formation on the *Geologic Atlas of Texas* sheets).

So, in spite of the obvious physical continuity of these strata, by the beginning of the 1980s separate stratigraphies evolved in Texas and New Mexico without regard for the priority of established names on either side of the state line, and without any serious attempt to trace named strata from one state to -the other. This practice would be analogous in paleontology to naming a new species without comparing it to similar or identical taxa, without documenting how it differs from them, and without determining if it had already been named.

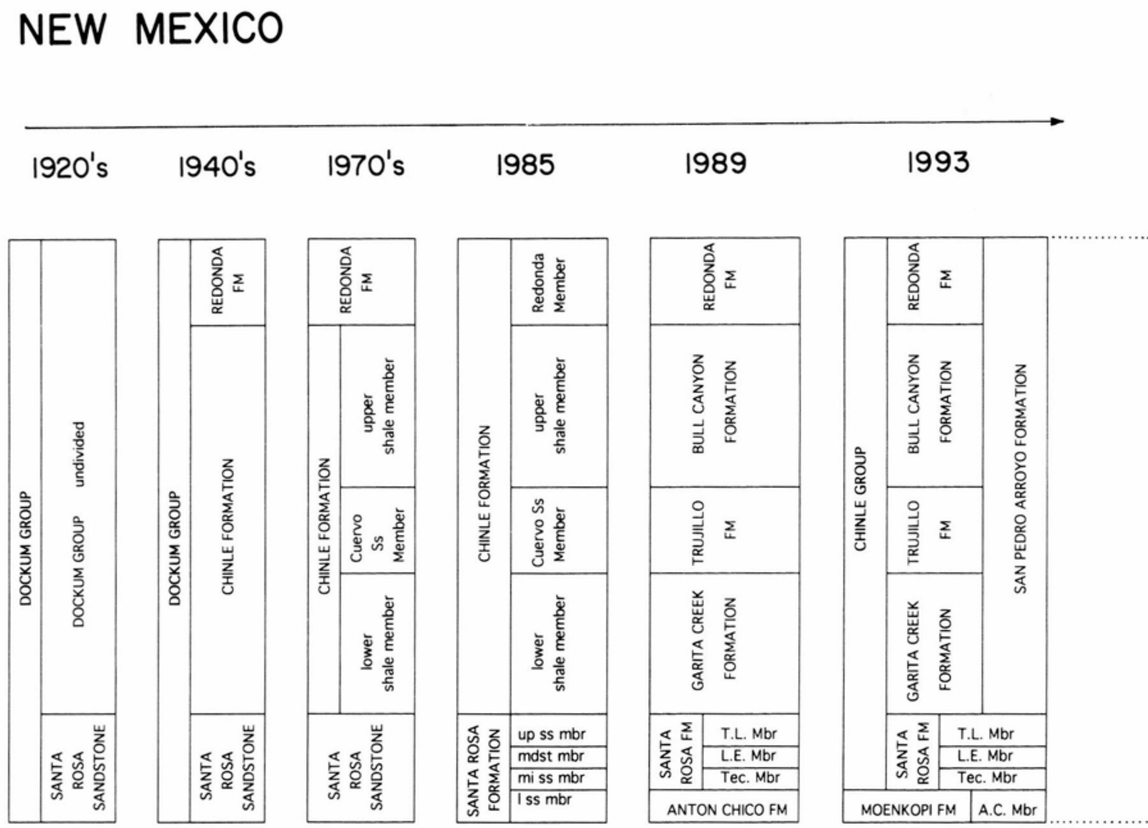


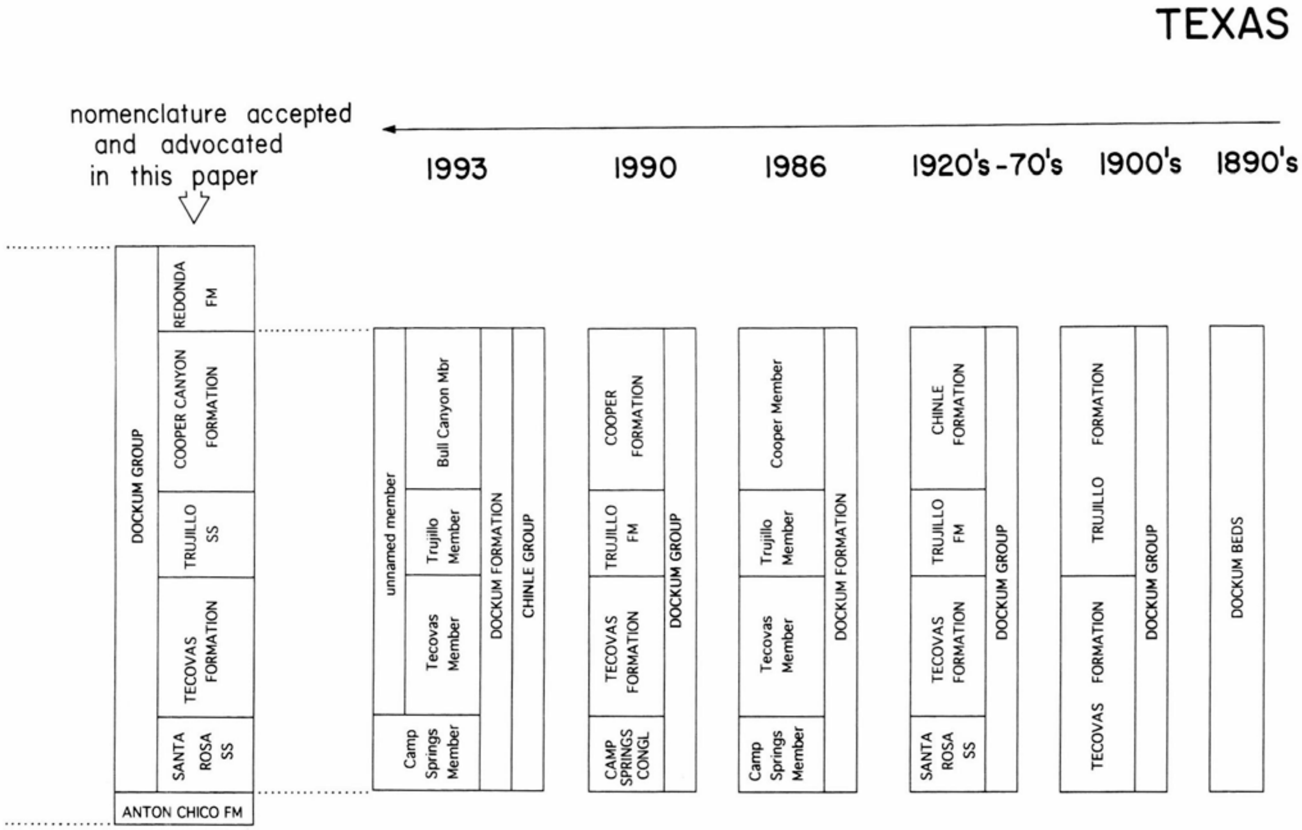
FIGURE 2—History of stratigraphic nomenclature for the Dockum Group in Texas and New Mexico showing nomenclature advocated in this paper. Sources for the stratigraphic subdivisions in New Mexico are: 1920s (Darton, 1928); 1940s (Dobrovolny and Summerson, 1946); 1970s (Kelley, 1972); 1985 (Lucas et al., 1985); 1989 (Lucas and Hunt, 1989); 1993 (Lucas and Anderson, 1992). Sources for the

The revisions of Lucas and colleagues

Beginning in the 1980s and continuing to the present, S. G. Lucas of the New Mexico Museum of Natural History & Science and various colleagues, most notably A. Hunt and 0. Anderson, have provided new names and various changing subdivisions for parts of the Dockum Group in both New Mexico and Texas. In less than 10 years, these revisions have been presented in more than 20 published papers and a like number of abstracts with various authorship arrangements (e.g. Lucas, 1991a; Lucas, 1991b; Lucas and Anderson, 1992; Lucas and Anderson, 1993; Lucas and Hayden, 1989; Lucas and Hayden, 1991; Lucas and Hunt, 1987; Lucas and Hunt, 1989; Lucas and Hunt, 1990; Lucas, Hunt, and Huber, 1990; Lucas, Hunt, and Morales, 1985; Hunt and Lucas, 1990; Hunt and Lucas, 1991a; Hunt and Lucas, 1991b; Kietzke and Lucas, 1991). Citations for these papers are given in the reference list, however in the following discussion I refer to these collectively as the works of Lucas and colleagues.

From 1985 to 1988 Lucas and colleagues generally accepted the standing division of Triassic strata in eastern New Mexico into the Santa Rosa and Chinle Formations, and the subdivisions of these strata proposed by earlier workers. Although earlier workers had avoided the issue, Lucas and colleagues explicitly rejected inclusion of these strata within the Dockum Group stating that "the term Dockum lacks specificity and refers to rocks that represent variable amounts of Triassic time" and that "the Triassic sequence in east-central New Mexico includes strata both older and younger than the Dockum Group of western Texas" (Lucas et al., 1985, p. 176). As continued justification for use of the name Chinle in eastern New Mexico, they also argued that Triassic deposits may have formerly been continuous between the Colorado Plateau and eastern New Mexico, and are thus genetically related. Neither of these reasons constitutes adequate justification for abandonment of the Dockum Group nomenclature. In fact, the North American Strati-graphic Code (1983) clearly states that "inferred time-spans, however measured, play no part in differentiating or determining the boundaries of any lithostratigraphic unit" (Article 22e). Similarly, "inferred geologic history, depositional environment, and biological sequence have no place in the definition of a lithostratigraphic unit" (Article 22d). The lithic characteristics and physical continuity of these beds outweigh all other considerations and reveal, without question, that the strata on either side of 103° W longitude are identical.

In 1989 (pp. 151-152) Lucas and Hunt reversed their earlier view and recognized that extension of the name Chinle Formation into eastern New Mexico had been a mistake all along, stating that "strata equivalent to the Chinle of the Colorado Plateau in east-central New Mexico include not just those strata previously referred to as Chinle, but the Santa Rosa Formation as well," and that "much of the Upper Triassic section in east-central New Mexico was deposited in a separate basin (or basins) than Chinle deposition to the



stratigraphic subdivisions in Texas are: 1890s (Cummins, 1890); 1900s (Gould, 1906); 1920s–1970s (Adams, 1929; *Geologic Atlas of Texas*, 1969); 1986 (Chatterjee, 1986); 1990 (Hunt and Lucas, 1990); 1993 (Lucas and Anderson, 1993). Abbreviations for local subdivisions of the Santa Rosa Sandstone in New Mexico are: Tec. = Tecolotito Member, L.E. = Los Esteros Member, T.L. = Tres Lagunas Member.

west." They now (as Chatterjee did in 1986) explicitly reject use of the term Chinle in eastern New Mexico. In spite of this, Lucas and Hunt (1989, p. 152) again refused to recognize these strata as part of the Dockum Group, stating that "Dockum is not a particularly precise or useful stratigraphic term." They were, however, compelled to accept one of the Dockum's constituent formations, the Trujillo Formation (as mapped by the *Geologic Atlas of Texas* and advocated by Chatterjee), as valid and equivalent to Kelley's Cuervo Sandstone Member of the Chinle in eastern New Mexico. Inexplicably, however, they did not recognize the equivalence of the overlying and underlying shale sections. This set the stage for the provision of new names of their own design for each of the units. In 1989, again without mapping or tracing the strata into Texas, or seriously investigating the Dockum type area, Lucas and Hunt named strata equivalent to the Tecovas Formation the Garita Creek Formation in New Mexico (Fig. 2). Further, they named strata equivalent to Chatterjee's Cooper Formation in Texas the Bull Canyon Formation in New Mexico.

Lucas and Hunt (1987) also assigned formal names to all of the informal local subdivisions of the Santa Rosa Sandstone that had been recognized earlier by Gorman and Robeck (1946) and Kelley (1972a). They separated out the lowermost sandstone unit of the Santa Rosa Sandstone as the Anton Chico Formation and redefined the remainder as the Santa Rosa Formation with several formal members (Tecolotito, Los Esteros, and Tres Lagunas Members: Fig. 2). Map distribution beyond a square mile of the type section was not included. However, Lucas and Hunt (1989) demoted the Anton Chico to member status within the Moenkopi Formation, extending use of this name from the Colorado Plateau into eastern New Mexico, a practice they strictly rejected in case of the Chinle in the same paper.

Coming full circle in 1992, Lucas and Anderson again return all Triassic strata in eastern New Mexico above the Anton Chico (member of the Moenkopi Formation) to the Chinle, now elevated to group rank (Fig. 2). The Santa Rosa, Garita Creek, Trujillo, Bull Canyon, and Redonda Formations are now contained within the Chinle Group. Hence, the net effect of their revisions has been to elevate most units in rank and give formal names to those previously recognized informally. Lucas (1991a) and Lucas and Anderson (1992) also propose another name, the San Pedro Arroyo Formation, to include the entire Chinle Group in eastern New Mexico above the Santa Rosa Sandstone where these strata cannot otherwise be locally subdivided (Fig. 2).

Turning to Texas in 1987, Lucas and Hunt accepted the stratigraphic revision of the Dockum offered by Chatterjee, but reinstated the Dockum as a unit of group rank with all units (Tecovas, Trujillo, and Cooper) identified as formations. They also used the name Camp Springs Conglomerate (or member) for the basal quartzose conglomerate of the Tecovas Formation, recognized as the Santa Rosa Sandstone by others. In 1992, however, Lucas and Anderson again demoted

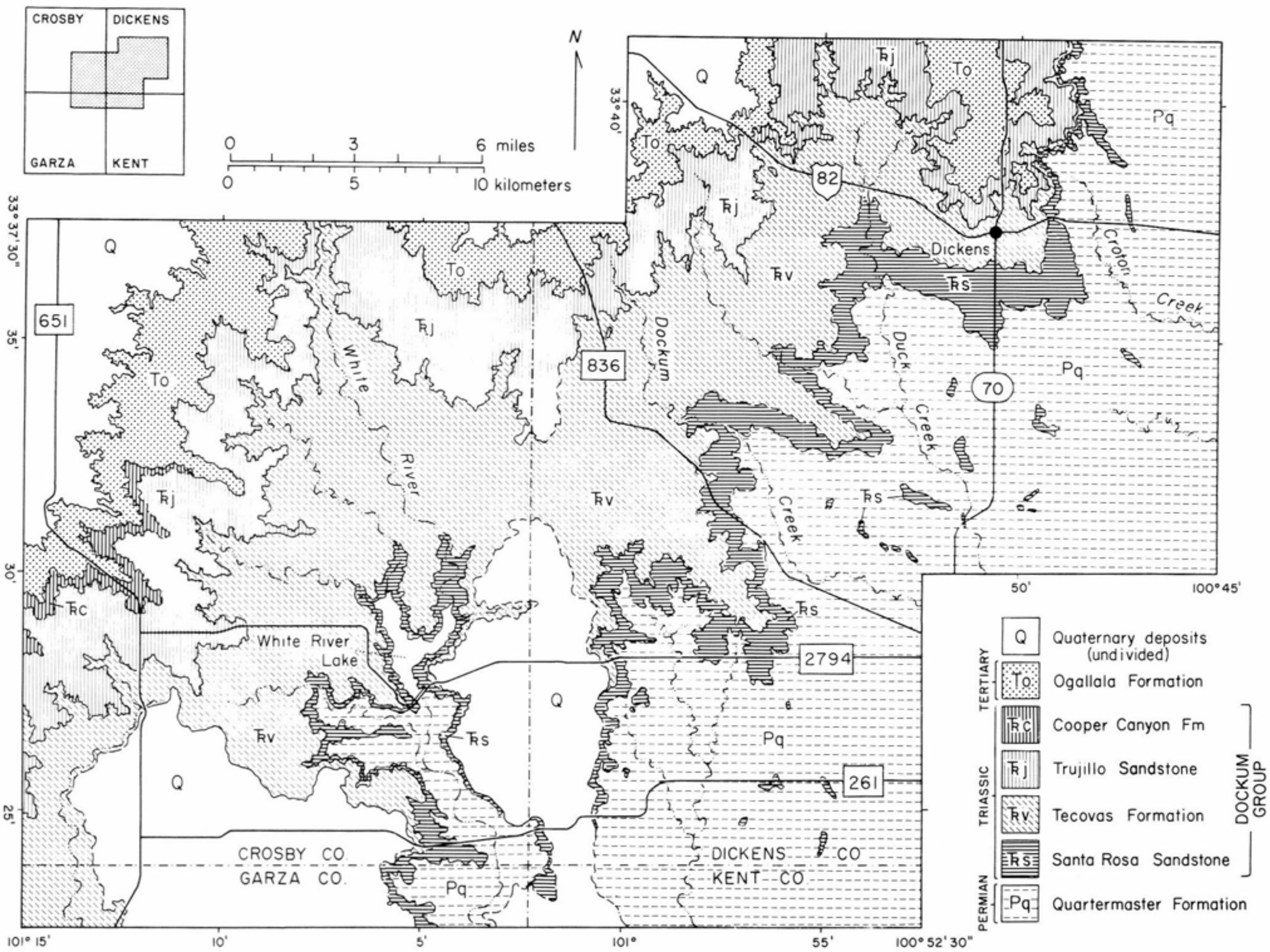


FIGURE 3—Geologic map of the Dockum Group type area in Crosby and Dickens Counties, Texas. Thin surficial covering by Quaternary alluvium, colluvium, and eolian sediment is not shown in some areas. See Figures 1 and 4 for location of this map area within the Dockum Group outcrop belt. Figure is based on mapping of 7.5 minute topographic quadrangles by T. Lehman and J. Schnable.

the Dockum to formation rank, now within the Chinle Group, extended into Texas without regard to the former rank and priority of the Dockum over Chinle. All formations have now become members again. In 1993, Lucas and Anderson abandoned the name Cooper Formation (now member again) and replaced it with Bull Canyon Formation from New Mexico (Fig. 2). The Bull Canyon now becomes a member of the Dockum Formation in Texas, but remains a formation in the Chinle Group across the border in New Mexico. Similarly, the Trujillo Sandstone of Texas remains a formation in the Chinle Group in New Mexico, but is demoted to a member of the Dockum Formation in its home state of Texas. Lucas and Anderson (1993) also contend that an as yet unnamed member of the Dockum exists: if past experience is a guide, this unit will not remain unnamed for long (Fig. 2).

It is this state of confusion that has brought about the present paper. The nomenclatural collage advocated by Lucas and collegues would be amusing were it not for the serious consideration it must be given by the geological community. Remember, in all of this the actual physical stratigraphy of the Dockum Group is not terribly confusing at all, and was for the most part worked out around the turn of the century. What has brought about this unfortunate and confusing situation? Several factors have contributed: 1) a lack of interaction or cooperation among stratigraphers working in adjoining states, 2) a lack of regard of respect for earlier generations of geologists and for the traditional courtesy accorded to other workers, 3J a lack of adherence to the code of stratigraphic nomenclature—both its letter and spirit, 4) the "naming syndrome" and achievement of stratigraphic immortality through assigning formal names to strata, and 5) the practice of assigning formal names to units recognized informally by other workers without physically tracing the strata or showing their distribution on maps (any serious attempt to show the distribution of these strata by mapping would have revealed, by physical continuity, that names had already been given to them).

I review below several specific cases which illustrate some of these problems.

The case of the Cooper Canyon Formation

When Chatterjee applied the name Cooper Member in 1986 to what had formerly been the upper shale section of the Trujillo Formation (the upper beds of Drake, or upper shale member of the Chinle Formation as it was then mapped in eastern New Mexico), this was a clear attempt to address the problem of the relationship between the Chinle and Dockum. Chatterjee explicitly stated that the Cooper Member was to include the section of predominantly red shale above the Trujillo Sandstone (in the restricted sense, as mapped in the *Geologic Atlas of Texas),* and he indicated that these strata thickened into eastern New Mexico. It was therefore inappropriate when in 1989 Lucas and Hunt applied the name Bull Canyon Formation to the same red shales above the Trujillo Formation in New Mexico. It was evident in 1989 that Lucas and Hunt were providing a name for a stratigraphic unit that already had one. They made no attempt to relate their unit to the previously named Cooper Member, which they continued to use and accept as valid in several publications and even elevated it to formation rank (e.g. Hunt and Lucas, 1990; Fig. 2). The stratigraphic code (1983, Art. 7b) states that responsibility for avoiding use of different names for the same unit rests with the proposer. Physical tracing of the strata in outcrop prior to naming would have revealed the synonymy. The name Bull Canyon Formation is a unneeded synonym of the Cooper (now Cooper Canyon) Formation.

Nevertheless, continuing investigation of the Cooper Formation revealed additional problems. The name Cooper Formation is quite similar to a number of stratigraphic names already in use in North America. For example, a survey of the recent lexicon of U.S. stratigraphic names (Swanson et al., 1981) reveals the following: Cooper Limestone, Cooper Marl, Cooper Creek Limestone, Cooper Peak Dolomite, Coopers Lake Member, and Cooper Arroyo Sandstone Member. Was the name Cooper Formation preoccupied? Strictly speaking, no; the lithologic modifier was different. The lexicon reveals many stratigraphic names that differ only in minor ways, such as the geographic or lithologic modifier (see below). However, to reduce similarity to other names, an additional geographic modifier was provided, hence the revision to Cooper Canyon Formation (Lehman et al., 1992). Does this revision constitute a violation of the code? No. Article 7(c) of the stratigraphic code allows for modification of a name as long as the need is explained. Moreover, it was discovered that the Cooper Canyon Formation was much thicker in its type area than originally recognized by Chatterjee. As it was clearly Chatterjee's intent (1986, p. 142), and the published view of Lucas and colleagues (e.g. Hunt and Lucas, 1990), that the entire section of red shale above the Trujillo be included in the Cooper, the type section was lengthened to include this entire section. Does this revision violate the code? No. The stratigraphic code indicates that redescription of a unit and revision of its boundaries are preferable to abandonment (Articles 7c, 19a).

Lucas and colleagues have nevertheless seized upon this revision to suggest that the name Cooper (now Cooper Canyon) Formation, a name with priority which they had previously accepted as valid, should now be rejected in favor of the name Bull Canyon Formation, clearly a junior synonym. They state (Lucas and Anderson, 1993, p. 60) that the Cooper Formation was "ill-defined and improperly named." This is analogous to the situation in paleontology where, because of a minor perceived violation of the code of zoological nomenclature, an established name with priority is abandoned in favor of a new name, one conveniently supplied by the revisionist (e.g. the case of *"Rioarribasaurus"—a.k.a. Coelophysis;* see Hunt and Lucas, 1991a; Dodson, 1993).

Superseding these legalistic arguments, however, it should be remembered that there is a spirit as well in the code of stratigraphic nomenclature. We should respect that spirit. Chatterjee's *intent* was clear. Regardless of minor problems with his original proposal of the Cooper Formation, the spirit of the code is respected by fixing those problems, not by throwing priority away and substituting a new name.

The case of the Camp Springs conglomerate

Viewed in light of the debate over the Cooper Canyon Formation, the case of the Camp Springs conglomerate seems even more inexplicable. Various workers had used the name Camp Springs conglomerate informally for the basal sandstone of the Tecovas Formation in Texas—the same unit that Darton had named the Santa Rosa Sandstone in New Mexico. The name Camp Springs conglomerate had been informally proposed by Beede and Christner (1926, p. 16) for "the basal member of the Triassic" in west Texas. Lucas and colleagues adopted use of this term and continued this practice in Texas, despite the fact that no thickness had ever been given for this unit, no section (let alone type section) had ever been measured of this unit, its distribution had never been shown on a map, and (in their interpretation) it was clearly equivalent to the Santa Rosa Sandstone. The case for synonymy of the Camp Springs conglomerate (in the restricted sense advocated by Lucas and colleagues) with the Santa Rosa Sandstone is clear. Physical tracing through the Canadian River valley from New Mexico into Texas and southward along the Caprock Escarpment dearly reveals that they are the same unit.

The Texas Water Development Board, as well as many subsurface geologists and hydrologists, had long ago extended use of the term Santa Rosa Sandstone into Texas, where it is thoroughly ingrained in the literature and has long been in use for the so-called "lower Dockum aquifer" or "Santa Rosa aquifer" (e.g. Shamburger, 1967). In 1987 (p. 29), Lucas and Hunt frowned upon this practice, stating that "most uses of the term Santa Rosa in southeastern New Mexico and western Texas" are incorrect, and that workers have applied this term to what is actually the Trujillo Sandstone. More recently, however, Lucas and Anderson (1992) reversed this view and extended use of the term Santa Rosa at least into southeastern New Mexico.

Nevertheless, miscorrelation of the Santa Rosa and Trujillo does occur. Confusion arises from the fact that, in many areas, erosion prior to deposition of the Trujillo Sandstone removed much or all of the intervening Tecovas Formation, and the Trujillo Sandstone rests on the Santa Rosa Sandstone or directly on underlying Permian strata. This is particularly true in the southern part of the High Plains region and, unfortunately, in the probable "type" area for the Camp

Springs conglomerate (Fig. 4). In this area the Trujillo Sandstone rests alternately either directly on Permian strata, on a markedly thinned section of the Tecovas Formation which itself overlies lenticular "remnants" of the Santa Rosa Sandstone, or directly upon remaining lenses of the Santa Rosa Sandstone (Fig. 4).

The sandstone exposed at the community of Camp Springs, and to the west and south, is (as stated by Lehman, 1992, and shown by mapping here in Fig. 4) equivalent to the Trujillo Sandstone; sandstone beds exposed to the north and east of Camp Springs are outlying remnants of the Santa Rosa Sandstone (Fig.

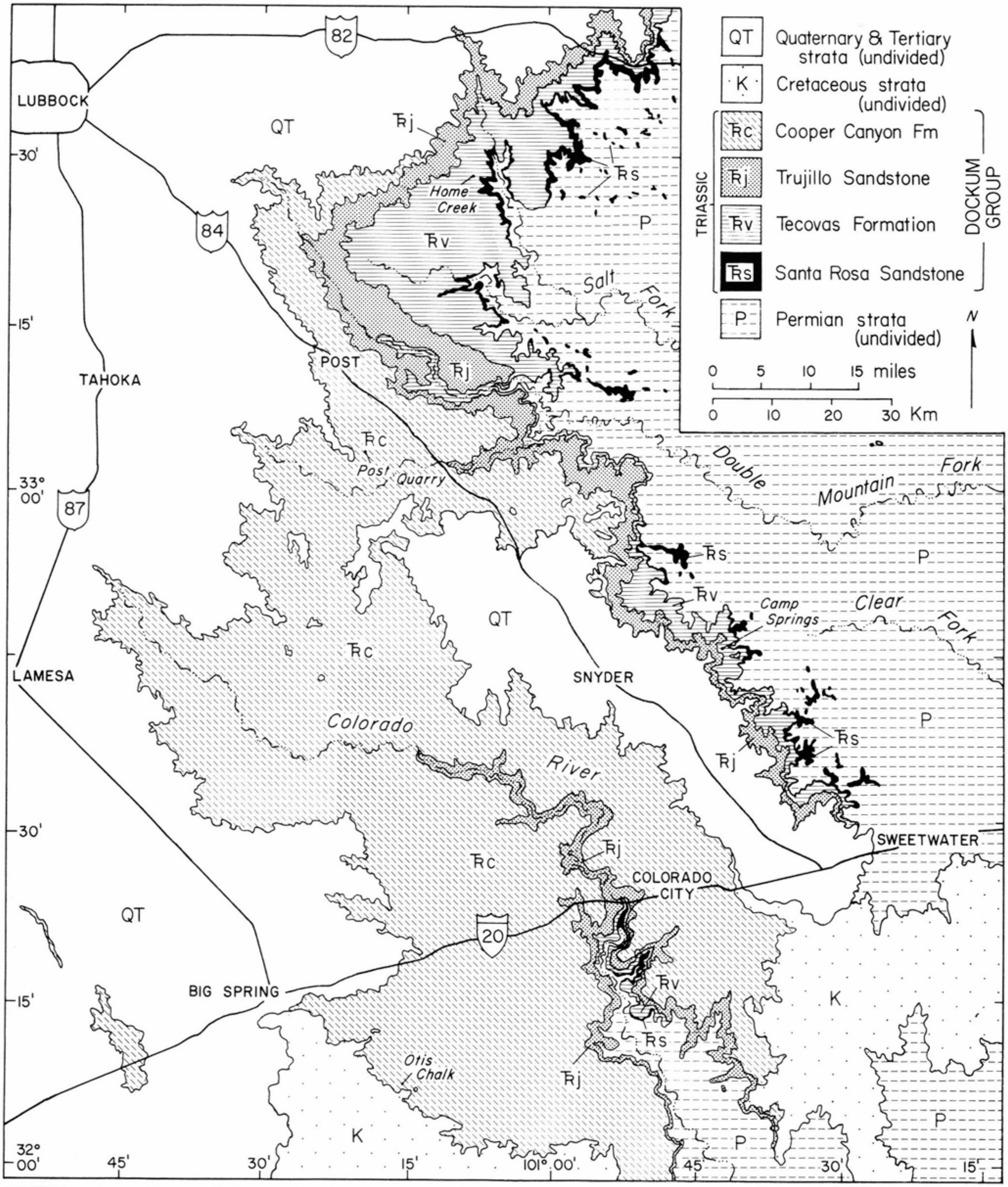


FIGURE 4—Generalized geologic map showing exposures of the Dockum Group in the upper Brazos and Colorado River valleys, Texas. See Figure 1 for location of this map area within the Dockum Group outcrop belt. The type area of the Dockum Group is at the northern edge of this map (detail shown in Figure 3). The locations of several important exposures discussed in the text are shown (e.g. Camp Springs, Otis Chalk). Areas of thin surficial covering by Quaternary alluvium, colluvium, and eolian sediment, and some exposures of Cretaceous strata are not shown. Figure is based in part on mapping of undivided Dockum Group exposures shown on *Geologic Atlas of Texas* Lubbock and Big Spring sheets (scale: 1:250,000), and on topographic base maps by T. Lehman, C. Bunting, and D. Mabbitt.

should not strata on both sides of the fence have the same names?

The solution is clear. The name Dockum Group should be retained as valid for much of the Triassic strata east of the Rocky Mountains, and the Chinle Formation (or group) should be retained for the equivalent strata west of the front range. This arrangement preserves tradition in both regions without forcing the issue of priority. What of the outlying exposures between these two regions? That problem must be addressed arbitrarily by those involved with actually mapping the intervening areas, as it is in many similar cases. The solution is not to assign new names in these areas (e.g. the San Pedro Arroyo Formation advocated by Lucas and colleagues), but to choose one of the existing stratigraphic nomenclatures that best fits the area.

Are Triassic strata of the Colorado Plateau and High Plains genetically related? Perhaps yes, perhaps no. It does not matter. Were strata ever completely contiguous between the two areas? It does not matter. They are not now, and we may never know. Moreover, the code of stratigraphic nomenclature (Article 22d) explicitly states that lithostratigraphic units must be based on lithic characteristics and are independent of inferred geologic history.

The letter and spirit of the code

As its purpose, formal stratigraphic nomenclature seeks to clarify the relationships among strata to facilitate mapping and ease of communication. While excusable in the past, it is critically important today to fully explore and map the extent of a stratigraphic unit prior to proposing a formal name for it. It may already have a name. Formal nomenclature should not be used to provide a name for every bed, to emphasize subtle regional facies variations, or conjectured age relationships based on biostratigraphy. Moreover, in a revision of stratigraphic nomenclature it is preferable to respect the spirit and intent of previous workers, and to preserve tradition and continuity with the older literature. Hence, there is a spirit as well as a letter to the stratigraphic code. The code is not a law book, it is a set of guidelines proposed to avoid problems like those examined above. These are not merely problems of semantics, but of ethical behavior and respect. The stratigraphic code allows for endless legalistic harangue, but hopes to enforce respect where it does not already exist. Where egos collide, the code provides a means of independent review to evaluate specific contentions. Such an evaluation may have little effect, however, if stratigraphers map their own states, without crossing the fence to see what is on the other side.

Several examples illustrate how the spirit of the code should be respected in addition to its letter. The lexicon of North American stratigraphic names is replete with formal names that differ by only a few letters, a geographic modifier, or a lithologic modifier. This does not necessarily invalidate any of them. For example, there is a Tecolote Member of the Santa Rosa Island Formation (Quaternary) in California. Could this be confused with Lucas and colleague's Tecolotito Member of the Santa Rosa Formation (Triassic) in New Mexico? Similarly, there is a Gartra Formation in the Chinle Group of Arizona. Can this be confused with Lucas and Hunt's (1989) Garita Creek Formation in the Chinle Group of New Mexico? The lexicon also reveals the following names, all very similar to the Bull Canyon Formation: Bull Formation, Bullion Canyon Formation, Bull Creek Limestone, Bull Fork Formation, Bull Hill Member, Bull Lake Till, Bull Ridge Member, Bull Run Shale, Bully Creek Formation, and Bullion Creek Formation. Similarity of the names Bull Canyon Formation and Bullion Canyon Formation, or Cooper Formation and Cooper Marl is not important. Obviously, the purpose of requiring different names is to avoid confusion, not to split hairs.

Does an inaccurate measurement of the thickness of a unit in its type area invalidate the name? No. For example, Lucas and Hunt (1987) reported the thickness of their Los Esteros Member of the Santa Rosa Sandstone in its type area as 9.4 m. The section was measured on the upstream side of the dam at Santa Rosa Lake. However, their section does not include strata below the normal level of the lake. The actual thickness of the type section should be 15.5 m (e.g. Fritz, 1991). Similarly, the thickness of the type section of the Anton Chico Formation, given by Lucas and colleagues as 22 m, should be 42 m. Does this justify abandonment of these names, as Lucas and colleagues have suggested in case of the Cooper Canyon Formation? No. Later workers may simply correct inaccuracies.

The names Bull Canyon Formation and Garita Creek Formation were formally proposed in a largely unrefereed in-house publication of the New Mexico Museum of Natural History distributed as a guidebook to participants of a field trip. Does this constitute valid publication according to the code (Article 4a, b)? Perhaps not. Similarly, Lucas and colleagues' designation of a lectostratotype section for the Camp Springs conglomerate was published in transactions distributed to the participants at a section meeting. Does this constitute valid publication according to the code? Perhaps not.

Strictly speaking, the present restriction of the names Trujillo Sandstone and Santa Rosa Sandstone to some part of their former definition is a violation of the code (Article 19g). Most would agree, however, that these are "good" violations, reflecting more natural stratigraphic breaks as well as recent practice. Should we follow the letter of the code and reinstate the Santa Rosa and Trujillo Formations with their former boundaries? No, such a revision would generate even more confusion than already exists.

Similarly, recognition of the Dockum Group as a valid unit with priority over the Chinle would suggest (in contrast to Lucas and colleagues' notion that virtually all Late Triassic strata in North America be subordinated within the Chinle Group) that the Chinle be subordinated as a formation within the Dockum Group. Should this be done? No. Such a revision, though perhaps adhering to the letter of the code, certainly would violate the tradition and respect due to several generations of venerated geologists. The outcry of Colorado Plateau stratigraphers would most certainly be heard in Texas.

4). There is little stratigraphic break between these sandstone beds. The name Camp Springs conglomerate (or member) should most assuredly be abandoned for the following reasons: 1) Beede and Christner never specifically indicated what part of this section was to be identified as the Camp Springs, 2) they did not indicate how this unit was related to previously named formations in the Dockum Group, 3) they did not give a thickness, 4) they did not measure a section or show the unit on a map, and 5) the name was not used for several decades. Clearly the Camp Springs conglomerate does not meet the requirements for a formal stratigraphic unit. The condensed stratigraphic section in the "type" area spans virtually all of the Dockum Group. Even if Lucas and colleagues have correctly isolated Beede and Christner's intent to refer only to the lowermost unit exposed in the "type" area, the name Santa Rosa Sandstone has clear priority for this unit. There remains no justification for retaining the name Camp Springs conglomerate. In the restricted sense advocated by Lucas and colleagues it is lithologically and genetically part of the Santa Rosa Sandstone and can be physically traced in outcrop and subsurface into the Santa Rosa type area.

Hence, in the case of the Camp Springs conglomerate (or member), Lucas and colleagues have attempted to preserve a name that was never defined, never measured, and never shown on a map, in favor of a name with overwhelming tradition and priority (the Santa Rosa Sandstone). This contrasts with the Cooper Canyon Formation, a unit with clear priority that was defined, measured (if inaccurately), and shown on a map, which is being abandoned in favor of its junior synonym, the Bull Canyon Formation.

The case of the Otis Chalk problem

Over much of the southern part of the High Plains region, the lower part of the Dockum Group (Santa Rosa and Tecovas) was markedly thinned and in many areas removed by erosion prior to deposition of the Trujillo Sandstone (Fig. 4). Hence, in these areas the Trujillo Sandstone rests on or close to underlying Permian strata, and the entire overlying section belongs to the Cooper Canyon Formation. Failure to recognize this has led to many problems of correlation, such as the mistaken identification of the Trujillo Sandstone with the Santa Rosa, as noted above. Such problems persist to this day.

In the southern part of the High Plains region, Lucas and Anderson (1992) mistakenly identified the entire basal-sandstone interval of the Dockum as the Santa Rosa Sandstone (on the New Mexico side) or its synonym, the Camp Springs conglomerate (on the Texas side). Based on this misidentification and the observation that there is no major persistent sandstone interval stratigraphically higher in the overlying section of dominantly red shale (where the Trujillo Sandstone "should" be), Lucas and Anderson (1992, 1993) concluded that two new names are necessary for these strata—the San Pedro Arroyo Formation (on the New Mexico side) and the "unnamed member" of the Dockum (on the Texas side, Fig. 2).

Lucas and colleagues' correlation is based in part or entirely on biostratigraphic grounds and reflects their belief that the red-shale section overlying the basal-sandstone series must be equivalent to the Tecovas Formation (Hunt and Lucas, 1990; Lucas and Anderson, 1993). Several well known vertebrate fossil localities occur high in this section of predominantly red shale near the community of Otis Chalk (Fig. 4). Although there is disagreement regarding the age of the fauna from these localities (e.g. Murray, 1989), Lucas and colleagues believe that the fauna is temporally equivalent to that of the Santa Rosa and Tecovas. They have based their lithostratigraphic nomenclature on this assumption. However, the basal-sandstone interval of the Dockum in this region is a condensed section with the Trujillo Sandstone resting directly on, or just above, the Santa Rosa Sandstone (Fig. 4). In some areas the Trujillo Sandstone is the basal sandstone and no Santa Rosa is present. The red-shale section is the Cooper Canyon Formation. This can readily be shown by physical tracing in outcrop southward from the type area of the Cooper Canyon Formation (Fig. 4), and it is supported by the marked contrast in lithology and paleocurrent orientation between the Santa Rosa and Trujillo (Lehman, 1992). Regardless of their fossil vertebrate fauna, the Otis Chalk localities are within the Cooper Canyon Formation and at least 60 m above the top of the Trujillo Sandstone. There is no justification for use of the names San Pedro Arroyo Formation in southeastern New Mexico or for the "unnamed member" in Texas. These strata already have a name—the Cooper Canyon Formation. The Otis Chalk "problem" illustrates a case of confusing biostratigraphy with lithostratigraphy.

The fate of the Dockum Group

Early in their revisionist work, Lucas and colleagues rejected the validity of the Dockum Group, going so far as to say that only the Trujillo Sandstone was present in the type area of the Dockum Group on Dockum Creek. This is not true. Recent mapping reveals that the section in the type area of the Dockum Group is quite complete, with all units except the Redonda Formation present (Fig. 3). Lucas and colleagues also originally rejected use of the term Chinle Formation in eastern New Mexico, whereas in more recent versions they have accepted the validity of both the Dockum and Chinle, but with the Dockum subordinated as a formation within the Chinle Group. This in spite of the fact that the name Dockum Group is valid and has clear priority over Chinle "Group."

The fortuitous location of the type area of the Trujillo Sandstone on Trujillo Creek, straddling the Texas/New Mexico state line, forces the issue (Fig. 1). We can thank Gould for his foresight in choosing such a location. If, as generally agreed, the Trujillo Sandstone can readily be correlated around exposures in both Texas and New Mexico, cannot the shale section above (the Cooper Canyon Formation) and the shale section below (the Tecovas Formation) likewise be traced? The answer is, of course they can. Similarly, if the Santa Rosa Sandstone can be easily correlated from the Pecos River valley into the Canadian River valley in New Mexico, why not a few more miles into Texas? The answer is, it can. Given this recognition, These examples illustrate that in many cases upholding the spirit of the code is as important as upholding its letter. Often the more important question is not what is "legal," but what is the *right* thing to do. More valuable than strict adherence to the letter of the law is the question of what is ethical. What accords respect to the intentions, if not the words, of earlier workers? What preserves uniformity and tradition in a region?

A revision of stratigraphic terminology should do its best to repair and refine existing nomenclature, even if in its original form it falls short of one's perception of perfection. A revision should not search for legalistic loopholes needed to discard older established names in order to substitute names of one's own design.

Recommendations

I recommend that most of the revisions in the stratigraphic nomenclature of the Dockum Group offered by Lucas and colleagues be rejected because they violate both the spirit and letter of the stratigraphic code, as well as the intentions of previous workers. None of their revisions have been accompanied by mapping areas of more than a square mile or so around the type sections, and thus do not satisfy Article 12 of the code. In this paper the following stratigraphic conclusions are supported: 1) the Dockum Group has a clear priority over the Chinle Group (Article 7c), 2) the Tecovas Formation has a clear priority over the Garita Creek Formation, 3) revision of the Cooper Canyon Formation is allowed by the code and this name has priority over the Bull Canyon Formation, 4) the Santa Rosa Sandstone has priority over the Camp Springs conglomerate, and 5) the Anton Chico Formation should be recognized as separate from the Santa Rosa Sandstone, and should not be considered a member of the Moenkopi Formation for the same reason why the Dockum should not be considered part of the Chinle.

The simple stratigraphic nomenclature advocated here respects the priority of established names and tradition. It also returns to a more accurate picture of Texas/New Mexico Triassic stratigraphy true to the intent of stratigraphers at the turn of the century, perhaps before state boundaries became so marked. This simple nomenclature emphasizes the fact that these strata are common to both states. The type areas for two of the formations are in Texas (Tecovas and Cooper Canyon), two are in New Mexico (Santa Rosa and Redonda), and one (Trujillo) straddles the state boundary (Fig. 1).

The practice of naming strata should be every bit as exacting and rigorous as that of naming new species. Paleontologists should enlist the help of practicing stratigraphers to delineate and map the units for which they wish to provide formal names. Revisions of stratigraphic nomenclature should not be taken lightly and should be fully justified with supporting maps. A stratigraphic unit must be demonstrably different from previously named strata with which it is physically contiguous if it is to receive a new formal name.

Acknowledgments

This paper constitutes a rallying cry to save the Dockum Group from its untimely end. Having grown up, been educated, and spent much of my adult life in New Mexico and now teaching across the border in Texas, I am in a unique position to evaluate the condition of the Texas/New Mexico boundary "fault." The observations presented in this paper were developed during supervision of graduate-student research on the Dockum Group at Texas Tech University. Several of these students are now employed as professional geologists and educators in New Mexico. I thank Andrew Frelier, Brent and Susan May, Teri Fritz, John Schnable, Craig Bunting, and Derald Mabbitt.

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Postscript-What's in a name?

In their reponse to my critique of their work, Lucas et al. (this volume) acknowledge that the physical continuity and lithologic similarity of Triassic strata on either side of the Texas/New Mexico state line are not disputed. What remains debatable is the nomenclature that should be applied to these strata, and whether or not separate names are needed in Texas and New Mexico. The purpose of my critique has been to review this nomenclatural problem and to justify my choice of available formal names for use in the ongoing mapping program in west Texas. I have not proposed any new formal names, nor have I demonstrated any new or unusual stratigraphic correlations. I have simply argued that what we call these strata is important, and that the priority of previously established names should be respected.

Simply put, Lucas et al. (this volume) argue that 14 formal names are needed to describe these strata. In a period of five years they have proposed 10 new formal names for stratigraphic units previously recognized informally by earlier workers and have changed the name or rank of the remaining units. In contrast, I contend that the stratigraphic relationships of these units were largely deciphered by earlier workers, and that only six previously proposed formal names are necessary to describe them. Although Lucas et al. (this volume) suggest that **I** have applied a "double standard" in deciding which names should be accepted, in reality I have applied a single, simple standard—in each case only the name with priority is accepted for each unit. I also suggest, in accordance with the Code of Stratigraphic Nomenclature, that these formal names should be based on lithologic criteria and not on inferred biostratigraphic correlation or on subtle, unspecified depositional facies changes. Lucas et al. (this volume) suggest that I do not understand the procedure involved in applying formal names to strata, that mapping is not required when applying formal names to strata, and that I offer no new data. Arguments regarding interpretation of the Code of Stratigraphic Nomenclature are marginal to the real issues of this debate and illustrate the legalistic harangue that ensues when the letter of the code is used in defense of the proliferation of formal stratigraphic names. Moreover, the weight of superficial data amassed in more than 20 of their publications does not make the nomenclature they propose correct. Lucas et al. (this volume) have failed to respond adequately to the following questions.

1) Is the Dockum Group a valid stratigraphic unit with priority over the Chinle Group? Although Lucas et al. (this volume) quote extensively from Cummins' original 1890 paper on the Dockum beds, they ignore the much more thorough account published by Cummins' assistant Drake in 1892. Drake clearly traced the Dockum Group entirely around the High Plains of Texas and New Mexico. In the course of circumambulating the High Plains, Drake studied all of the major exposures of Triassic strata recognized today and measured sections in the Colorado River valley, along the Caprock Escarpment, through the Canadian River valley to Tucumcari Mountain, and southward along the Pecos River valley in New Mexico from Fort Sumner to Eddy, and from there to Pecos, Texas. It is significant that Lucas et al. (this volume) have chosen to largely ignore this important paper. I implore interested stratigraphers to read Drake's landmark paper of 1892, and the later detailed accounts of the Dockum Group in the Canadian River valley by Gould (1907) and Patton (1923). These papers, as well as mapping provided in the *Geologic Atlas of Texas* published in the 1970s and early 1980s, clearly document the extent and continuity of the Dockum Group in both Texas and New Mexico, and leave no question that the Dockum Group as originally conceived and subsequently mapped encompasses all of these Triassic strata. The *Geologic Atlas of Texas* Tucumcari Sheet (1983) is particularly instructive in this regard, and accurately depicts the extension of both the Tecovas and Trujillo Formations as part of the Dockum Group into New Mexico (contra Lucas and others). Lucas et al. (this volume) have ignored this important map. The most recent geologic map of Texas (Barnes, 1992) also retains the Dockum Group as a valid unit (contra Lucas and others). Lucas et al. (this volume) remark that my suggested subdivisions of the Dockum Group were not adopted in this recent map of Texas. This is not surprising, since I have only now reviewed this nomenclatural problem. Moreover, the nomenclature advocated by Lucas et al. (this volume) has not been adopted, and, given the scale of recent mapping, the Dockum Group is largely shown undivided. In summary, the name Dockum Group is clearly valid, used in all recent mapping, well established in the literature through use over more than a century, and must be given priority over the Chinle Group of Lucas and others. Lucas et al. (this volume) have not satisfactorily demonstrated otherwise.

2) Is the Camp Springs conglomerate lithologically different from the Santa Rosa Sandstone? The units are physically contiguous with one another and occupy the same stratigraphic position in the base of the Dockum Group. Both units are composed of a lower quartzose fluvial sandstone with chert-pebble conglomerate, and locally an upper, lenticular quartzose deltaic sandstone that intertongues with the overlying Tecovas Formation. The Camp Springs conglomerate is thinner, more lenticular, and in places more conglomeratic than the Santa Rosa Sandstone in its type area. Do the thickness difference and "facies change" justify the use of different names for this unit on either side of the state line? No. Continental sandstone units such as the Santa Rosa Sandstone commonly exhibit such subtle thickness and fades changes. Lucas et al. (this volume) have not demonstrated why two names are necessary for this unit.

3) Is the Garita Creek Formation lithologically different from the Tecovas Formation? The units occupy the same stratigraphic position and are physically contiguous with one another. Both units are composed predominantly of shale. Both units have a lower variegated lacustrine shale interval that intertongues with the underlying Santa Rosa Sandstone, and an upper red fluvial shale interval unconformably overlain by the Trujillo Sandstone (as first documented by Gould, 1907). In Texas much of the upper red shale interval was removed by erosion prior to deposition of the Trujillo Sandstone, and thus the Tecovas Formation is thinner there. In northeastern New Mexico the upper red shale interval escaped pre-Trujillo erosion in most areas, and is therefore thicker. Do the the thickness change and "facies change" justify the use of different names on either side of the state line? No. In fact, this is not a facies change at all, but a result of partial erosional truncation. Lucas et al. (this volume) have not demonstrated why two names are necessary for this unit. Lucas and others have applied the names San Pedro Arroyo Formation and Iatan Member to sections composed predominantly of red shale, which they believe to be broadly equivalent to some part of the Tecovas Formation. They have not demonstrated the stratigraphic position of these units relative to the Tecovas and Trujillo Formations, nor have they shown how these strata differ *lithologically* from the Tecovas or Cooper Canyon Formations. I contend that neither of these names is necessary.

There is no debate regarding the physical continuity and lithologic characteristics of the Trujillo Sandstone, Cooper Canyon Formation, and Redonda Formation in New Mexico and Texas. Rather the debate concerns only what these units should be called.

The Otis Chalk problem revisited

The only significant (non-nomenclatural) issue raised in my critique involves the equivalence of Dockum

Group strata exposed in the Colorado River valley of Howard and Mitchell Counties, Texas. I contend that these strata are lithologically identical to, and physically contiguous with, the Santa Rosa, Tecovas, Trujillo, and Cooper Canyon Formations exposed a few miles to the north and east across the drainage divide in the Brazos River valley. I have illustrated the distribution of these strata by mapping (Fig. 4). In contrast, Lucas et al. (this volume) contend (without mapping or demonstrating the relationships between these units and those exposed to the northeast) that yet another name, the latan Member, is required for these strata, and, furthermore, that only the lowermost part of the Dockum Group (Santa Rosa through Tecovas) is exposed in the Howard/Mitchell County area. The resolution of this issue is very important, and it is critical to the biostratigraphic zonation of Triassic strata advocated by Lucas et al. (this volume).

Simply put, the correlation of strata in the Howard/Mitchell County area suggested by Lucas et al. (this volume) is geometrically impossible. Construction of a simple cross section illustrates this (Fig. 5). As mapped by myself (Fig. 4) and Lucas et al. (this volume, fig. 4), the Santa Rosa, Tecovas, and Trujillo Formations all are readily recognized in exposures along the east side of the drainage divide between the Brazos and Colorado Rivers, for example, near the community of Camp Springs (Fig. 5). The stratigraphic relationships in this area are not disputed. In the Camp Springs area, the top of the Santa Rosa Sandstone lies at an elevation of approximately 2200 ft, and the top of the Trujillo Sandstone lies at an elevation of approximately 2300 ft. These strata dip less tha 1° to the .southwest, beneath the drainage divide and into the subsurface of the Midland Basin. All three units are exposed again in the canyon of the Colorado River about 20 mi to the southwest, at a slightly lower elevation in accordance with the regional dip of these strata, and maintaining the same stratigraphic relationships observed farther to the northeast (Figs. 4, 5). The lowermost sandstone, resting directly on underlying Permian strata and exposed at an elevation of approximately 2050 ft in the canyon of the Colorado River, is a quartzarenite with chert-pebble conglomcerate—the Santa Rosa Sandstone. Overlying this sandstone is a thin interval of variegated gray, purple, and red shale—the Tecovas Formation. Resting on this shale is the spectacular cliff-forming sandstone of the Colorado River canyon. This sandstone is a highly micaceous litharenite with conglomerate composed of reworked sedimentary-rock fragments. This sandstone is lithologically identical to, and physically contiguous with, the Trujillo Sandstone as mapped in areas to the north and east. Readily accessible exposures of the Trujillo Sandstone may be observed along the canyon of the Colorado River and its tributaries, for example on Bull Creek downstream from Lake J. B. Thomas, along the bluffs south of the town of Colorado City, and on Morgan Creek at Lake Colorado City. Lucas et al. (this volume) have failed to demonstrate why this unit is not the Trujillo Sandstone. The extensive exposures of red, slope-forming shale to the west and east of the Colorado River are demonstrably *above* the Trujillo Sandstone and physically contiguous with the type section of the Cooper Canyon Formation farther north (Fig. 4). Throughout this region and elsewhere the Cooper Canyon Formation contains isolated discontinuous sandstone beds that are lithologically similar to those of the underlying Trujillo Sandstone.

The correlation of the Howard/Mitchell County area suggested by Lucas et al. (this volume), but not substantiated by mapping, would require that the Trujillo Sandstone *rises* more than 200 ft in elevation to the

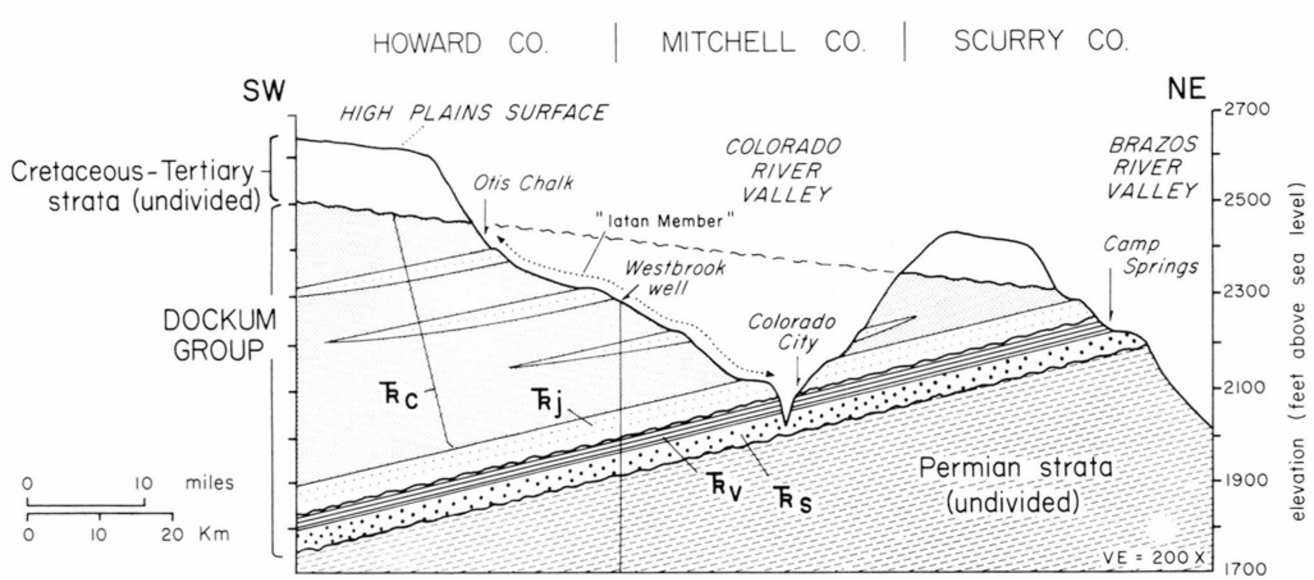

FIGURE 5—Geologic cross section showing the subsurface distribution of Triassic strata in Howard, Mitchell, and Scurry Counties, Texas. This section contrasts the interpretation of Dockum Group stratigraphy advocated in this paper with that of Lucas et al. (this volume). The line of section runs from the vicinity of Camp Springs in Scurry County to Colorado City in Mitchell County, and from there to the vicinity of Otis Chalk in Howard County (see Figure 4 for location of section). The position of the Westbrook well site in western Mitchell County (Lucas et al., their figure 5) is shown, as is the surface section described as the Iatan Member by Lucas et al. (this volume). Subdivisions of the Dockum Group are the Santa Rosa Sandstone (TRs), Tecovas Formation (TRv), Trujillo Sandstone (TRj), and Cooper Canyon Formation (TRc).

southwest, in opposition to the regional dip of Triassic strata, in order for it to rest *above* the Iatan/Otis Chalk section. Given the position of undisputed exposures of the Trujillo Sandstone east of the Colorado/ Brazos drainage divide, the correlation proposed by Lucas et al. (this volume) would also require a dramatic dip reversal in overlying Triassic strata, erosional truncation of almost 200 m of Triassic strata, and exposures of the Trujillo Sandstone to occur at high elevations along the headwaters of the Colorado River—none of which are observed. Even if the Triassic strata were perfectly horizontal (a physical impossibility given the westward decline in elevation of the Permian/Triassic contact), the Iatan/Otis Chalk area would remain above the level of the Trujillo Sandstone, as documented in undisputed exposures to the northeast.

Furthermore, the geophysical log from a well drilled near the town of Westbrook in Mitchell County, illustrated by Lucas et al. (this volume, fig. 5), also depicts stratigraphic relationships that are completely incompatible with their interpretation. Lucas et al. (this volume) state that this well log "allows clear recognition" of the entire Santa Rosa through Trujillo interval. The well site is situated *on the outcrop* of their Iatan Member, yet strata that they identify as the Trujillo Sandstone are encountered 300 ft below the surface, at an elevation of 1900 to 2000 ft in this boring (Fig. 5). This requires that all strata above 2000 ft are younger than the Trujillo Sandstone. Their type section of the Iatan Member runs from a surface elevation of about 2000 ft up to 2500 ft, and thus includes only beds that are demonstrably *above* the level of the Trujillo Sandstone encountered in the boring. Strata in the boring that Lucas et al. (this volume, fig. 5) identify as the Iatan Member are encountered at an elevation of 1500 to 1700 ft. Given the undisturbed, gentle southwest dip of these strata, beds encountered at 1500 to 1700 ft in the boring (which they "clearly recognize" as the Iatan Member) should not crop out anywhere west of the Colorado River! Nowhere in Mitchell County does the surface elevation drop below 1900 ft. The well log is, however, quite compatible with my mapping of this region and with the cross section shown here (Figs. 4, 5).

Lucas et al. (this volume) regard my mapping of the type area of the Dockum Group farther north as correct, and a "useful contribution." However, my map of the Howard/Mitchell County area is regarded as "erroneous" and "clearly wrong." This is unusual in view of the fact that all units were physically traced in exposure southward from the type area and the same criteria were utilized consistently in identification of each stratigraphic unit. Simply to state that this mapping is incorrect does not suffice. It is incumbent upon Lucas and others to demonstrate by mapping *how* this map is inaccurate and to show the southern extent of the Trujillo and Cooper Canyon Formations in this area, as well as their relationships to the Iatan Member. Furthermore, if my mapping of this region is upheld, it demonstrates that the Triassic tetrapod biostratigraphy proposed by Lucas et al. (this volume) is untenable. Localities such as those near Otis Chalk, which bear a vertebrate fauna considered to be primitive ("Otischalkian") by Lucas et al. (this volume), actually occur stratigraphically *above* localities that yield a fauna they consider to be much younger ("Revueltian"), such as the Post Quarry. This suggests that the ranges of many of these tetrapod taxa actually overlap and thus do not have the biochronological significance accorded them by Lucas et al. (this volume).

Finally, although Lucas et al. (this volume) are apparently unconcerned about the priority of established names, I am compelled to point out that the name "Iatan Member" is preoccupied by the Iatan Limestone, a unit variously included as a member of the Stranger Formation or as a formation in the Douglas Group of Iowa, Kansas, and Missouri, and in use since 1899 (Swanson et al., 1981).


all-white on adobe

Exploration potential of the Diablo Platform—Delaware Basin margin, Trans-Pecos Texas

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Abstract—Additional gas reserves remain to be discovered in the western Delaware Basin. Preliminary results of an integrated geophysical and geological study of a part of the Delaware Basin–Diablo Platform margin document a number of potential gas plays within that basin. The study area straddles the Reeves–Jeff Davis county line along the Davis Mountain front in Trans-Pecos Texas, long an area of structural conjecture.

Modern interactive reprocessing of inexpensive, older 2-D seismic data offers an economic reconnaissance tool to focus future exploration efforts. Such reprocessing techniques applied to early 1970s-vintage group shoot data from the Delaware Basin have dramatically improved the seismic image, aiding subsequent geological interpretation. Reprocessed "off-the-shelf" seismic data clearly delineate a regional, northwest-trending, high-angle reverse fault (approximately 2500 ft of throw) forming the boundary between the western flank of the Delaware Basin and the eastern edge of the Diablo Platform. This fault, mapped for more than 40 mi, appears similar in style and magnitude of throw to faults penetrated in wells along both the northwestern margin (Huapache monocline) and the eastern margin (Central Basin Platform) of the Delaware Basin. Seismic stratigraphic interpretation of the reprocessed profile suggests several possible structural and stratigraphic trapping mechanisms. Depositional patterns indicate that the hinge line of the Diablo Platform has been periodically active since Early Ordovician time. At least one fault may have been active prior to deposition of the Devonian Woodford Shale, although most displacement is post-Mississippian.

Possible gas plays along the western margin of the Delaware Basin include:
1) sand "thicks" in the Delaware Mountain Group, comparable to Casey Draw (Bell Canyon) field;
2) Wolfcampian carbonate-debris flows similar to those producing in the Midland Basin, developed over the upthrown blocks;
3) Bone Spring, Wolfcampian, and Pennsylvanian biogenic (crinoidal) carbonate mounds developed on the crests of upthrown fault blocks;
4) Wolfcampian stratigraphic pinch-out traps developed in multiple tongues of elastic detritus shed from the hanging wall of the Diablo Platform margin fault;
5) Devonian Thirtyone Formation erosional truncation traps developed along the flanks of up-tothe-basin fault blocks;
6) lower Paleozoic structural traps in large anticlines (more than 500 ft of closure) developed in front of the platform boundary fault; and
7) lower Paleozoic structural–stratigraphic traps on counterregional up-to-the-basin fault blocks.

Introduction

The Permian Basin of west Texas and southeastern New Mexico is one of the most prolific hydrocarbon-producing provinces in the world, having a cumulative production of 25.3 billion barrels of oil and 14.9 trillion cubic feet of proved gas reserves as of 1985 (Tyler and Banta, 1989). During the last 10 years low prices for oil and gas have led to a reduction in exploratory drilling activity in the Permian Basin. Reserve growth from existing reservoirs has recently accounted for 97% of the additions to hydrocarbon reserves in west Texas (Holtz and Beike, 1991). Although future basinwide reserve growth is anticipated to come principally from previously discovered reservoirs, a large part of the basin is relatively poorly explored and offers great potential for discovery of additional gas reserves. In particular, the pre-Permian strata of the southwestern Delaware Basin, a sub-basin in the western part of the Permian Basin, contain very little proven oil and gas production, have sparse well control and seismic data, and are relatively unexplored. The purpose of this paper is to review the depositional and tectonic history of the pre-Permian strata of the southwestern Delaware Basin and to identify exploration targets in one of the least explored parts of the Permian Basin.

This paper presents preliminary results from an ongoing project of the Bureau of Economic Geology, The University of Texas at Austin, and the Department of Geology, The University of Texas of the Permian Basin. The purpose of the larger study is to investigate the syntectonic depositional and thermal history of the lower and middle Paleozoic strata of the Tobosa Basin of Galley (1958) and those of its late Paleozoic successor, the Delaware Basin, formed during the collision of the Marathon—Ouachita terrane with North America.

One of the primary objectives of this paper is to demonstrate that older "off-the-shelf" 2-D seismic tapes can be reprocessed to display features of potential economic interest at a cost within reach of the independent operators in the Permian Basin. Reprocessing has improved the migrated product sufficiently to allow (1) determination of structural style through accurate fault profiling and (2) delineation of syntectonic sequence-stratigraphic boundaries. Such results will aid the petroleum industry by directly demonstrating the cost-effective use of older 2-D data in modern seismic stratigraphic interpretation and by highlighting the utility of this inexpensive reconnaissance tool for accurately locating exploration leads that need more detailed 3-D surveys.

Another purpose of this paper is to reconstruct the structural and depositional history of the Diablo Platform margin, with the goal of identifying potential exploration plays. Integrating this local history with soon-to-be-completed studies in other portions of the basin will help us better understand the genesis of the entire Delaware Basin and locate its undiscovered hydrocarbon reserves.

Location

The study area, 60 mi long and 30 mi wide, straddles the southwestern margin of the Delaware Basin (Fig. 1). The southeastern limit lies 10 mi northwest of the northeast-trending Glass Mountains (Fig. 2). Physiographically, that area includes the northeastern flanks of several generally northwest-trending mountain ranges and a pediment extending eastward into the Toyah Basin of the southern Great Plains. The ranges include the Barilla, Davis, and Apache Mountains. The Barilla and Davis Mountains are primarily composed of Teritary rhyolitic ash-flow tuffs that were extruded between 32 and 38 m.y.a. (Henry et al., 1986). The Apache Mountains have exposures of Cretaceous and Upper Permian strata (DeFord, 1951).

In the study area, Cenozoic Basin and Range structures overprint the tectonic framework inherited from the Permian (Horak, 1975). The Barilla, Davis, and Apache Mountains are the easternmost uplifts of the Basin and Range province. To the north, the north-trending Delaware Mountains, Rustler Hills, and Guadalupe Mountains form the continuation of the eastern limit of the Basin and Range province. The more northwestward trend of the Barrilla, Davis, and Apache Mountains continues on the west side of the Salt Flat Graben as the alignment of the Sierra Diablo and several isolated Tertiary stocks that together form

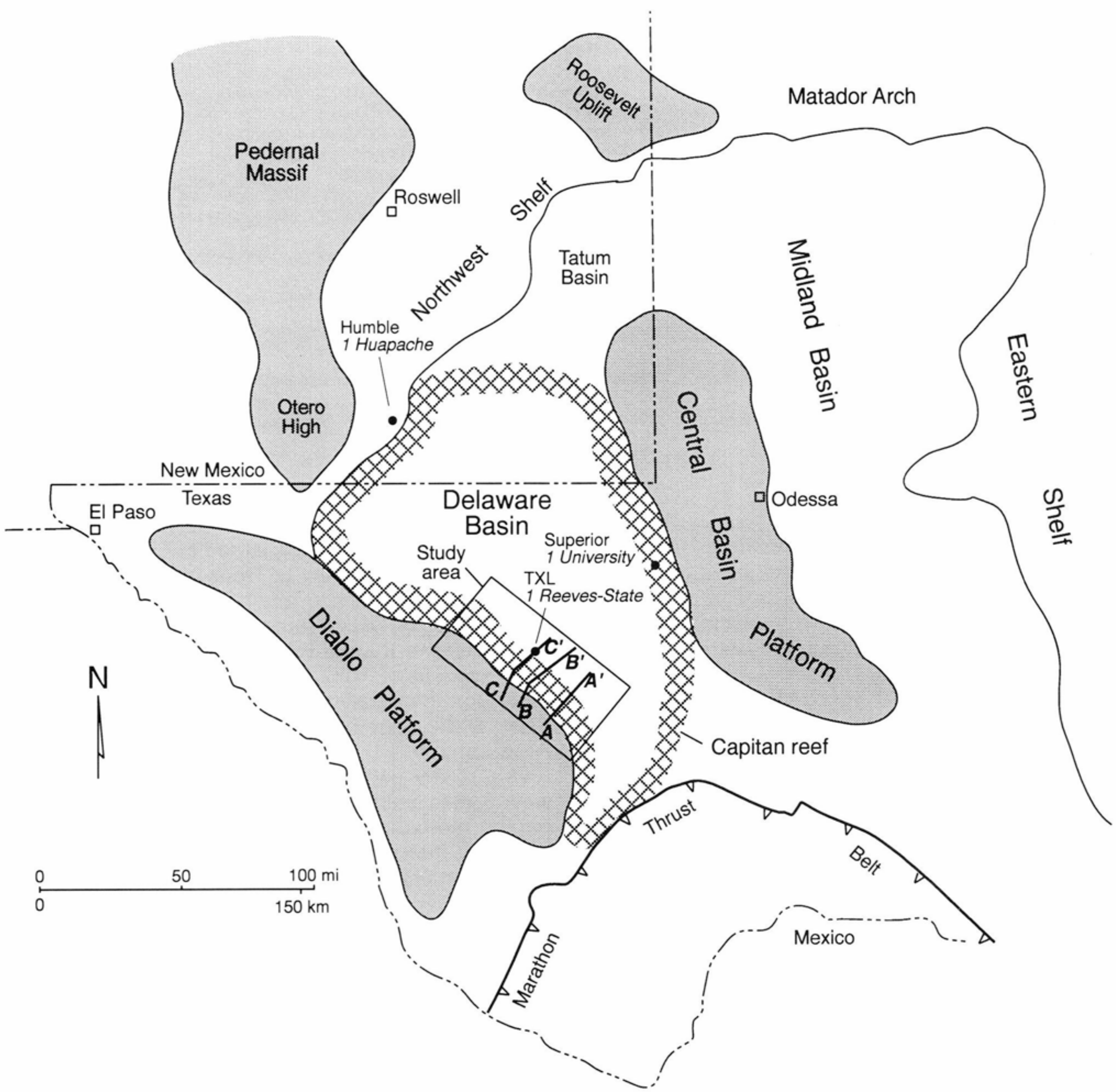

FIGURE 1—Index map to study area and major structural features of Pennsylvanian and Permian age in west Texas and southeastern New Mexico.

the northeastern flank of the Diablo Plateau (Fig. 2). The Diablo Plateau (less commonly the Sierra Diablo Plateau) is a heavily dissected, flat-topped physiographic upland covering approximately 2500 mi[l] (Richardson, 1904, 1909). It includes the Sierra Diablo, Hueco Mountains, Finlay Mountains, Sierra Blanca, Sierra Tinaja Pinta, Cornudas Mountains, Black Mountains, and Cerro Diablo (Richardson, 1909). No lower Paleozoic strata are exposed in the study area; the nearest exposures occur in the central and western ranges of the Diablo Plateau (King, 1965; Lucia, 1971).

Previous work

The Diablo Plateau has never been considered an attractive area for oil and gas exploration. Beede (1920) discounted its economic potential because of the paucity of bituminous shales and porous reservoir strata in outcrop. During the 20 years following Beede's report, the Diablo Plateau was virtually ignored by the oil industry. As production boomed in the Per mian Basin, the Diablo Plateau was simply regarded as the nearest place to study outcrops of the producing formations.

The first published representation of a northwest-trending Western Platform bounding the Permian Basin appeared in Cannon and Cannon (1932), although they made no observations on its structure or evolution. King (1942) renamed it the Diablo Platform in a paper that was presented orally in 1938. King's Diablo Platform trends northwest to southeast, extending from eastern Jeff Davis County through southern Culberson County and the northern two-thirds of Hudspeth County. It may have connected to the north—south trending Pedernal Massif and certainly had a significant effect on sedimentation in west Texas.

Several episodes of movement characterized the long positive history of the Diablo Platform (King, 1935, 1942). Movements on several faults in the Sierra Diablo vary in age from pre-Ordovician to Cenozoic. The lower Paleozoic section thins significantly between

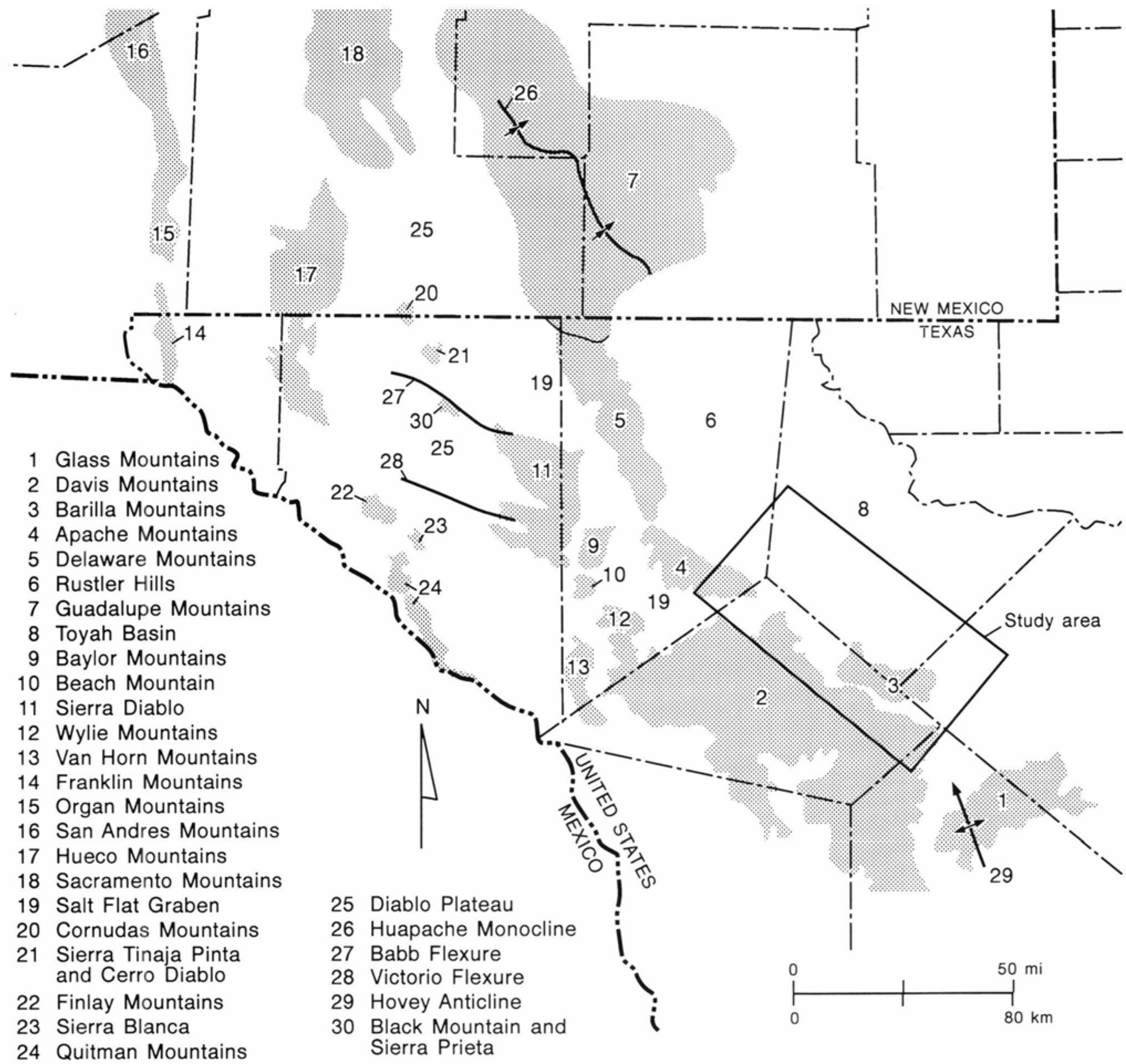

FIGURE 2—Location map of physiographic features in west Texas and southeastern New Mexico.

the Franklin Mountains and Beach Mountain, some 120 mi to the east (Lucia, 1971). Facies patterns in the Fusselman Formation suggest a shallow bathymetric high in the Sacramento—Beach Mountain area during the Early Silurian (Lucia, 1971).

The Diablo Platform was active throughout Lower and Middle Pennsylvanian time and was uplifted most strongly at the end of the Pennsylvanian (Galley, 1958). The center of uplift during this period of deformation is located near the present Sierra Diablo. Here the Precambrian was exposed by erosion before middle Wolfcampian time (King, 1965). The Babb and Victorio flexures of the Sierra Diablo are Permian in age. The Hovey anticline extends across the center of the Glass Mountains and folds Permian strata. Plunging to the northwest, it may have formed the southwestern margin of the Delaware Basin during Permian time. A well that tested the anticline northeast of Fort Davis penetrated Permian reef-facies limestones (King, 1942). The Diablo Platform was a southern extension of the Pedernal Massif (Hills, 1942) and may have connected the Pedernal Massif with the Coahuila Platform during the Permian (Shepard and Walper, 1983). The Sierra Diablo area was uplifted again before being onlapped by Lower Cretaceous strata (King, 1965).

The platform was raised yet again in Cenozoic time by block faulting. King (1942) observed that the Permian "reef zone" in the Apache Mountains is exposed along Cenozoic faults. Middle Tertiary uplifts in northern Trans-Pecos Texas and adjacent New Mexico tilted the west flank of the Delaware Basin along an ancient hinge line following a Precambrian fault zone (Hills, 1968). That fault, the western boundary fault of the Guadalupe Mountains, is carried through central Culberson County and into central Jeff Davis County, west of the location of the Diablo Platform boundary fault as drawn by other authors (e.g. King, 1942). Pearson (1985) proposed that Tertiary structures along the front of the Davis Mountains (e.g. the Hovey anticline) may not be related to Basin and Range deformation but to the buried boundary between the Permian Diablo Platform and the Delaware Basin.

Analysis of reflection seismic data

Between 1970 and 1972, Geophysical Services Incorporated (GSI) shot more than 1700 line miles of dynaseis data in the Delaware Basin for a consortium of oil and gas companies. To demonstrate that modern processing techniques can substantially increase the exploration value of older 2-D data, segments of GSI' s northeast—southwest line DBGS-114 were chosen for reprocessing. This line was selected because of its location across the Diablo Platform margin, an area of sparse seismic and subsurface control, and because several key segments of the original line were of very poor quality (Figs. 3, 4). DBGS-114 is one of relatively few seismic lines available in the western part of the Delaware Basin.

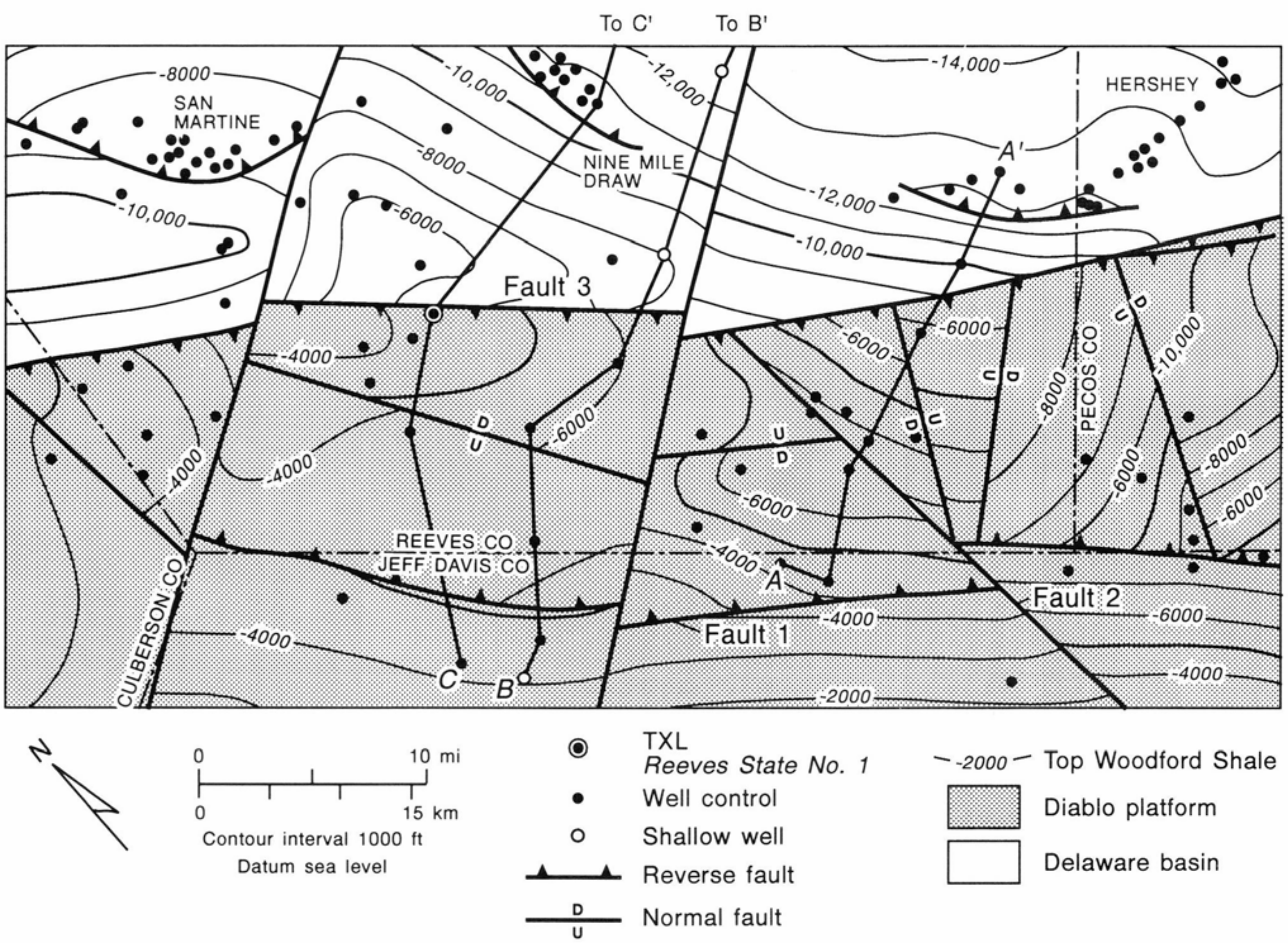

FIGURE 3—Structural map contoured on top of the Woodford Shale (scale 1:480,000).

Initial acquisition

DBGS-114 was acquired in the early spring of 1971 using a parallelogram dynaseis source array containing three elements in the inline direction and six elements in the cross-line direction. The shotpoint interval was 440 ft. A DFS seismograph recorded 24-channel, 4-millisecond data to a depth of 4 sec. Filter settings were 8-36-52 Hz, and a notch filter was set at 60 Hz. Each receiver array consisted of 54 geophones configured in the form of a nine-arm star having a diameter of 600 ft. Seismic data were shot pushing the spread, using an off-end spread geometry. The geophone group interval was 440 ft, with a near trace offset of 1980 ft. This acquisition program produced maximum 12-fold data.

Original processing

The original field tapes were processed in 1971. GSI continued working with the data for several years thereafter, improving presentation quality. Paper prints of DBGS-114 (Fig. 4) obtained for this study were processed by GSI in 1983. The general processing sequence used by GSI in 1983 is compared to the processing used in our investigation in Table 1.

TABLE 1—Comparison of processing streams: GSI, 1983 and UTPB, 1993.

Geophysical Services Inc. (1983)	UTPB - ProMAX (1993)
True Amplitude Recovery Trace Mix-2:2	F-K Filter Fan filter parameters -4500, +4500, 5, 32 True Amplitude Recovery
	Spike and Noise-Burst Edit Low and high frequency Trace Kill/Reverse
	Elevation Statics
Designature-SPC Domain Time Variant Equalization First Break Suppression	Trace Mute First Break Spiking Deconvolution Operator length 120, 150, 120 ms Bandpass filter 2-5-32-37 Hz Automatic Gain Control
	F-K Filter Fan filter parameters -4500, +4500, 5, 32
Normal Moveout Correction Automated High Frequency Statics	Residual Statics 3 passes of velocity and statics Normal Moveout Correction
	Automatic Gain Control
Common Depth Point Stack Floating datum Dip Filter F-K cut +11 and -11 ms/trace Wave Equation Migration-Dip Limited Kirchoff F-K domain 90% stacking velocities	Common Depth Point/Ensemble Stack Floating datum F-X Deconvolution L2 normative adaptive 6-32 Hz Steep-Dip FD Time Migration 5 Hz minimum, 6500 ft - 32 Hz, 27,000 ft - 27 Hz greater or equal to 90 degree dip 100% stacking velocities
Time-Variant Filter 10-30 Hz, 0.0-1.1 sec 5-20 Hz, 1.5-4.0 sec Time-Variant Equalization	

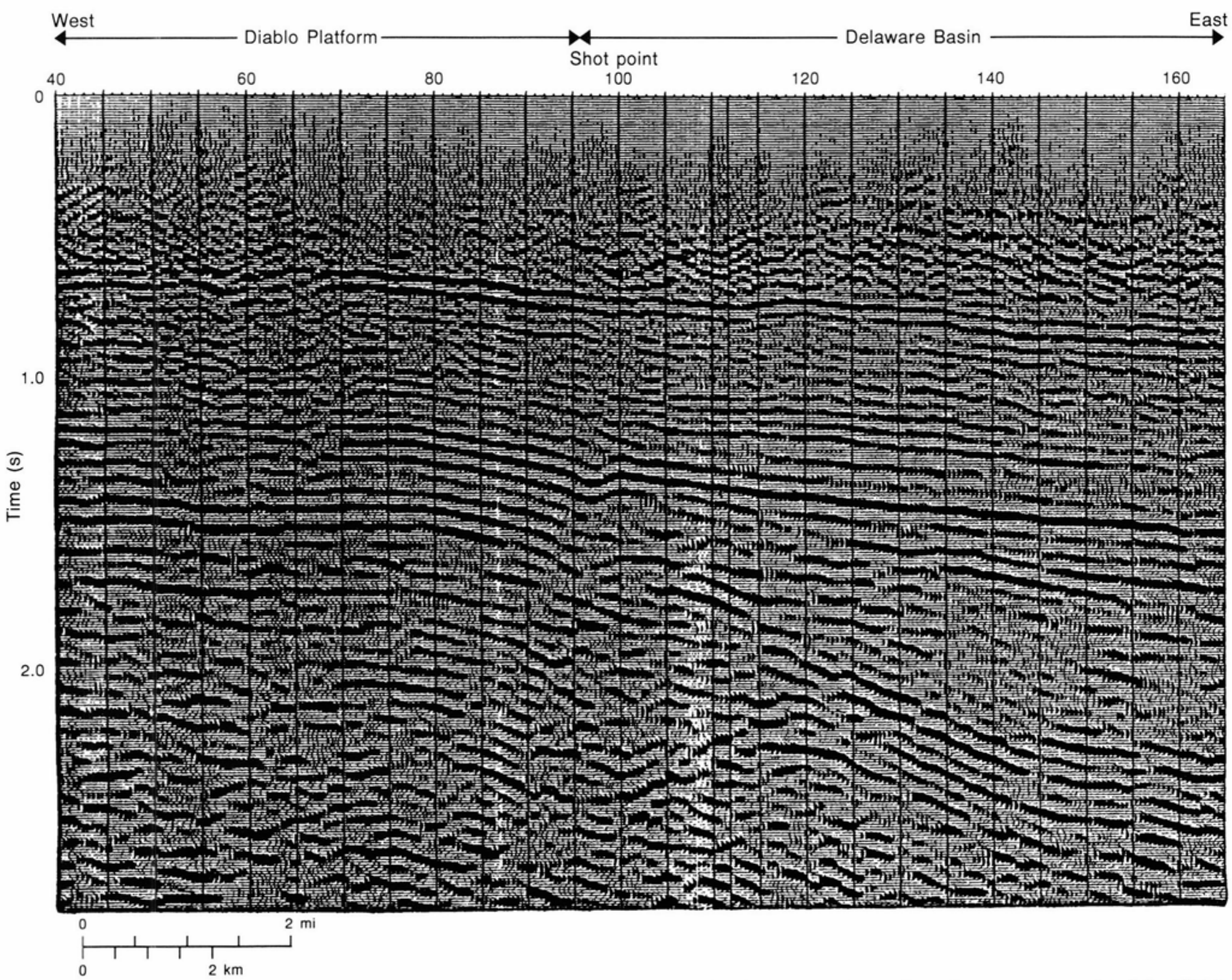

FIGURE 4—Seismic line DBGS-114, 1983-reprocessed migration. The structural and stratigraphic style at the eastern margin of the Diablo Platform near SP 97 is not imaged on the original processing. Data provided by Chevron USA.

Data quality

Several segments of the 1983 migrated version of DBGS-114 are poor to unusable. Four poor-data zones are particularly prominent. One of the most interesting segments of DBGS-114 is the westernmost end crossing the flank of the Diablo Platform, but poor data quality causes stratigraphic and structural uncertainty (Fig. 4: SP 50-70, 1.0-1.5 sec). This zone displays a major breakup in reflection continuity, possibly caused by problems with statics or velocities. A second zone of poor data lies along the Diablo Platform margin (Fig. 4: SP 95, 1.2-2.3 sec). The 1983 processing of DBGS-114 lacks the clarity necessary to locate faults and determine fault geometry previously identified along this margin (King, 1965; Hills, 1985; Pearson, 1985). As such, these data are of little use in determining the tectonic style of deformation. A similar lack of reflection clarity hides any structural complexities in the footwall east of the fault zone (Fig. 4: SP 95-110, 1.5-2.5 sec). Several events suggest reversal of dip, but this is equivocal. The fourth poor-data zone prevents using these data for seismic stratigraphy. The stratigraphic details of the syntectonic and post-tectonic sedimentary wedge on the basin margin are hidden by reflection discontinuity on the 1983 version of DBGS-114 (Fig. 4: SP 117-end of line, 1.8-2.2 sec). Unfortunately, the four poor-quality segments of DBGS-114 obscure its most prospective features.

Reprocessing

The western portion of DBGS-114 was specifically selected for reprocessing because of poor data quality. "Field" tapes, field notes, and paper prints from the 1983 processing were available. The only field tapes available to this project had already been vertically stacked by GSI, and these stacked field tapes became the inital input to the reprocessing sequence.

Much of the original processing sequence was followed during reprocessing, which allowed us to make a direct comparison between the original and the new algorithms. However, there are distinct differences between the two processing streams (Table 1). In the new processing sequence, spike and noise-burst editing were applied within the raw-shot domain to reduce both spikes and low- and high-frequency noise. Extremely noisy traces were omitted, although this was kept to a minimum because of the low fold (only 1200%). All static corrections were made to adjust to a floating datum. F—K filtering to reduce air blast, ground roll, and other coherent noise was implemented in both the raw-shot and common-midpoint (CMP) domains. Automatic gain control was applied to the data before stacking. The original processing

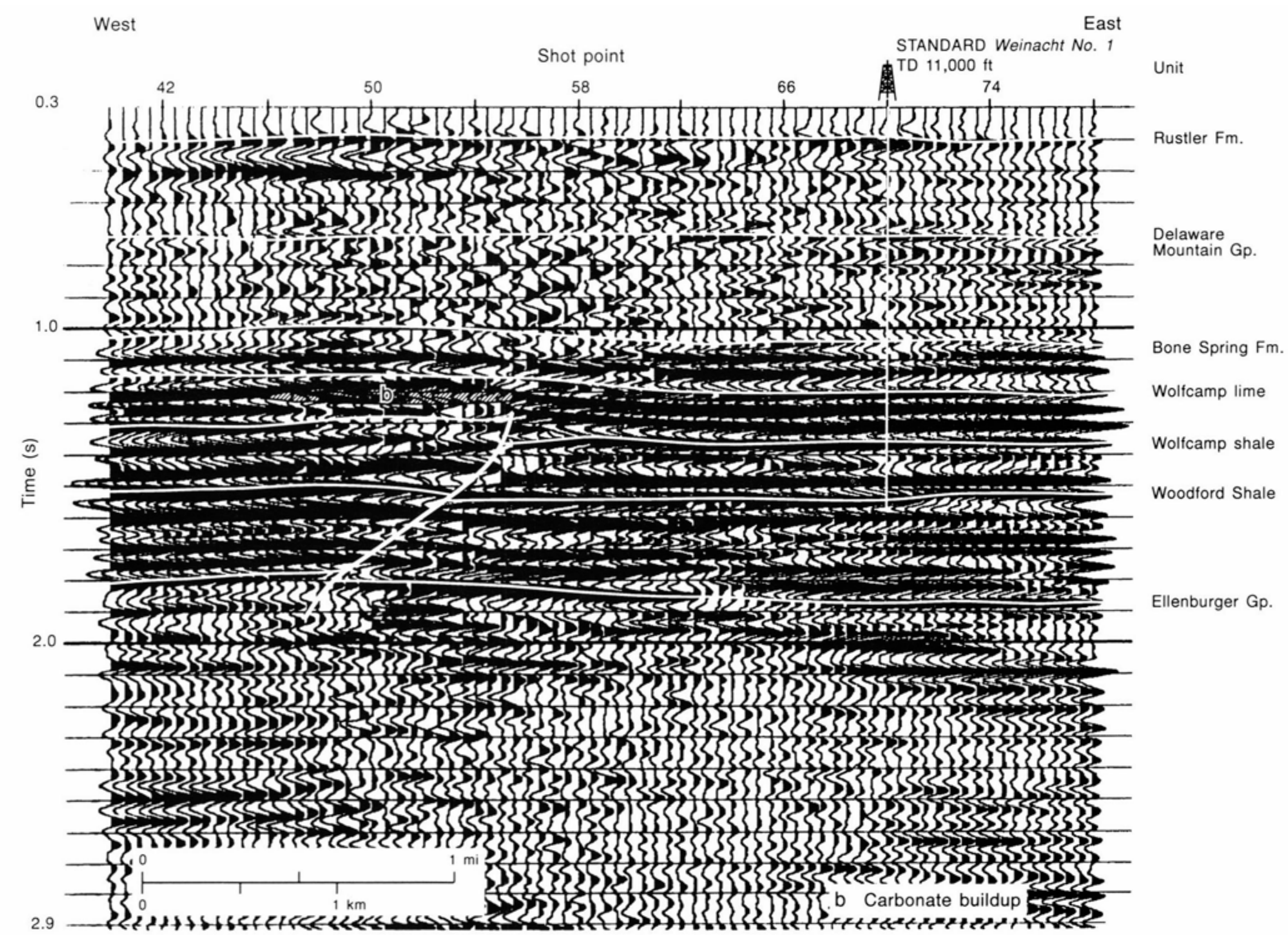

FIGURE 5—Seismic line DBGS-114, 1993-reprocessed migration, Diablo Platform. At SP 45–56 on the Diablo Platform, a slight reversal near 1.2 sec is caused by thickening between reflectors below the top of the Wolfcamp limestone. Additional reversal at depth is associated with a reverse fault. The Balmorhea (Wolfcamp) Field is 1 mi from this section of DBGS-114. Data provided by Chevron USA, processed at the University of Texas of the Permian Basin.

applied time-variant filtering and time-variant equalization after migration. In the new reprocessing sequence, F—X deconvolution was applied after stacking in order to remove any remaining random noise. Because this process was applied to an assemblage of traces, lateral amplitude variations were preserved on the stacked image by keeping the number of samples in the prediction filter to a minimum of four or five traces per assemblage.

Two other important differences in the reprocessed version involve (1) residual statics and velocities and (2) the type of migration applied. Three separate passes of velocities and statics were applied to the data. These greatly helped to enhance the horizontal continuity of the stacked data and to build the signal-to-noise ratio. The velocities were picked using an interactive velocity analysis that simultaneously displayed a CMP gather, a superstack, a semblance plot, and the current stacking velocity function for the entire line. Velocities were routinely chosen every 20 CMP or every 10 CMP if a greater variation in velocity was suspected.

Working interactively on the workstation enabled us to compare a number of operators. In the 1983 processing stream, a dip-limited Kirchoff migration operator was applied. In this study best results were obtained using a 90° approximation, steep-dip, finite-difference migration. The 90° approximation requires more computer time than lesser dip, finite-difference algorithms. However, this approximation ensures proper imaging of steep dips along the eastern margin of the Diablo Platform and dips near 30° in the Delaware Basin. The final plots of the reprocessed version are displayed at approximately 1:1 scale (Figs. 5-7).

Interpretation

Synthetic seismograms were created for three wells: Standard Oil of Texas No. 1 Weinacht, Shell No. 1215 Bush, and Sun No. 1 Terrill State. The synthetics were used to locate the tops of the Rustler Formation, Delaware Mountain Group, Bone Spring Formation, Wolfcamp limestone, Wolfcamp shale, Woodford Shale, and Ellenburger Group. Only one of these wells (Standard No. 1 Weinacht) is located on the portions of the reprocesssed line shown here (Fig. 5).

Examination of the reprocessed profile reveals detailed structural and stratigraphic features not well displayed on the original seismic section. Lateral reflection continuity has been improved on the reprocessed line (compare Fig. 4 and Fig. 5: SP 50-70, 1.0-1.5 sec). A small dip reversal at 1.2 sec from shot points 45 to 56 is caused partly by thickening below the Wolfcamp limestone marker and partly by folding associated with a reverse fault (Fig. 5). This fault has offset reflectors approximately 175 ft (assuming a velocity of 10,000 ft/sec) and may have localized subsequent carbonate thickening. Crinoid packstones that are 280 ft thick were encountered in the Exxon No. 1

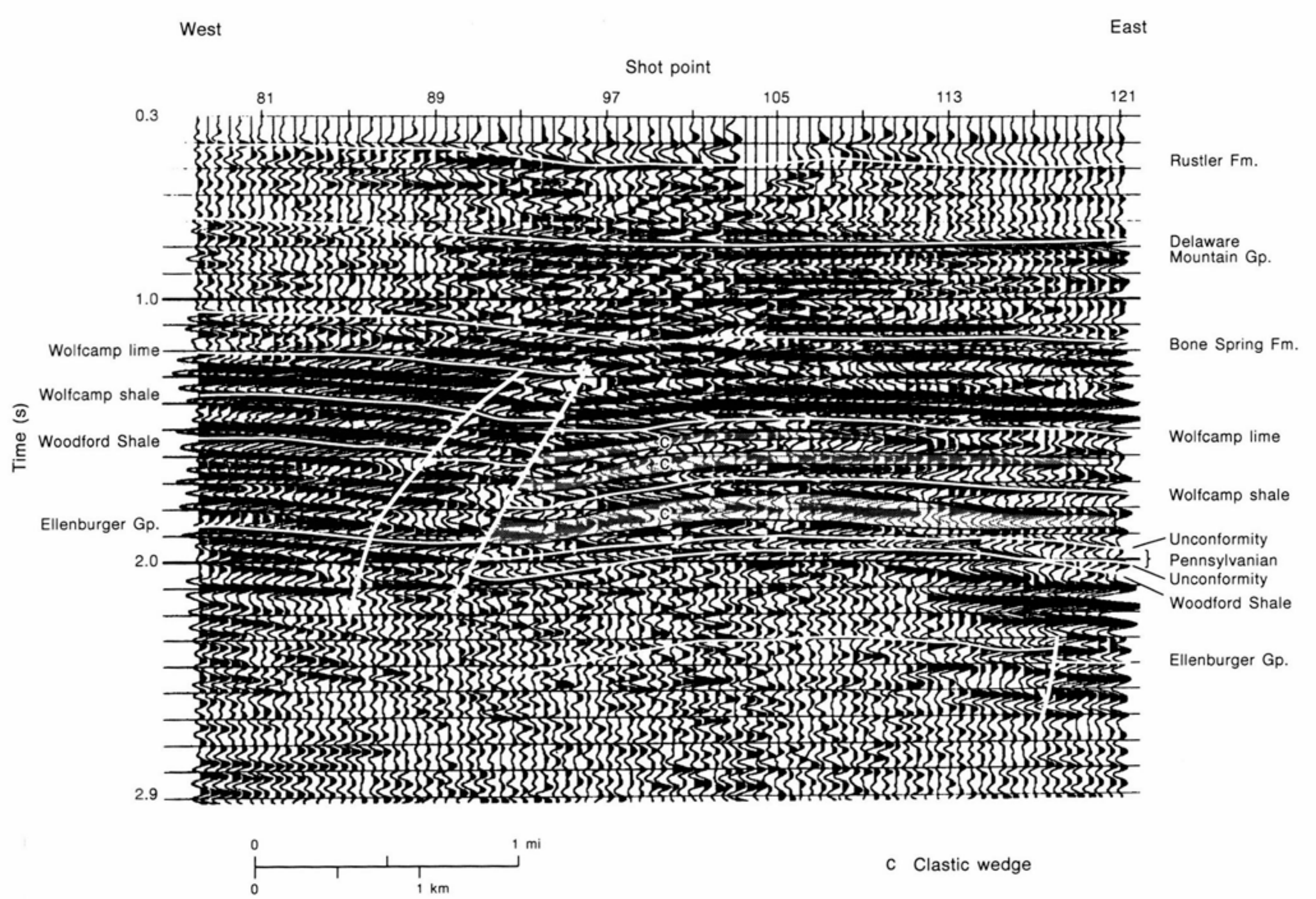

FIGURE 6—Seismic line DBGS-114, 1993-reprocessed migration, Diablo Platform boundary faults. The eastern margin of the Diablo Platform near SP 97 is bound by two reverse faults having a combined throw of at least 2500 ft at the Ellenburger level. Dip reversal in the footwall at the Woodford Shale level is approximately 500 ft. Data provided by Chevron USA, processed at the University of Texas of the Permian Basin.

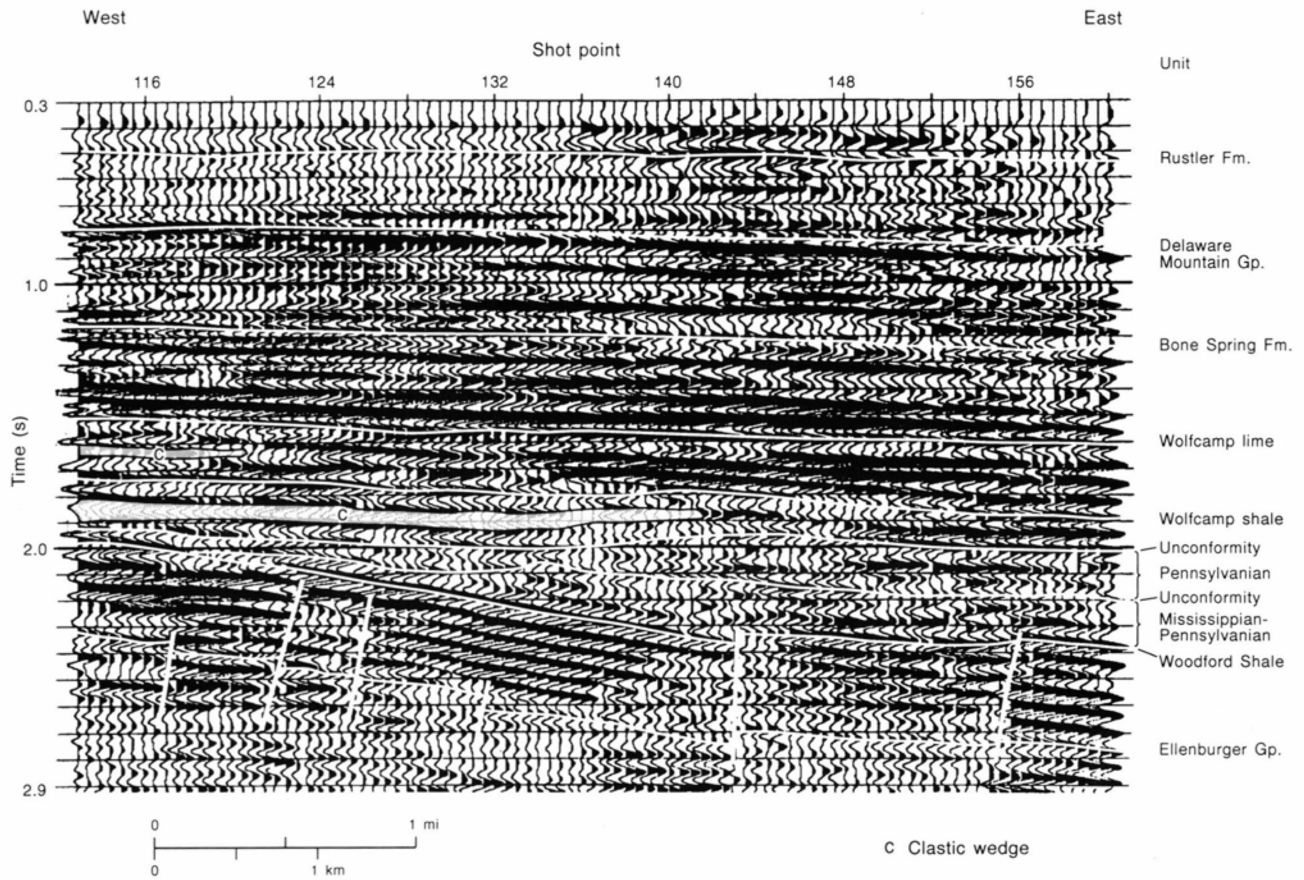

FIGURE 7—Seismic line DBGS-114, 1993-reprocessed migration, Delaware Basin fill. Near the Diablo Platform margin, a major unconformity marks the truncation of most of the Mississippian and Pennsylvanian strata in the Delaware Basin (SP 113, 1.97 sec to SP 100, 2.200 sec). Data provided by Chevron USA, processed at the University of Texas of the Permian Basin.

French Ranch on the upthrown side of an up-to-thebasin fault immediately to the west (Fig. 8: well 4). Stratigraphic thickening within the Delaware Mountain Group was also identified on the platform (Fig. 5: SP 43-78, 0.83 sec).

At least two reverse faults were identified along the eastern margin of the Diablo Platform (Fig. 6: west of SP 97). The smaller fault may have less than 100 ft of displacement. The larger fault, however, has at least 2500 ft of throw at the top of the Ellenburger Group (assuming a velocity of 10,000 ft/sec). Thickening of the stratigraphic section above the Woodford Shale is expressed as seismic events that merge basinward. These are interpreted as at least four major tongues of clastic detritus shed from the hanging wall of the platform. These tongues may represent four pulses of tectonic activity along this fault margin. There is potential for stratigraphic entrapment of hydrocarbons in these clastics, where they pinch out updip against the Diablo Platform margin. Local dip reversal in the footwall of the fault is well displayed on the reprocessed section (Fig. 6: SP 64-121). At least 500 ft of dip reversal in the footwall is present at the Woodford level.

Farther basinward, several faults offset Ellenburger through at least Woodford strata. The relative displacement on these faults (reverse, normal, or strike—slip) is uncertain because of the high angle of dip of the fault planes. Significant basinward thickening of Mississippian, Pennsylvanian, and possibly lower Wolfcampian deposits occurs above these faults (e.g. Fig. 7: SP 113, 1.92-1.97 sec, to SP 160, 2.02-2.20 sec). Most of the Mississippian and Pennsylvanian strata have been removed beneath a major unconformity along the eastern margin of the footwall anticline, timing early faulting and uplift of the Diablo Platform (Fig. 7: SP 113, 1.97 sec, to SP 160, 2.20 sec). The faulting, stratigraphic thickening, and the unconformity were not clearly imaged by the original data processing. The reprocessing of DBGS-114 has significantly enhanced these features.

Analysis of geologic data

Methods

A grid of stratigraphic cross sections was built from wireline logs of wells across the Delaware Basin. Acoustic logs were available for most of the wells because many of them were drilled during the past 30 years when acoustic logs were the most commonly used porosity tool in the basin. Thus we used acoustic logs wherever possible to maintain uniformity and to support the geophysical study. Other types of logs were employed where necessary. Sample logs, scout-ticket information, paleontological data, and insoluble-residue data were incorporated into the correlation grid. Logs were correlated for all available pre-Permian penetrations using the cross-section grid as a reference standard.

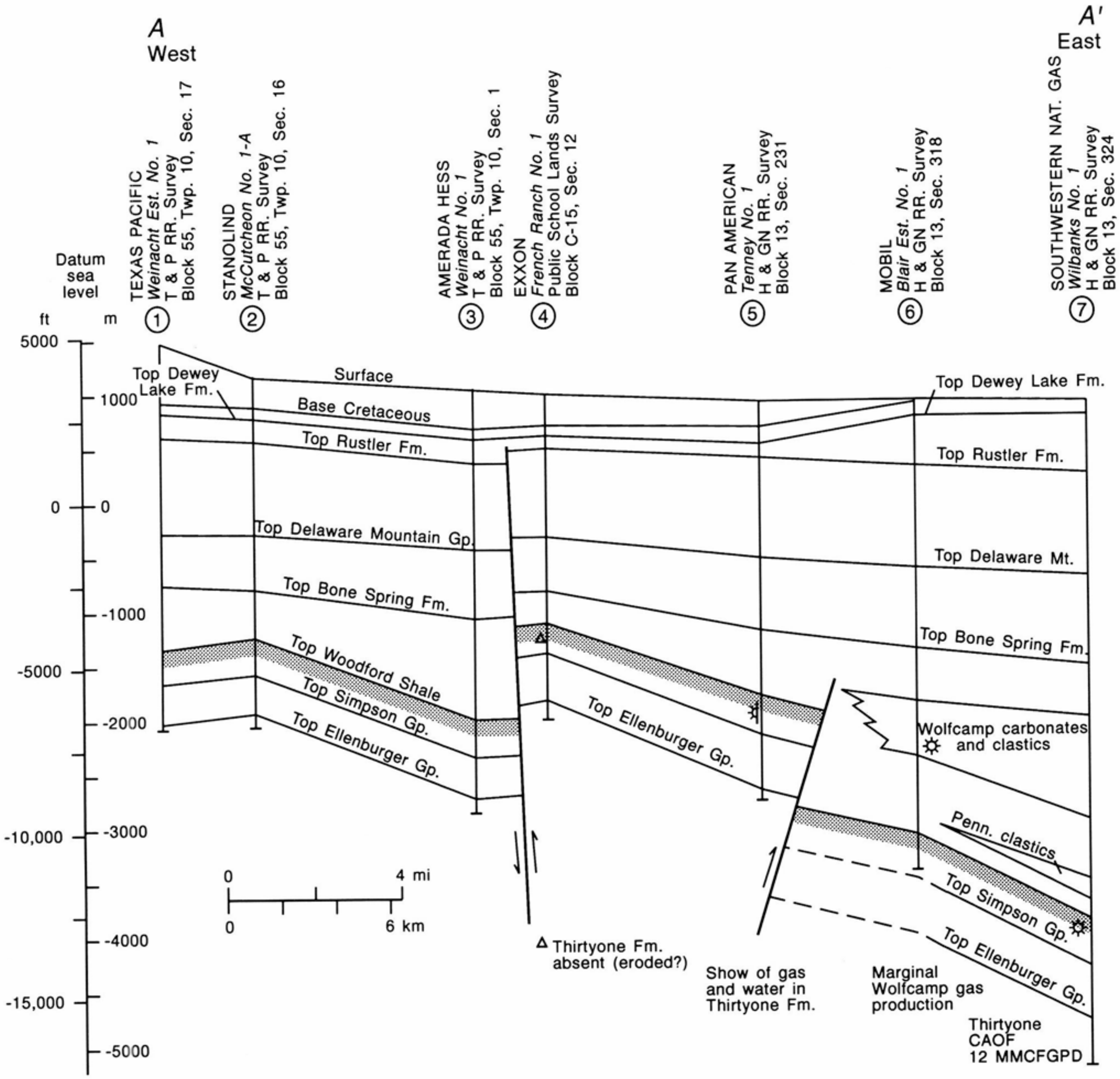

FIGURE 8—Southwest–northeast structural cross section A–A' from Diablo Platform to Delaware Basin. Location shown in Fig. 3.

Interpretation

A structure map contoured on top of the Woodford Shale is shown in Fig. 3. Similarly complex structure exists along the platform margin to the southeast (Borger, 1990). Two long northwest—southeast-trending fault zones are apparent in Fig. 3. The more westerly fault zone is depicted as a counter-regional, up-tothe-basin, high-angle fault zone (Fig. 3: fault 1). Displacement along this feature is approximately 1000 ft (Figs. 9, 10). Movement appears to have occurred in Wolfcampian time. DBGS-114 did not extend far enough westward to image this feature. Along the northwestern margin of the Delaware Basin, the western Guadalupe Mountain border fault is a similar upto-the-basin fault (Hills, 1968). A relatively competent Delaware Basin, because of differential subsidence along its eastern margin, may have rotated along an axis in the center of the basin, placing substantial stress upon the western hinge line. The resulting rupture and up-to-the-basin faulting, when found in the subsurface, have excellent trapping potential.

The up-to-the-basin fault indicated on cross section A—A' (Fig. 8: wells 3, 4), although similar to faults shown in sections B—B' and C—C', is significantly different (Fig 3: fault 2). Throw is approximately 2500 ft, and displacement may have begun in the Late Devonian. The lower Paleozoic section displays little depositional thinning between these wells, but as much as 200 ft of displacement may have occurred prior to deposition of the Woodford Shale. During that time the Thirtyone Formation of Devonian age was stripped from the crest of the upthrown block. During the Mississippian there appears to have been no additional movement. No Pennsylvanian strata are present in either well, thus the timing of the onset of major movement is conjectural. Most of the structural dis-

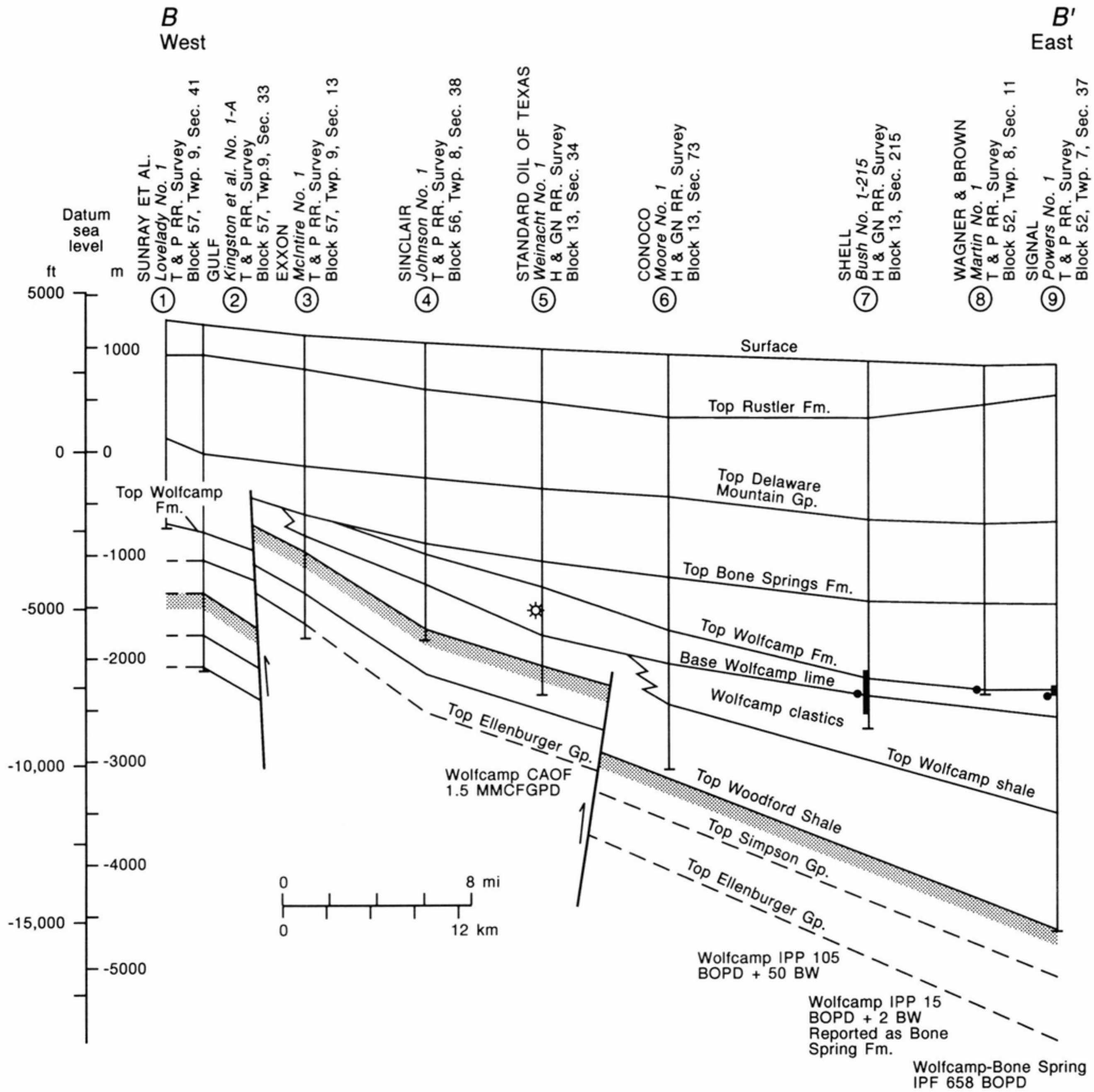

FIGURE 9—Southwest–northeast stratigraphic cross section B–B′ from Diablo Platform to Delaware Basin, in part parallel to DBGS-114. Location shown in Fig. 3.

placement took place during Pennsylvanian and Permian (Wolfcampian) time. Between these two wells there is a substantial difference in the Wolfcamp section, which complicates structural interpretation but provides evidence of at least three episodes of movement. Differences in elevations of correlation markers in the Delaware Mountain Group and Rustler Formation appear too large to be caused solely by regional dip. Basinward, the Exxon French Ranch No. 1 (Fig. 8: well 4) penetrated the Delaware Mountain Group and the Rustler Formation approximately 450 ft higher than did the Amerada Weinacht No. 1 (Fig. 8: well 3). Only the uppermost Permian Dewey Lake Formation and overlapping Cretaceous strata demonstrate regional dip. Thus, there may have been Late Permian movement.

The second regional fault trend of note is the high-angle reverse fault that forms the eastern margin of the Diablo Platform (Fig. 3: fault 3). The existence of such faults along the Delaware Basin margin has been well documented. Figure 11 is an interpretation of the fold and high-angle reverse fault underlying the Huapache monocline on the northwestern edge of the Delaware Basin (Fig. 1). The well bore cuts several repeated sections having at least 3850 ft of total throw. Thin-bed correlations show apparent thickening in the footwall caused by penetration at an angle of almost 45°. For example, 100 ft of Woodford Shale was

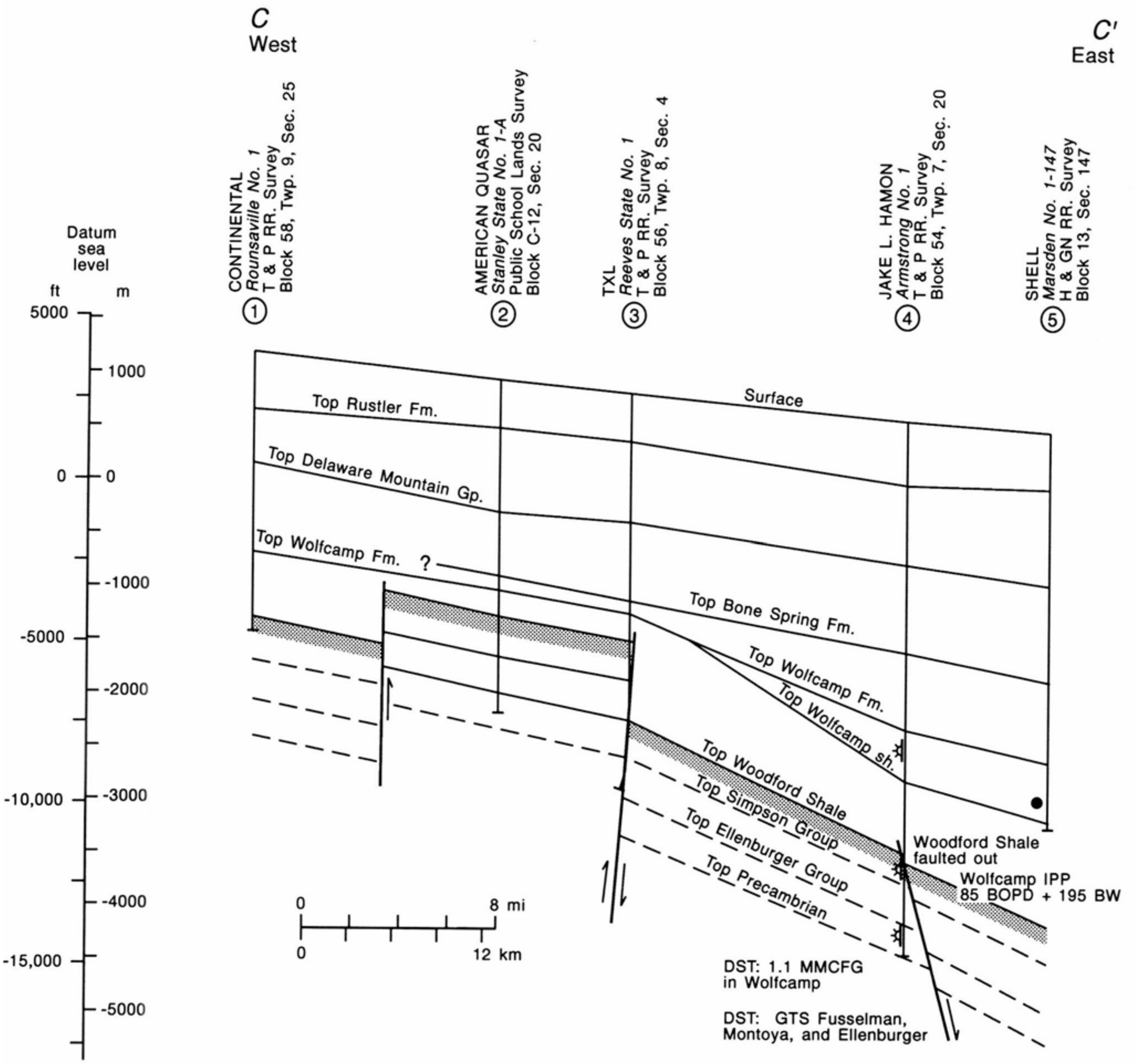

FIGURE 10—Southwest–northeast stratigraphic cross section C–C′ from Diablo Platform to Delaware Basin. Location shown in Fig. 3.

penetrated in the hanging wall, whereas the footwall section was 235 ft thick. Easily correlated subunits within the Woodford were all proportionately thickened. This structure is similar to a feature imaged on DBGS-114.

The high-angle reverse fault bordering the Diablo Platform has been penetrated in the TXL Reeves State No. 1 (Figs. 3, 12). The well was drilled out of the Lower Ordovician Ellenburger Group into the Devonian Thirtyone Formation, repeating approximately 2650 ft of section. After reaching the Simpson Group in the footwall, the well bore entered Precambrian metamorphic basement, either recrossing the fault (Fig. 12) or cutting an unmapped normal fault in the foot-wall. This well had good gas shows in the Delaware Mountain Group, but the lower Paleozoic formations tested wet (Fig. 10).

In comparison with the structural style along the Diablo Platform margin, the eastern margin of the Delaware Basin along the Central Basin Platform is more varied. Several wells have penetrated substantial repeated sections across multiple faults, comparable to the Humble Huapache No. 1 (Fig. 11). Other portions of the Central Basin Platform are bounded by fairly tight, unfaulted folds. Yet other wells have encountered relatively gentle folding associated with major reverse faults comparable to the structure in the TXL No. 1 Reeves State (Fig. 12). Figure 13 is an interpretation of such a fold and high-angle reverse fault, having approximately 2500 ft of vertical displacement in the Superior University "K" No. 1. This well was completed in the Atoka and Wolfcamp Formations from clastics shed off the Central Basin Platform. Similar structural and depositional relationships exist along the Diablo Platform border fault imaged on DBGS-114. The similarity in structural style indicated by these three wells implies a common structural history for both eastern and western margins of the Delaware Basin. The differences between the structures of the two sides of the basin are more related to scale than to style (see, e.g. Ewing, 1991).

Structural history of the Diablo Platform

The Tex-Mex Arch (Wright, 1979) was a Late Cambrian and earliest Ordovician landmass trending southeastward from the Pedernal Massif across the future site of the western Tobosa Basin. The Tex-Mex Arch was rimmed to the south by sandstone of the latest Cambrian and earliest Ordovician Bliss Formation. The Bliss Formation thins from approximately 300 ft in the Franklin Mountains to 105 ft at Beach Mountain, located 30 mi west of this study area (Fig. 2) (Lucia, 1971). From the few wells along the Diablo Platform margin that penetrated the base of the Ellenburger, we conclude that the Bliss Formation is present only in the most southerly portion of the study area in Pecos County. Along the western flank of the Diablo Platform, the El Paso Group (Ellenburger

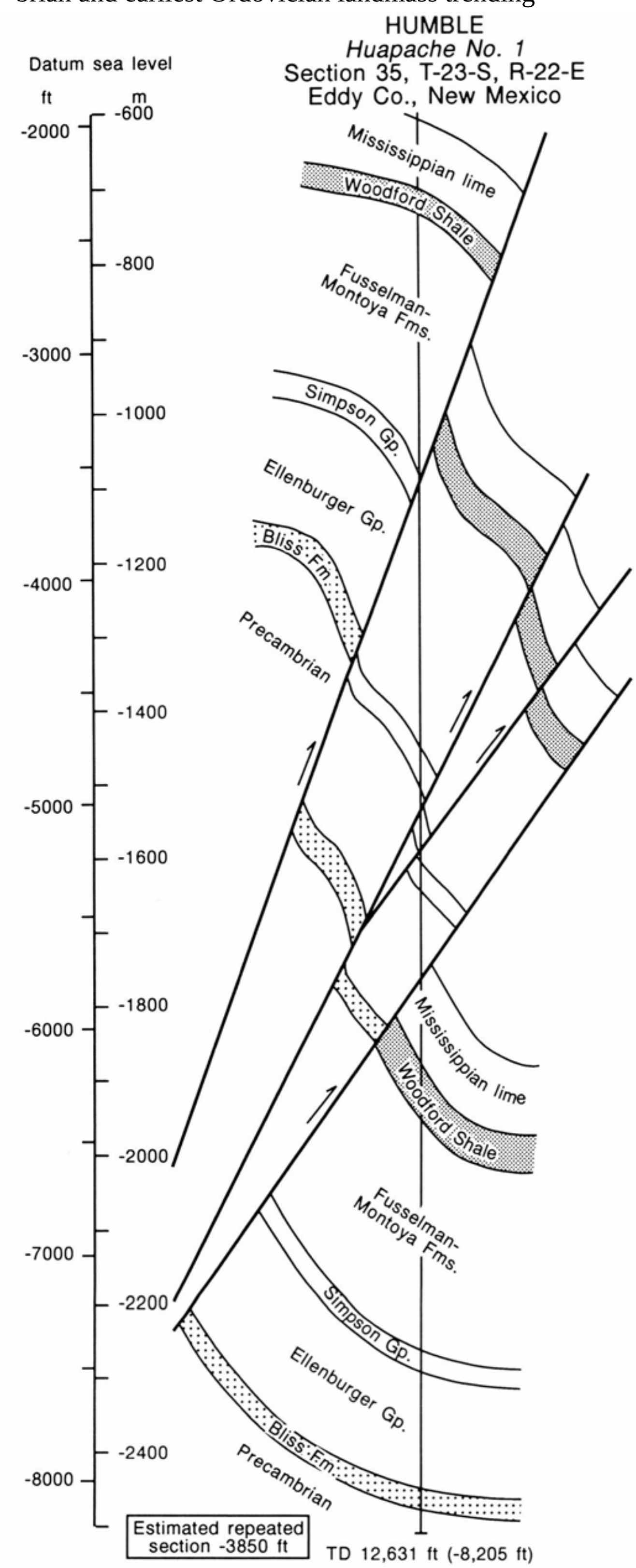

FIGURE 11—Fault interpretation along the northwestern Delaware Basin margin, Huapache monocline, Eddy County, New Mexico. Location shown in Fig. 1.

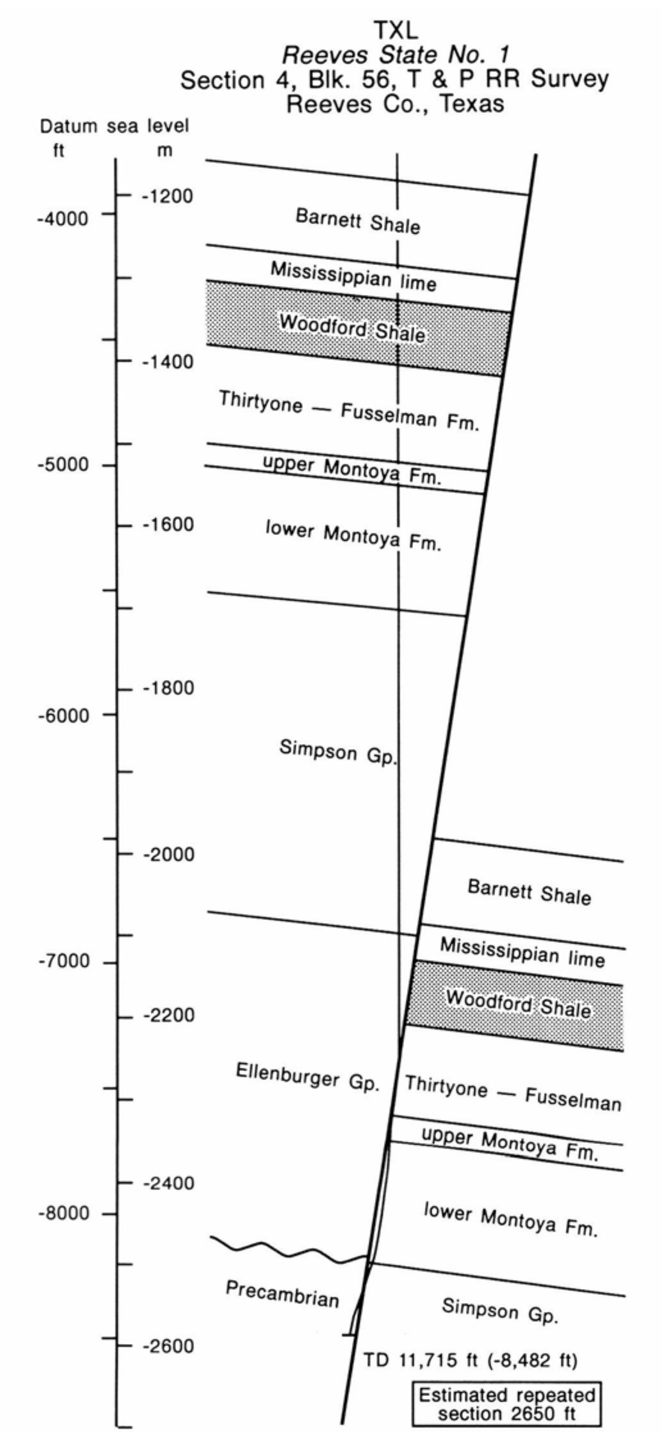

FIGURE 12—Fault interpretation along the southwestern Delaware Basin margin, Diablo Platform, Reeves County, Texas. Location shown in Figs. 1 and 3.

equivalent) thins eastward from 1500 ft in the Franklin Mountains to 950 ft at Beach Mountain (Lucia, 1971). From there eastward to the study area the Ellenburger thickens to 1500 ft, demonstrating the first presence of the Diablo Platform in Early Ordovician time.

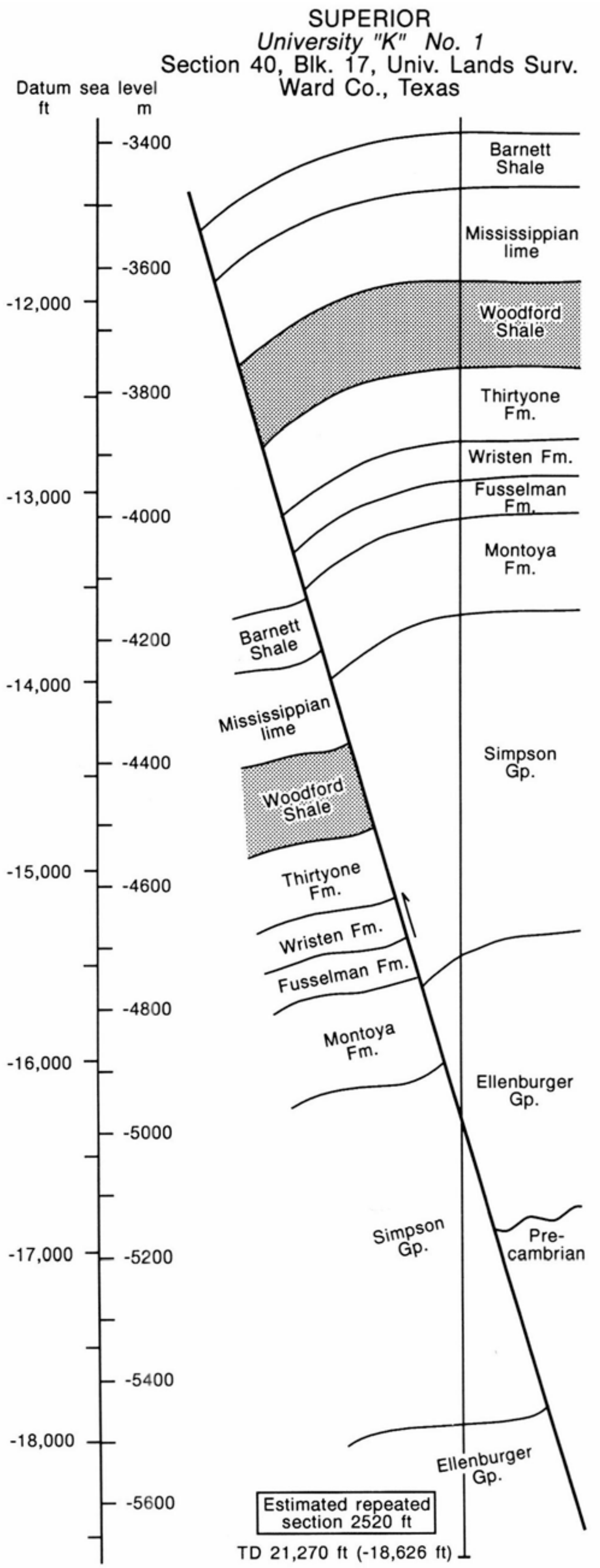

FIGURE 13—Fault interpretation along the eastern Delaware Basin margin, Central Basin Platform, Ward County, Texas. Location shown in Fig. 1.

Available well control along the Delaware Basin margin enables us to demonstrate recurrent movement of the Diablo Platform after Ellenburger time. The lower, middle, and upper Simpson Group expands rapidly across a Middle and early Late Ordovician hinge line (Figs. 8, 14A: wells 4, 5). Only about 100 ft of Simpson strata are exposed in outcrops in the Baylor Mountains (Suhm and Ethington, 1975), but more than 2000 ft are present in the eastern part of the study area. The Upper Ordovician Montoya Formation thins eastward from 400 ft in the Franklin Mountains to approximately 300 ft at Beach Mountain (Lucia, 1971). Much of that thinning is the result of the truncation of the upper Montoya Cutter Member to the east. Throughout the study area, however, the thickness of the cherty limestone of the Montoya is uniformly between 500 and 600 ft (Figs. 8, 14B). Although the Montoya thickens noticeably from Beach Mountain to the platform margin, the margin itself shows relative structural stability. The character of the cherty limestone is uniform. The Lower Silurian Fusselman Formation also thins eastward from the Franklin Mountains (approximately 700 ft) to the Beach Mountains (310 ft) (Lucia, 1971). The Fusselman along the margin is usually less than 100 ft thick, showing little evidence of structural influence. Conversely, the Devonian Thirtyone Formation thins westward, culminating in its erosional truncation upon the platform, west of the study area. Significant westward thickening across the Diablo Platform boundary fault reoccurs between the base of the Woodford Shale and the top of the Barnett Shale (Figs. 8, 14C).

Major movement occurred on the platform during the late Paleozoic, as has been detailed above. Post-Permian deformation may have occurred prior to local sediment deposition during the Early Cretaceous (King, 1965). Renewed movement certainly did occur on many platform structures during the Cenozoic as part of Trans-Pecos Basin and Range deformation. This youngest episode has continued into historical times. Differences in elevation measured along leveling line profiles indicate that the Diablo Plateau has risen almost 7 inches in 20 years this century (Brown et al., 1978). On the basis of studies of earthquake epicenters, two of the three most seismically active areas in west Texas are along the northwestern flank of the Diablo Plateau and in the south-central part of the plateau, 15 mi southwest of the study (Davis et al., 1989). However, the last of those most active regions is on the Central Basin Platform along the Andrews shear zone of Gardiner (1990) and the Precambrian cataclastic belt of Flawn (1956). This swarm is surrounded, perhaps not coincidentally, by some of the most prolific oil fields in Texas.

Exploration potential

A sharp distinction exists between the exploration potential of the Diablo Platform and that of the western margin of the Delaware Basin. The Platform has long been considered unprospective for hydrocarbons (Beede, 1920; Pearson, 1983; DeJong and Addy, 1992a, b). Exploration is hindered because several of the few important wells drilled on the Diablo Platform are older wells documented with only poor-quality

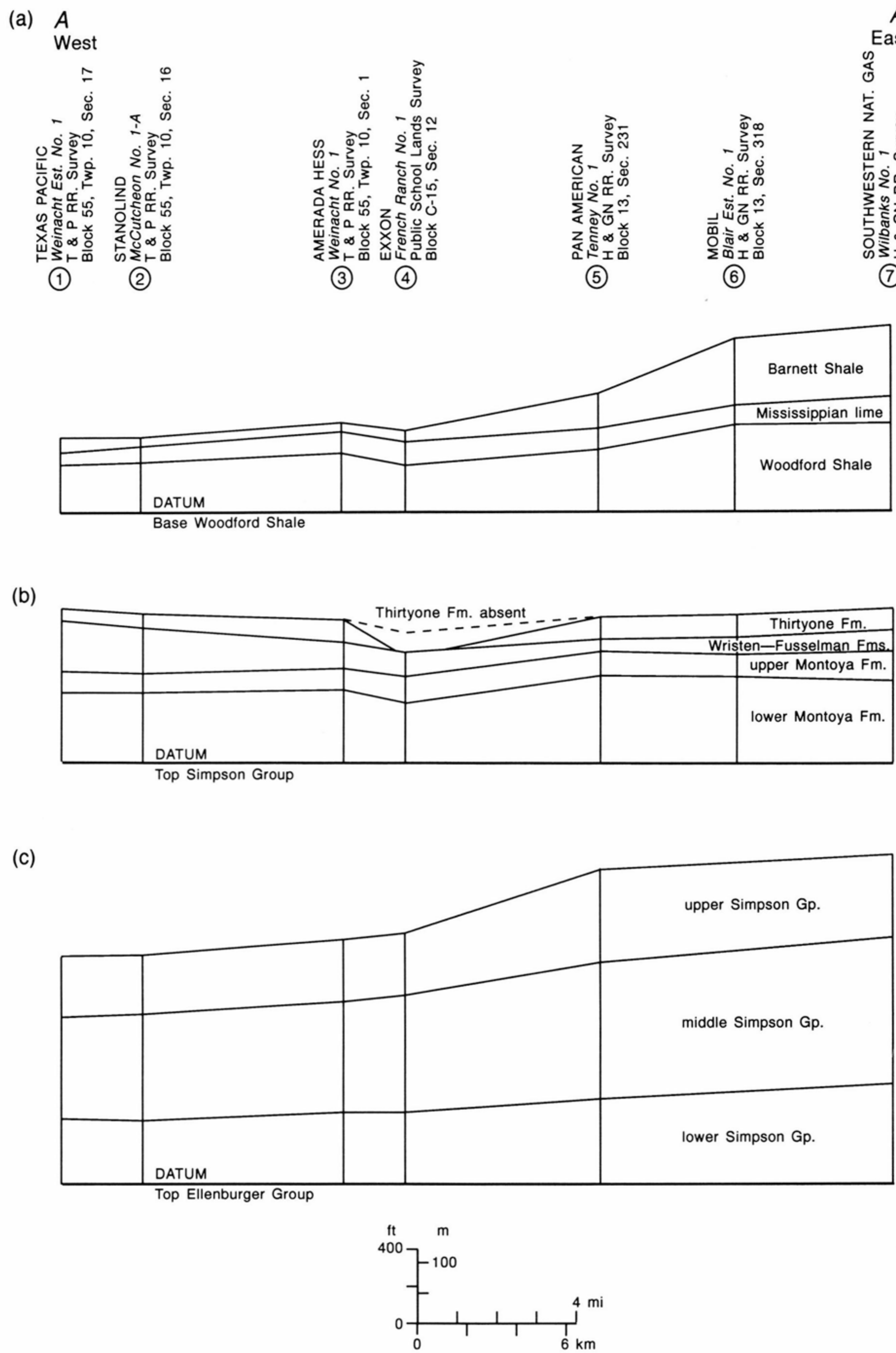

FIGURE 14—Southwest–northeast stratigraphic cross section A–A′. These cross sections reproduce the Simpson Group through Barnett Shale of Fig. 8 at a larger vertical scale. **A**, Simpson Group, datum = top of Ellenburger Group. **B**, Montoya Formation to Thirtyone Formation, datum = top of Simpson. **C**, Woodford Shale to Barnett Shale, datum = base of Woodford Shale. Location shown in Fig. 3. Wells listed in Fig. 8.

electric logs or sample descriptions. However, although well density decreases significantly from east to west across the Delaware Basin, substantial deep-subsurface control does exist along the western flank of the basin, and production has been established in a number of fields. Productive intervals within the study area include the Delaware Mountain Group at San Martine, Casey Draw, Weinacht, and Chancellor Fields; the Wolfcamp Formation at San Martine, San Martine Southwest, Balmorhea, Bush, Verhalen, Pec-Reeves, Barilla and Hershey Fields; the Mississippian lime at San Martine and Five Mile Draw Fields; the Thirtyone Formation at Pec-Reeves, Hoefs-TK, Hershey, and Hershey West Fields; the Fusselman Formation at San Martine, Nine Mile Draw, and Hershey Fields; and the Montoya Formation at Hershey and Hershey West Fields. In spite of this established production, the western flank of the basin has not been thoroughly explored.

Ordovician—Mississippian

Basinward of the platform border fault, production has been established from the Montoya through the Mississippian in a number of small- to medium-sized fields. Within the middle Paleozoic producing formations, reservoir-quality porosity and permeability are often incompletely developed across structures in the western Delaware Basin. An example is a well in the Pec-Reeves Field completed in the Thirtyone Formation that produced 1 BCFG before being abandoned (Fig. 8: well 7).

Potential exists for subcrop traps in the Devonian along its updip truncated edge below a Woodford Shale seal. The Amerada No. 1 Weinacht, on the downthrown side of the fault, has a well-developed section of Devonian Thirtyone Formation chert (Fig. 8: well 3). The Devonian has been removed by erosion in the Exxon No. 1 French Ranch on the upthrown block of the fault (Fig. 8: well 4). The Pan American No. 1 Tenney (Fig. 8: well 5), downdip of the Exxon well, tested gas and water in drillstem tests in the Thirtyone Formation.

The number of up-to-the-basin faults may be related to the downwarping of the eastern margin of the Delaware Basin (Hills, 1968). These up-to-the-basin faults offer excellent opportunities for entrapment, as hydrocarbons migrate updip toward the platform area and reach a fault barrier laterally sealed with Woodford and/or Barnett Shale. These organic-rich shales, along with Pennsylvanian and Permian basinal shales, are probably the petroleum source rocks for these reservoirs.

Wolfcampian

The Standard Oil of Texas Weinacht No. 1, 1 mi northeast of DBGS-114, was completed as the one-well Balmorhea (Wolfcamp) Field in 1963 at a calculated absolute open flow rate of 1.5 MMCFGPD (Fig. 9: well 5). This well was completed in a 65 ft thick carbonate bed at the base of the Wolfcampian section. Cumulative production was only 187 MMCFG and 5 MBO, but this zone has an appearance similar to that of flank wells in significantly productive carbonate debris flows of the Midland Basin. Similar flows can reasonably be anticipated along the western flank of the Delaware Basin. If comparable debris flows are found, an increase in reservoir thickness, as seen on DBGS-114 and cross section B—B', should substantially improve the economics of such a play (Figs. 5, 9). Other Wolfcamp production in the area also appears stratigraphically trapped (Fig. 8: well 5; Fig. 9: wells 7-9; Fig. 10: well 5).

Delaware Mountain Group

DBGS-114 lies 10 mi southwest of Casey Draw (Bell Canyon) Field, a gas field discovered in 1976. There the pay section is the Ramsey "Sand," the uppermost sandstone in the Bell Canyon Formation of the Delaware Mountain Group. Before abandonment, this dry gas field produced 1.04 BCFG, mostly from two wells at depths between 3800 and 3920 ft. The thickening seen on DBGS-114 may represent a local sand accumulation within the Bell Canyon that can be imaged with properly processed seismic data. Pay sandstones in the Delaware Mountain Group having more than 22% contrast in porosity with the "trap rock" facies having less than 18% porosity. This contrast produces an approximately 1200-ft/sec difference in velocity between the two rock types. Pay zones within the Ramsey and other Delaware Mountain Group sandstones are detectable as amplitude anomalies when the pay section is sufficently thick. This technique has proven successful in delineating pays in the Cruz-Paduca-producing trend of Lea County, New Mexico.

The effect of post-Permian tectonic activity on trap integrity is a major concern for exploration on the Diablo Platform and western Delaware Basin. Wells drilled on the western Diablo Platform have had hydrocarbon shows that have usually been ascribed to breached reservoirs. The Texaco No. 1-FP State of Texas, drilled south of Cornudas Station, is an example. Samples recovered from the Fusselman were half tar balls and half dolomite rhombs. Considerations of safety led the company to switch from an air drill to a mud system. During the switch, a welder accidentally set fire to gas coming up and around the kelly. After the well had been shut in overnight, the tool pusher placed a fire bucket in front of the blow line and opened it. Flames rose well above the crown, but shortly thereafter decreased to a steady 10-foot flare. We conclude that the reservoir had been breached during Cenozoic tensile deformation, allowing the lighter hydrocarbons to escape over time.

Conclusions

Full understanding of the tectonic history of the Delaware Basin must include consideration of its western margin along the Diablo Platform. The Diablo Platform is a complex, long-lived positive feature that has undergone periods of reactivation from Early Ordovician until the present. Faults associated with the Diablo Platform have been active in the Devonian, Pennsylvanian through Wolfcampian, and possibly the Late Permian. A hinge line associated with the growth of the platform during the early Paleozoic formed the southwestern margin of the Delaware Basin. That hinge line was active repeatedly during the early and middle Paleozoic before its greatest movement in the Wolfcampian. The tectonic regime was dominantly compressive and marked by high-angle reverse faulting comparable to the northwestern and eastern flanks of the Delaware Basin.

Older 2-D seismic data can be acquired relatively inexpensively and reprocessed interactively on affordable workstations. The seismic image can be significantly improved by enhancing static and velocity analyses. New structural and stratigraphic insights resulting from integrating the reprocessed geophysical interpretation with geological data suggest that the western margin of the Delaware Basin has additional exploration potential. We have identified seven potential plays with our seismic and geological analyses.

(1) Wolfcampian carbonate-debris flows adjacent to the platform are analogous to productive strata in the Midland Basin. Areas where local thickening of these flows has occurred (Fig. 5: SP 50-70) are favorable targets for exploration (Fig. 9: well 5). Deposition from debris flows may occur upon deceleration, producing thicks over incipient structural highs.

(2) Carbonate buildups are present on structural highs along the complex platform/basin margin. These may be anticipated in the Pennsylvanian, Wolfcampian, and, possibly, the Leonardian Bone Spring Formation (Fig. 5: SP 45-56). The 280 ft thick, clean, crinoidal packstone in the Exxon French Ranch No. 1 is an example (Fig. 8: well 4).

(3) Sandstones in the Delaware Mountain Group are thickened locally (Fig. 5: SP 43-78, 0.83 sec). Reprocessing of old seismic data can produce images that substantially reduce the risk associated with exploring for additional gas fields similar to Casey Draw. Reprocessing can enhance amplitude anomalies which have been successfully utilized as an exploration tool in the Cruz—Paduca producing trend in Lea County, New Mexico. This technique is applicable along the western margin of the Delaware Basin in Culberson, Reeves, and Pecos Counties, Texas.

(4) Reprocessed seismic data indicate that four major tongues of clastic detritus were shed from the rising Diablo Platform. These tongues may represent four pulses of tectonic activity along this fault margin. There is exciting potential for updip strati-graphic entrapment of hydrocarbons in these clastics, where they pinch out along the Diablo Platform (Fig. 6: west SP 97).

(5) Dip reversal exists in the footwall of major fold—fault structures and is clearly displayed on reprocessed seismic records. One such structure, having an estimated 500 ft of reversal at the top of the Woodford Shale, is present along line DBGS114 (Fig. 6: SP 64-121).

(6) Up-to-the-basin faults offer excellent opportunity for hydrocarbons to migrate updip toward the platform and be trapped adjacent to laterally sealing (and sourcing) Woodford and Barnett Shales. Such faults are present along the western margin of the Delaware Basin from this study area northward into New Mexico (Hills, 1968).

(7) Devonian Thirtyone Formation chert could produce along its truncated edge beneath a Woodford Shale source and seal (Fig. 8: wells 3-5). Production at San Martine, Nine Mile Draw, and Hershey Fields demonstrates that large amounts of natural gas exist in the Devonian and Silurian formations in the western Delaware Basin. Similar truncation traps have been very productive in the Midland Basin and on the Central Basin Platform.

Acknowledgments

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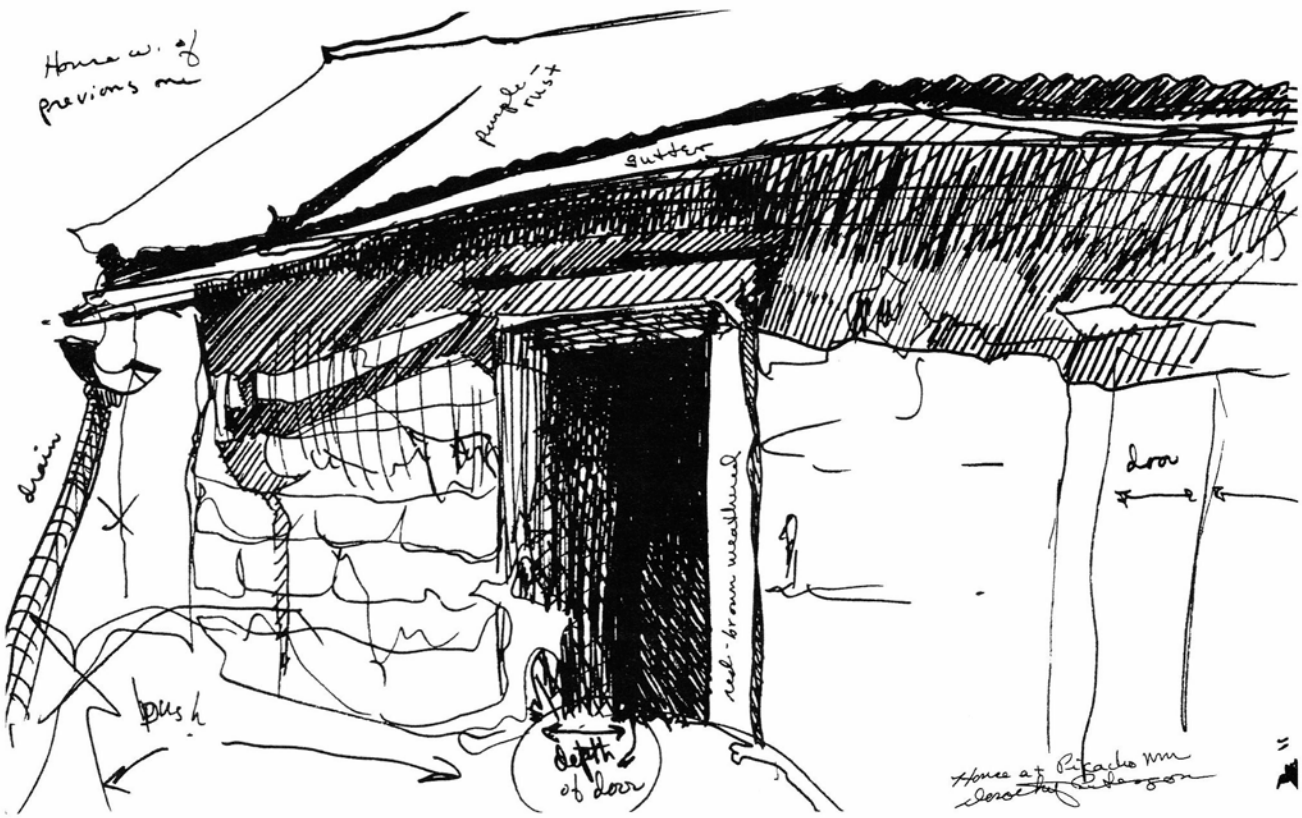

House w. of
previous one
purple-rust
gutter
drain
push
depth
of door
red-brown weathered
door
House at Picacho NM

Impact of late Cenozoic extension on Laramide overthrust belt and Diablo Platform margins, northwestern Trans-Pecos Texas

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Abstract—Late Cenozoic basins and normal faults were superimposed upon pre-existing Tertiary, Mesozoic, and older structures of northwestern Trans-Pecos Texas. We analyzed the structural and stratigraphic framework of the region using borehole, seismic, outcrop, and aerial-photograph interpretations; regional cross sections were prepared to record Mesozoic and Cenozoic structural attributes. Laramide thrusting displaced Cretaceous rocks northeastward and produced northwest-trending thrust faults and related normal faults, folds, and monoclines. Cenozoic extension that began 24 to 30 mya caused normal faulting that produced northwest- and north–northwest-trending, 3 to 30 mi wide, fault-bounded basins and adjacent mountain ranges. Tectonism continues to the present. The pre-late Cenozoic structural grain has at least partly controlled geometries of the late Cenozoic basins and associated faults.

The deepest Cenozoic basin of this area, the 105 mi long Hueco Bolson, developed along the leading edge of the Laramide thrust belt and the southwest margin of the Diablo Plateau and has as much as 9800 ft of Cenozoic basin fill. The most active Quaternary faults vertically displace middle Pleistocene deposits by about 33 to 105 ft. The 56 mi long Red Light Bolson, containing more than 2000 ft of Cenozoic deposits, also formed near the leading edge of the older thrust belt. A northwest-striking Quaternary fault zone bounds this basin on its east margin. A fault in southeast Red Light Bolson vertically displaces middle Pleistocene deposits by about 30 ft.

Two series of Cenozoic basins also have formed northeast of the overthrust belt. The 50 mi long Eagle Flat–Green River Basin system consists of three basins that contain 900 to more than 2000 ft of basin fill. Late Tertiary–Quaternary tectonism has not been as active there as in the other large basins. The 124 mi long Salt Basin graben system comprises five basins and marks the east edge of Quaternary faulting in this region. Cenozoic fill is more than 2000 ft thick, and the most active Quaternary faults vertically displace middle Pleistocene deposits by at least 13 to 36 ft.

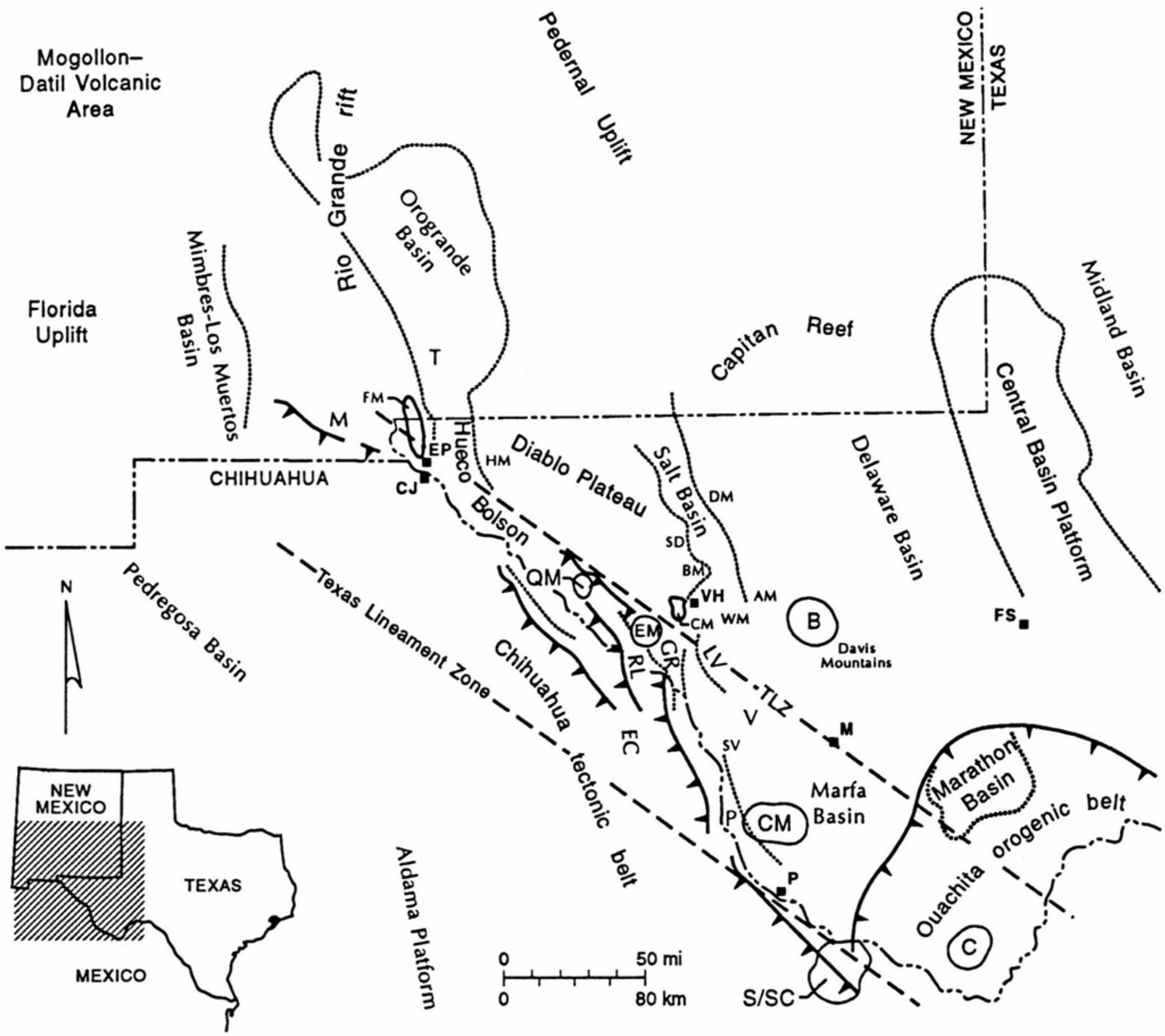
Introduction

We describe herein intermontane basins and associated normal faults in northwest Trans-Pecos Texas and adjacent Chihuahua, Mexico, that formed during late Cenozoic extension. The late Cenozoic tectonic elements have been superimposed upon pre-existing early Cenozoic, Mesozoic, and older structures (Fig. 1). As a result, the pre-late Cenozoic structural grain has at least partly controlled the geometries of the late Cenozoic basins and associated faults. Basin orientations reflect the earlier structural grain, and abrupt changes of Quaternary fault strikes may be partly caused by pre-existing zones of crustal weakness. In our study area, late Cenozoic basins formed along the southwest margin of the Paleozoic Diablo Platform and along and northeast of the leading edge of the Laramide thrust belt that strikes northwest across the region. These late Cenozoic basins are near the southeast edge of the southern Basin and Range—Rio Grande rift tectonic province, an area that marks the east margin of Quaternary faulting in the province.

We also report herein general basin sizes, thicknesses of Cenozoic fill, attributes of Quaternary basin-bounding faults, and possible relationships between pre-existing structural grain and Cenozoic tectonic elements. Detailed study of Quaternary faults provides clues to the development of the basins and rupture histories of the basin-bounding fault zones. We thus describe Quaternary fault geometries, scarp morphologies, amounts of offset on strata of different ages, average slip rates, average recurrence intervals of large ruptures, and amounts of offset during single surface-rupture events.

Methods

We used borehole, seismic, outcrop, and aerial-photograph interpretations to analyze the structure and stratigraphy of the region. Regional cross sections were prepared to help document Mesozoic and Cenozoic structural attributes. Our descriptions of Quaternary faults are based on aerial-photograph and field-geologic mapping, field observations, and measurements of fault scarps, outcrops, and excavations. Precise ages of faulted Quaternary and Tertiary deposits remain undetermined because too few materials are suitable for absolute dating. Relative ages have been estimated on the basis of field-stratigraphic relationships, the degree of calcic-soil development (Gile et al., 1966, 1981; Machette, 1985), and correlation with similar units in south-central New Mexico (Hawley, 1975; Gile et al., 1981). We estimated fault-slip rates on the basis of the vertical displacement of middle Pleistocene deposits and the youngest middle Pleistocene time of about 130,000 BP. These are maximum values because the displacements used in our estimates are from faulted middle Pleistocene deposits that may be more than 130,000 yrs old. To estimate ranges of average recurrence intervals between large ruptures, we estimated the number of large, approximately 3 to 6.5 ft, single-event ruptures that could have displaced middle Pleistocene deposits having stage IV calcrete horizons. We made the recurrence-interval estimations by assuming that the faulted middle Pleistocene deposits are between 250,000 and 500,000 yrs old. We follow the published nomenclature herein by referring to several basins as bolsons, even though they currently exhibit no internal drainage.



CITIES		MOUNTAINS		CALDERAS		BASINS	
EP	El Paso	FM	Franklin	QM	Quitman Mountains	T	Tularosa
CJ	Ciudad Juarez	HM	Hueco	EM	Eagle Mountains	M	Mesilla
VH	Van Horn	DM	Delaware	B	Buckhorn	RL	Red Light
M	Marfa	SD	Sierra Diablo	CM	Chinati Mountains	GR	Green River
P	Presidio	BM	Baylor	S/SC	Santana/San Carlos	LV	Lobo Valley
FS	Fort Stockton	AM	Apache	C	Chisos	EC	El Cuervo
		WM	Wylie			V	Valentine
		CM	Carrizo			P	Presidio
		SV	Sierra Vieja				

FIGURE 1—Map showing major regional tectonic features of west Texas and adjacent areas of New Mexico and Mexico. Modified from Keller and Peeples (1985) and Muehlberger and Dickerson (1989).

Geologic setting of Cenozoic basins

Northwest Trans-Pecos Texas and adjacent Chihuahua, Mexico, consist of the broad Diablo Plateau and a series of mountain ranges and adjacent basins resulting from normal faulting that probably occurred in the last 24 my (Henry and Price, 1985, 1986). Bedrock exposed in the mountain ranges and in the plateau consists of rocks that record the long geologic history of the region (Henry and Price, 1985; Muehlberger and Dickerson, 1989). Precambrian rocks show evidence of sedimentation, magmatism, metamorphism, and deformation before deposition of overlying Paleozoic marine strata. In the late Paleozoic the Ouachita—Marathon orogenic event produced a belt of strongly deformed Paleozoic strata across the southeast edge of the region, and structural highs such as the Diablo Platform were uplifted in the foreland of the Ouachita-Marathon belt (Fig. 2). Many northwest-trending features have been related to a regional structural zone called "the Texas Lineament" (Muehlberger, 1980), which strikes across Trans-Pecos Texas. Intermittent deformation has occurred along at least parts of the Texas Lineament from Precambrian times to the present (Horak, 1985; Muehlberger and Dickerson, 1989), but most deformation probably occurred during the Precambrian and the late Paleozoic. Mesozoic rocks comprise Jurassic(?) evaporites and overlying, dominantly marine Cretaceous deposits. These Mesozoic rocks were deposited in a deep sedimentary basin, the Chihuahua Trough (Fig. 3), which developed during the Jurassic Period in westernmost Trans-Pecos Texas and in Chihuahua, Mexico (DeFord and Haenggi, 1971; Henry and Price, 1985). Subsequent Laramide thrusting displaced Cretaceous rocks northeastward, perhaps along a décollement zone of Jurassic(?) evaporites, and produced northwest-trending thrust faults, folds, and monoclines along the northeast margin of the Chihuahua Trough (Gries and Haenggi, 1971; Gries, 1980; Henry and Price, 1985). The timing of Laramide deformation is not closely constrained, but it began no earlier than the Late Cretaceous, perhaps 80 mya (Wilson, 1971). Laramide thrust faulting and folding appear to have stopped by about 50 mya (Price and Henry, 1985), Laramide compressive stress by about 30 mya (Price and Henry, 1984; Henry and Price, 1989).

Volcanic rocks exposed throughout the Trans-Pecos region resulted from volcanic activity that occurred between 48 and 17 mya, mostly between 38 and 28 mya (Henry and Price, 1984, 1985; Henry and McDowell, 1986; Henry et al., 1986). Much of the volcanism in Trans-Pecos Texas occurred while the area was under regional east-northeast compression as Laramide deformation waned (Price and Henry, 1984; Henry and Price, 1985).

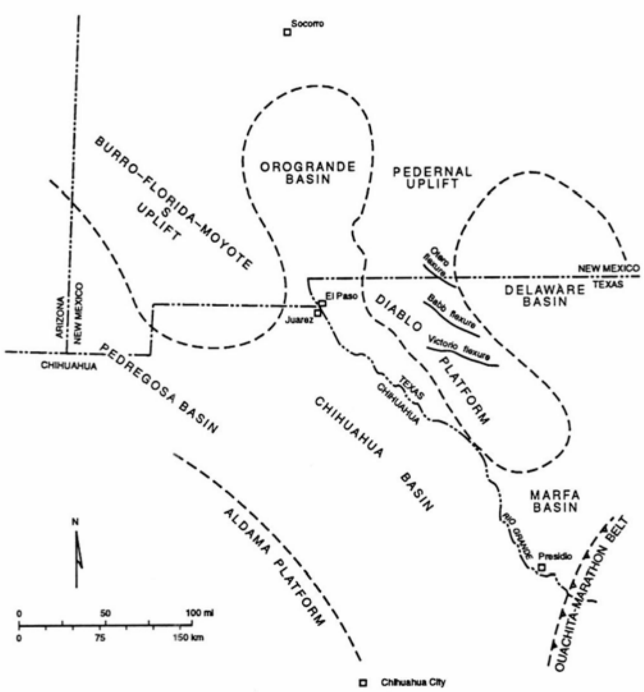


FIGURE 2—Map of Paleozoic tectonic setting.

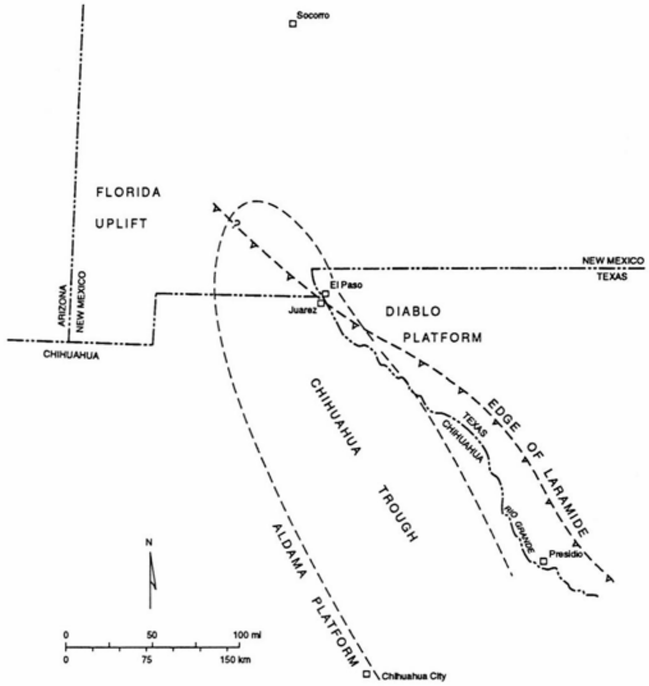


FIGURE 3—Map of Mesozoic–Laramide tectonic setting.

A transition to regional extension occurred about 30 mya, and subsequent normal faulting related to Basin and Range extension was well under way by about 24 mya (Henry and Price, 1985, 1986; Stevens and Stevens, 1985). This late Cenozoic normal faulting played a major role in the development of present mountain ranges and basins of the region. Basin and Range faulting and related sedimentation and magmatism in Trans-Pecos Texas and southern New Mexico have been episodic (Seager et al., 1984; Henry and Price, 1985; Mack and Seager, 1990). Precise times of accelerated fault movement and sediment deposition in most of the basins of the study area are not well constrained by available data. In Trans-Pecos Texas, periods of accelerated fault movement and sediment deposition in structural troughs may have occurred 24 to 17 mya and about 10 mya (Stevens and Stevens, 1985). Similar periods of deformation within the southern Rio Grande rift in southern New Mexico were also reported by Seager et al. (1984), Morgan et al. (1986), and Mack and Seager (1990). In Trans-Pecos Texas, field data indicate that early on regional extension was oriented east-northeast and later became oriented northwest (Henry and Price, 1985; Price and Henry, 1985), but the time of this shift has not been well established. A similar change in stress-field orientation occurred in other parts of the Rio Grande rift and Basin and Range province about 10 mya (Henry and Price, 1985; Aldrich et al., 1986; Morgan et al., 1986).

During the late Cenozoic, the fault-block mountains shed much sediment into the adjacent basins, partly filling them and constructing broad alluvial slopes, alluvial fans, and bajadas that surround the mountain ranges. During the Pliocene the westernmost basin of Trans-Pecos Texas, the Hueco Bolson, also was filled by great amounts of sediment from the northwest (Strain, 1971). Cenozoic basin fill consists mostly of gravel, sand, clay, and local evaporite beds. Basin-fill deposits represent deposition in different settings, including alluvial fan, lacustrine, fluvial, and eolian (Albritton and Smith, 1965; King, 1965; Strain, 1966; Akersten, 1967; Gustavos, 1991; Jackson et al., 1993). Some basins also contain volcaniclastic deposits.

Regionally, the least principal horizontal-stress direction of the southern Basin and Range—Rio Grande rift province is west—northwest, although local variations in the stress field may occur (Zoback and Zoback, 1980, 1989). No in-situ stress measurements of the stress field in our study area have been made; however, Quaternary faults occur throughout the region and provide some clues as to what local stress directions may be. Quaternary faults have strikes that span the compass, although most of these faults strike between N10°W and N70°W. Where slickenlines and grooves have been observed on main fault surfaces, slip has been parallel to subparallel to the dip of the fault surfaces. Slip indicators on the surfaces of three Quaternary faults located in three different basins show that local extension during the Pleistocene has been approximately N30-60°E. We have seen no evidence of lateral offset of surficial or bedrock deposits at any of the Quaternary faults in this area, although locally we have observed evidence of minor lateral slip on some pre-Quaternary and probably mid- to pre-Cenozoic faults. Even though vertical slip appears to be the main component of rupture in Quaternary faults of this region, some of the faults or even parts of faults possibly exhibit minor oblique slip that is difficult to recognize.

Cenozoic basins and associated Quaternary faults

At least 11 Cenozoic basins lie within our study area of northwest Trans-Pecos Texas and adjacent Chihuahua, Mexico. Geophysical investigations and borehole data (Gates et al., 1980; Keller and Peeples, 1985; Collins and Raney, 1991c; Jackson et al., 1993) indicate that the basins have different thicknesses of basin-fill deposits (Fig. 4), and it is likely that they have had different structural histories. Sediment thicknesses in the basins may reflect different sedimentation rates that were probably at least partly influenced by faulting rates. Cenozoic slip rates of faults within individual basins have also varied (Collins and Raney, 1991c).

The largest basin of this area, the Hueco Bolson, consists of two sub-basins that developed along the leading edge of the Laramide thrust belt and the southwest margin of the Diablo Platform (Figs. 2-4). Red Light Bolson also formed near the leading edge of the Laramide thrust belt. Two north—northeast-trending series of basins lie northeast of the overthrust belt and the Hueco and Red Light Bolsons. The westernmost series comprises the Northwest and

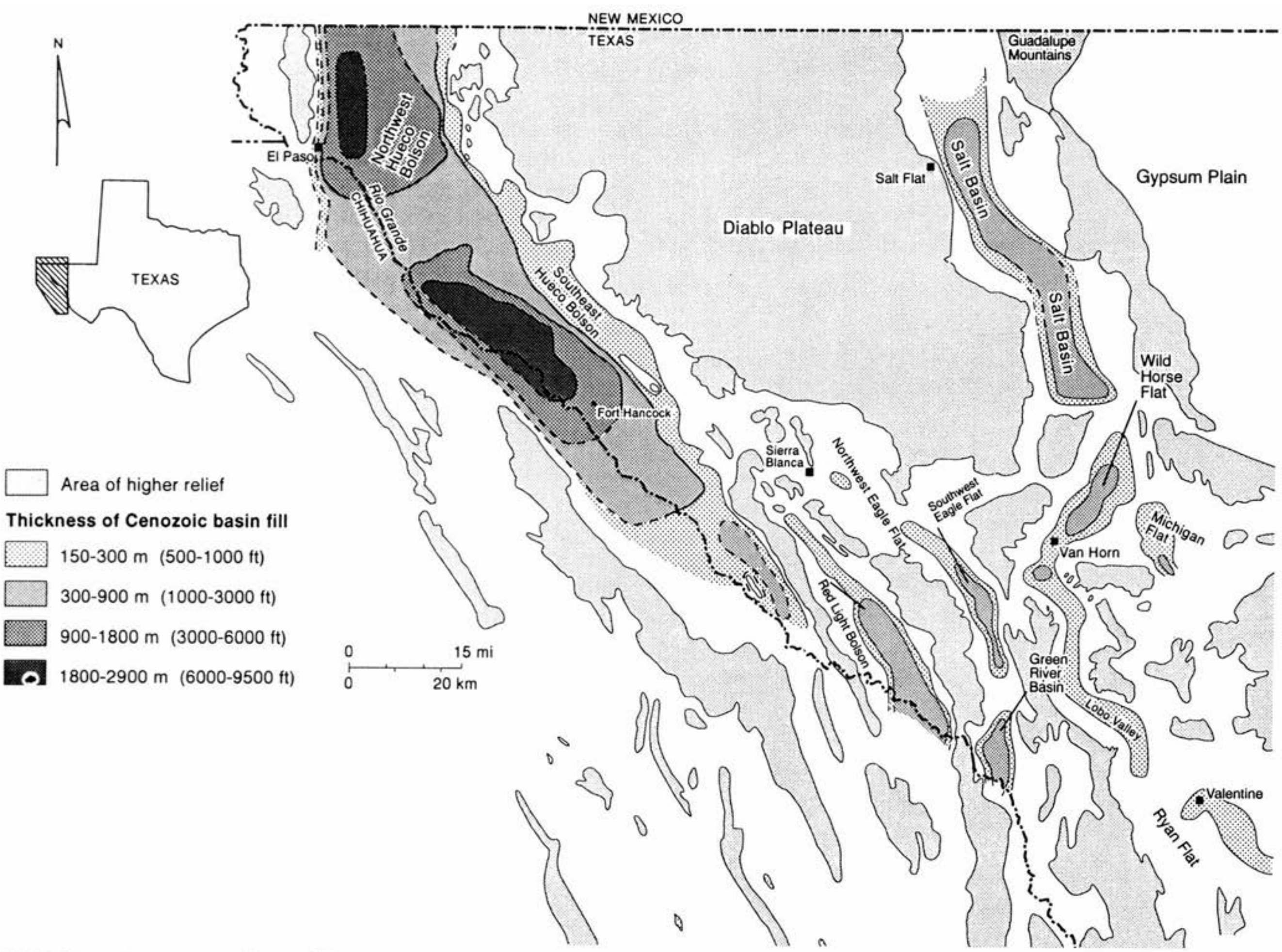


FIGURE 4—Locations and basin-fill thicknesses of Cenozoic basins, northwestern Trans-Pecos Texas. Basin-fill thicknesses from borehole and seismic-reflection data and from Gates et al. (1980) and Collins and Raney (1991c).

Southeast Eagle Flat Basins and the Green River Basin. The easternmost series comprises five basins of the Salt Basin graben system, the Salt, Wild Horse Flat, Michigan Flat, Lobo Valley, and Ryan Flat Basins.

Hueco Bolson

The Hueco Bolson, more than 105 mi long and most of it between 15.5 and 31 mi wide, is composed of two structural sub-basins (Collins and Raney, 1991c). The northwest Hueco Bolson trends northward and contains Quaternary faults that generally strike northward, whereas the southeast Hueco Bolson trends northwestward and contains faults that strike northwestward. The northwest Hueco Bolson is the southern extension of the Tularosa Basin in New Mexico. The southeast Hueco Bolson follows the pre-existing structural grain of the broad Texas Lineament, southwest edge of the Paleozoic Diablo Platform, and leading edge of the Laramide thrust belt. Cenozoic basin fill in both sub-basins is about 8800 to 9800 ft (Mattick, 1967; Ramberg et al., 1978; Wen, 1983; Collins and Raney, 1991c).

Numerous Quaternary faults (Fig. 5) exist in the Hueco Bolson (Seager, 1980; Henry and Gluck, 1981; Machette, 1987; Barnes et al., 1989a, b; Keaton et al., 1989; Collins and Raney, 1990, 1991a, b, c). Many of the faults of the northwest basin (fault zone 30, Fig. 5) are covered by wind-blown sand and have subtle surface traces. However, the East Franklin Mountains fault zone (faults 28a and 28b, Fig. 5), which has distinct scarps, has been one of the most active Quaternary fault zones in the bolson. This approximately 28 mi long fault zone can be subdivided into: (1) a 15.5 mi long north section, the East Franklin Mountains fault (fault 28a); and (2) a 15.5 mi long south section, the Southeast Franklin Mountains fault (fault 28b). Because the northern East Franklin Mountains fault (fault 28a) has been relatively undisturbed by El Paso development as compared with the southern fault section, it has been studied in the most detail (Machette, 1987; Collins and Raney, 1991c). This fault strikes N10°W—N10°E, dips eastward, and contains several fault strands. In general, scarps have compound-slope angles, the steepest slope angles ranging between 13 and 23°. Multiple rupture events have caused older Quaternary surfaces to be offset more than younger surfaces and most scarp heights range between 18 and 128 ft, although Machette (1987) measured scarps as small as 6.5 ft and as high as 197 ft. Middle Pleistocene sediments are vertically offset by at least 105 ft, middle to upper Pleistocene deposits are vertically displaced by at least 28 ft, and upper Pleistocene deposits are vertically offset by at least 14.5 to 19.5 ft. Machette (1987) reported that sediments of late Pleistocene to Holocene age are offset by this fault across a 12 ft high scarp. The approximate maximum throw during the

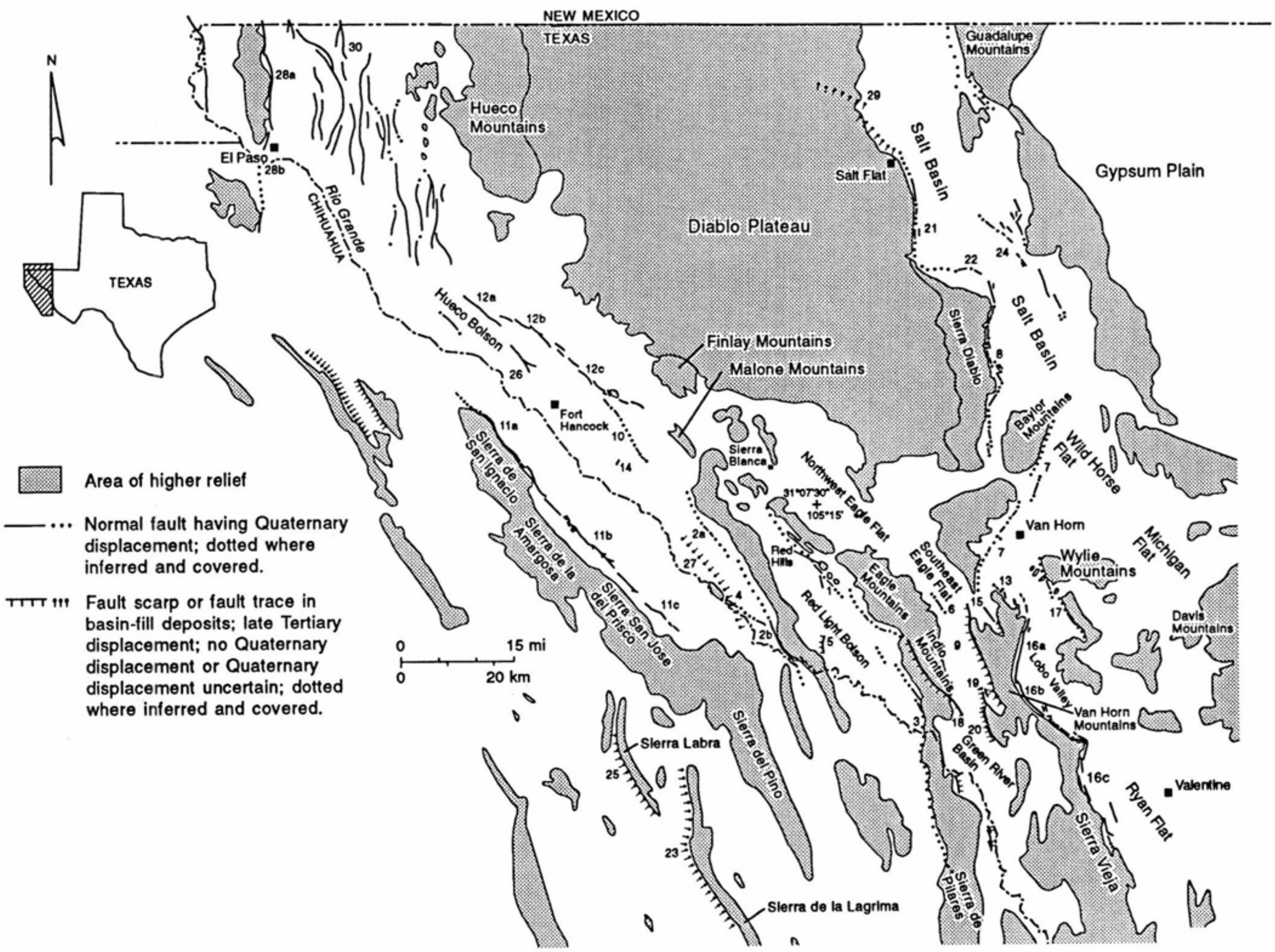


FIGURE 5—Map of Quaternary faults, northwestern Trans-Pecos Texas. Numbers identify faults discussed herein.

last rupture event ranged between 5.5 and 10 ft. The approximate average slip rate since the middle Pleistocene has been <0.25 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been roughly 15,000 to 30,000 yrs. Ongoing detailed investigations of this fault by Keaton (1993) may provide a more precise evaluation of the recurrence interval.

Quaternary faults of the southeast Hueco Bolson consist of two main zones that bound a 9 to 15 mi wide graben (Fig. 5). The Quaternary fault zone bounding the northeast margin of this graben is about 65 mi long and consists of six sections: (1) the 13 mi long Northwest Campo Grande fault (fault 12a), (2) the 13 mi long Middle Campo Grande fault (fault 12b), (3) the 21 mi long Southeast Campo Grande fault (fault 12c), (4) the 9.3 mi long Arroyo Diablo fault (fault 10),
(5) the 13.6 mi long North Caballo fault (fault 2a), and
(6) the 16 mi long South Caballo fault (fault 2b). These fault sections strike N25-75°W and dip southwestward between 60 and 89°. Grooves on the Southeast Campo Grande fault surface indicate dip-slip movement. Scarps of the fault sections are mostly between 5 and 37 ft high, and scarp slopes are locally as steep as 17, although they more commonly slope less than 7°. Scarps are well dissected, the trace of much of this fault zone being covered. The fault sections composing this zone have had different rupture histories. The Northwest Campo Grande fault (fault 12a) has vertically displaced middle Pleistocene deposits with stage IV—V pedogenic calcrete by 46 ft. The Middle Campo Grande fault (fault 12b) is covered by wind-blown sand and displacement is unknown. The Southeast Campo Grande fault (fault 12c) displays 32 ft of vertical displacement on middle Pleistocene deposits having stage IV—V calcrete, and 10 ft of vertical displacement on middle to upper Pleistocene deposits having stage **III—IV** calcic soils. Maximum vertical offsets during single faulting events of this fault have been 3 to 6.5 ft. Middle Pleistocene deposits having a stage N calcrete are vertically displaced by as much as 10 ft by the Arroyo Diablo fault (fault 10), and vertical displacement during the last surface rupture was about 2 ft. The North Caballo fault (fault 2a) has vertically displaced middle to upper Pleistocene deposits having stage III—IV calcic soils by 23 ft, and projection of an eroded middle Pleistocene alluvial-fan surface across the inferred fault trace suggests as much as 78 ft of vertical offset. Vertical offset during this fault's last surface rupture may have been as much as 5.5 ft. The South Caballo fault (fault 2b) is neither expressed by a scarp on middle Pleistocene fan surfaces nor does it displace colluvium that covers the fault at the base of the Quitman Mountains and edge of the basin. At some localities this fault does cut Quaternary(?)—Tertiary basin-fill sediments cropping out on both sides of the fault, but no scarp cuts fan surfaces.

Since the middle Pleistocene, average slip rates of these fault sections have ranged from <0.02 to <0.2 mm/yr. The North Caballo, Northwest Campo Grande, Southeast Campo Grande, and probably Middle Campo Grande faults have been the most active. The average recurrence intervals of large surface ruptures since the middle Pleistocene are approximately 20,000 to 40,000 yrs for the North Caballo fault, 35,000 to 70,000 yrs for the Northwest Campo Grande fault, 50,000 to 100,000 yrs for the Southeast Campo Grande fault, and 125,000 to 250,000 yrs for the Arroyo Diablo fault.

The fault zone flanking the southwest margin of the Hueco Bolson, the 43 mi long Amargosa fault zone, is composed of three sections (Fig. 5): (1) the 13 mi long Northwest Amargosa fault (fault 11a), (2) the 22 mi long Central Amargosa fault (fault 11b), and (3) the 6.2 mi long Southeast Amargosa fault (fault 11c). Fault sections strike N40-50°W and dip northeastward between 75 and 80° near the surface. This fault zone has the most distinct fault scarps in the southeast Hueco Bolson, scarp-slope angles ranging between 19 and 27°. Scarps are between 9 and 105 ft high, depending on the age of faulted sediments adjacent to the fault. Middle Pleistocene deposits having stage IV—V calcrete are vertically offset 78 ft across the Northwest Amargosa fault (fault 11a). Middle to upper Pleistocene deposits having stage III—IV calcic soils are vertically displaced by as much as 21.3 and 19.6 ft across the Northwest Amargosa and Central Amargosa faults, respectively. Younger upper Pleistocene deposits having stage II calcic soils are displaced vertically by 8.2 to 14.7 ft across the Northwest Amargosa fault. Results of aerial-photographic mapping suggest that young, possibly Holocene, deposits may be offset at some localities along this fault zone. The average slip rate since the middle Pleistocene of the northwest fault section has been <0.2 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been about 20,000 to 40,000 yrs.

Red Light Bolson

Red Light Bolson, about 56 mi long and 4 to 6 mi wide, trends northwestward and coincides with the northwest-striking, leading edge of Laramide thrust-faulting along the mountains east of the bolson (Figs. 3, 4). Crustal weakness related to the pre-Cenozoic structural grain probably influenced the development of this basin. Red Light Bolson contains several downto-the-southwest Quaternary fault scarps related to a major Quaternary fault zone along its east margin. Quaternary—Tertiary basin fill is thickest, more than 2000 ft thick (Gates et al., 1980), at the southeast part of the bolson.

The 54 mi long Quaternary fault zone at the east margin of the basin (Fig. 5) is composed of at least two sections, the 24.8 mi long West Eagle Mountains—Red Hills fault (fault 1) and the 31 mi long West Indio Mountains fault (fault 3). The West Eagle Mountains—Red Hills fault is expressed as a dissected 0.9 mi long scarp west of the Eagle Mountains and two en-echelon dissected scarps, 4.3 mi and 0.6 mi long, west of Red Hills. Much of this fault's surface expression has been eroded or is covered. This subtle scarp has scarp-slope angles only as much as 4° and scarp heights between 4.6 and 13 ft. Middle Pleistocene deposits having stage IV calcrete are vertically offset by 3 to 8 ft along the scarp west of Red Hills. An 11.5 ft deep trench that was dug across the fault trace revealed that the fault dips 85 to 88° southwestward and cuts gravelly deposits that include two faulted buried calcic soils on the downthrown block as well as a near-surface faulted calcic soil. Three surface ruptures have occurred since the middle Pleistocene. Throws of the surface-rupture events were between 1.6 and 4.2 ft. Maximum cumulative throw on middle Pleistocene deposits is 9 ft, whereas throw on middle to upper Pleistocene deposits is 1.6 ft. The approximate average slip rate of the West Eagle Mountains—Red Hills fault since the middle Pleistocene has been <0.02 mm/ yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been about 80,000 to 160,000 yrs.

The West Indio Mountains fault (fault 3, Fig. 5) consists of several strands, strikes N30-40°W, and dips about 70° southwestward. The scarp of one strand has a slope angle of 11 to 14° and a height of as much as 10 ft. Erosion has removed much of a middle Pleistocene alluvial-fan piedmont in this area, but projection of the fan piedmont on the upthrown and downthrown fault blocks at one locality suggests as much as 30 ft of vertical offset on these deposits. This fault strand vertically displaces middle—upper Pleistocene deposits having a 1 ft thick stage IV calcic soil by 6 to 8 ft, and upper Pleistocene deposits having a stage II to locally stage III calcic soil by 3 ft. Individual surface rupture events may have ranged from about 3 to 5 ft. Another fault strand of this fault section vertically displaces upper Pleistocene deposits by 8 ft. The average slip rate since the middle Pleistocene has been <0.1 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been approximately 40,000 to 80,000 yrs.

Northwest Eagle Flat, Southeast Eagle Flat, and Green River Basins

The Northwest Eagle Flat, Southeast Eagle Flat, and Green River Basins compose a north—northwest trending series of Cenozoic basins that lie immediately east of the leading edge of the Laramide thrust belt (Figs. 3, 4). Similar to the Red Light and southeast Hueco Bolsons, the pre-Cenozoic structural grain probably has influenced the orientation of these basins. Northwest Eagle Flat Basin trends northwestward and is about 15 mi long and as much as 7 mi wide. Most of this basin is filled by less than 500 ft of Cenozoic gravel, sand, silt, and clay; the thickest amount of basin fill penetrated by borings is about 900 ft (Gates et al., 1980; Jackson et al., 1993). Fault scarps do not occur in the middle Pleistocene to Holocene surficial sediments of the relatively shallow Northwest Eagle Flat Basin.

Southeast Eagle Flat Basin, about 25 mi long and 3 to 8.5 mi wide, has a trend that bends north—northwestward to northwestward and approximately parallels the structural grain of the leading edge of the Laramide thrust belt (Figs. 3, 4). This basin contains more than 2000 ft of Cenozoic basin-fill deposits (Gates et al., 1980). The deeper, south part of this basin is bounded by two normal faults that are expressed at the surface (Fig. 5), the 16.7 mi long West Van Horn Mountains fault (fault 9) and the 3 mi long East Eagle Mountains fault (fault 6). The west-dipping West Van Horn Mountains fault strikes northward at N30°W-N15°E at the southeast part of the basin. It is a well-expressed part of the regional Rim Rock fault zone (DeFord, 1969). Like Muehlberger et al. (1978), we found no evidence of Quaternary displacement along this fault. On the southwest margin of the basin, a short, 0.3 mi long scarp of the East Eagle Mountains fault (fault 6) strikes N10-20°W and dips eastward. This scarp cuts middle Pleistocene(?) alluvial-fan deposits and is currently inaccessible to ground investigations.

South of Southeast Eagle Flat Basin, the north-northwest-trending Green River Basin (about 15 mi long and 3 to 6 mi wide and similar to the Hueco and Red Light Bolsons), extends into Chihuahua, Mexico. Green River Basin contains more than 2000 ft of Cenozoic basin-fill deposits in its deepest, southernmost part. Subtle traces of three faults remain in the north part of this basin (Fig. 5), the 12.4 mi long Indio fault (fault 18), the 0.9 mi long China Canyon fault (fault 19), and the 3.4 mi long Green River fault (fault 20). Clutterbuck (1958) and Haenggi (1966) also mapped several short faults cutting Quaternary—Tertiary basin-fill deposits in the southern extension of the basin in Chihuahua, Mexico. The Indio fault, at the west margin of the basin and in the Indio Mountains, strikes N20-45°W, dips 65 to 75° southwestward, and contains multiple strands. Only the southeastern 3.7 mi of this fault exhibit a mappable trace along a fault-line scarp where Quaternary(?)—Tertiary gravel deposits are in contact with more resistant bedrock composed of Cretaceous limestone and sandstone and Tertiary trachyte and tuff. This fault has no demonstrable Quaternary fault displacement. The China Canyon and Green River faults have dissected but subtle scarps, and Quaternary(?)—Tertiary basin-fill deposits are faulted against Tertiary gravel. Whether these faults have ruptured since the late Tertiary is not known.

Salt Basin Graben system

The north—northwest-trending Salt Basin Graben system comprises a 124 mi long series of fault-bounded basins that from north to south include the Salt, Wild Horse Flat, Michigan Flat, Lobo Valley, and Ryan Flat Basins (Fig. 4). The west side of the Salt Basin Graben system is characterized by an approximately 105 mi long series of Quaternary faults (Fig. 5). Some Quaternary faults also exist along parts of the east side of the graben system. Many of the Quaternary faults of this system were previously identified by Twiss (1959), King (1965), Belcher et al. (1977), Goetz (1977, 1980), and Muehlberger et al. (1978, 1985). The long series of west boundary faults can be divided into (1) the 59 mi long West Salt Basin fault zone, (2) the 25 mi long East Carrizo Mountain—Baylor Mountain fault zone, and (3) the 40.3 mi long West Lobo Valley fault zone.

The northern Salt Basin is more than 62 mi long and 7.4 to 15.5 ml wide; the south part is sometimes referred to as the Salt Flat area. Tertiary to Quaternary basin fill in the Salt Basin is more than 2000 ft thick in some areas (King, 1965; Goetz, 1977, 1980; Gates et al., 1980). Goetz (1977, 1980) recognized that the graben is asymmetrical and that the thickest basin-fill deposits are on the west margin. At the west margin of the basin, the West Salt Basin fault zone consists of at least four sections: the 11.8 mi long Dell City fault (fault 29), the 14.2 mi long East Flat Top Mountains fault (fault 21), the 8.3 mi long North Sierra Diablo fault (fault 22), and the 23 mi long East Sierra Diablo fault (fault 8). The Salt Basin has developed across the Paleozoic Diablo Platform, and abrupt changes in strike in the west boundary Quaternary fault zone reflect the pre-Cenozoic structural grain and zones of pre-Cenozoic crustal weakness (Figs. 2, 5). Specifically, the North Sierra Diablo fault (fault 22) coincides with a part of the pre-existing Babb flexure, and the Dell City fault (fault 29) coincides with the pre-existing Otero fault of Goetz (1985). The boundary or gap between the south part of the East Sierra Diablo fault (fault 8) and the north part of the East Carrizo Mountain-Baylor Mountain fault (fault 7) may be a covered west-northwest-striking late Tertiary fault that coincides with a part of the pre-Cenozoic Victorio flexure.

Of the four Quaternary fault sections bounding the west margin of the Salt Basin, we studied the East Sierra Diablo fault (fault 8, Fig. 5) in the most detail. This fault, striking northward at N10°W-N20°E and dipping eastward, is composed of a series of at least 11 en-echelon fault strands and about 60% of the fault's length is covered or inferred. The longest continuous scarp, at the north part of the East Sierra Diablo fault, is 3.1 mi long and 6 ft high, exhibiting a scarp-slope angle of 8°. At the north part of this longest scarp, the faulted surficial sediments consist of an upper, unconsolidated, 6.5 ft thick alluvial-fan package of probable Holocene-upper Pleistocene boulder- to pebble-sized gravel and sand containing a stage II-I calcic soil. This upper sediment package overlies an older, middle Pleistocene gravel and sand alluvial-fan sediment package that has a more than 3 ft thick stage IV calcrete horizon which probably marks a buried alluvial-fan surface. Vertical offset on the upper sediment package is about 5 ft. Displacement of the lower, stage IV calcrete horizon cannot be measured along most of the scarp without excavation because the horizon is unexposed in most of the gullies on the down-thrown fault block. At one locality, however, along the south part of the 3.1 mi long scarp, the stage IV calcrete horizon is vertically displaced by 13 ft. The approximate average slip rate since the middle Pleistocene has been low at <0.03 mm/yr, although relatively young upper Pleistocene-Holocene deposits are faulted. The average recurrence interval of large surface ruptures since the middle Pleistocene has been about 80,000 to 160,000 yrs.

At the east margin of the Salt Basin the 40 mi long West Delaware Mountains fault zone (fault 24, Fig. 5) strikes N25-45°W and dips southwestward. This fault zone consists of multiple subparallel and en-echelon fault strands, and the north part of the zone consists of a broad, 1.8 to 3 mi wide zone. Most scarps are between 0.6 and 4.3 mi long. Our field studies focused on the scarp of the northwesternmost, 4.3 mi long fault strand of the zone. This scarp has a slope as great as 11° and a height of as much as 7.5 ft. Soils in this area are gypsiferous as well as calcic. Upper Pleistocene to Holocene(?) deposits having a soil that has a stage II calcic morphology are displaced vertically by about 5.2 ft. Where the scarp intersects a younger upper Pleistocene-Holocene(?) surface, the 4 ft high scarp has a slope of 9° and vertical displacement across these younger deposits is about 3 ft. Unfaulted arroyo terrace deposits are more than 5700 yrs old, according to a corrected radiocarbon date taken from carbon (humic soil material) in the unfaulted terrace (R. Langford, per. comm. 1993).

Wild Horse Flat Basin lies south of Salt Basin and is about 18.6 mi long and 9.3 mi wide (Fig. 4). Quaternary-Tertiary basin-fill deposits are thicker than 1000 ft (Gates et al., 1980) and the basin is bound on the west by a 25.4 mi long Quaternary fault zone, the East Carrizo Mountain-Baylor Mountain fault (fault 7, Fig. 5). This fault strikes northeastward at N10-40°E and dips southeastward. Although about 85% of this fault's length is covered and inferred, three subtle 0.6 to 1.8 mi long scarps are associated with it. One of the scarps west-southwest of Van Horn has a scarp-slope angle of 5° and height of 6 ft. Vertical displacement of middle Pleistocene deposits having a stage IV calcrete is 5.2 ft. The average slip rate since the middle Pleistocene has been <0.01 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been approximately 125,000 to 250,000 yrs.

Michigan Flat Basin, which lies east of Wild Horse Flat Basin, is about 16 mi long and 6 mi wide. Similarly to Wild Horse Flat Basin, it contains upper Cenozoic basin-fill deposits that are locally thicker than 1000 ft (Gates et al., 1980). Quaternary fault scarps are absent in this basin.

Lobo Valley Basin, south of Wild Horse Flat Basin, is about 34 mi long and 5.6 to 7.5 mi wide. Tertiary-Quaternary basin-fill deposits are mostly less than 1000 ft thick, but the asymmetrical basin has thicker Cenozoic fill along its west half (Gates et al., 1980). The west margin of the basin is bounded by the distinct 40.3 mi long West Lobo Valley fault zone which is composed of four sections (Fig. 5): the 2.5 mi long Fay fault (fault 13), the 11 mi long Neal fault (fault 16a), the 12.4 mi long Mayfield fault (fault 16b), and the 15.5 mi long Sierra Vieja fault (fault 16c). The boundary between the south part of the East Carrizo-Baylor Mountains fault (fault 7) and the north part of the West Lobo Valley fault zone (faults 13 and 16a, Fig. 5) is a broad, left-stepping en-echelon gap that coincides with the inferred northeast margin of the Texas Lineament (Muehlberger and Dickerson, 1989).

The Fay fault strikes N5-20°W, dips eastward, and consists of two en-echelon scarps. The scarp of the north part of this fault has a scarp-slope angle of 13° and height of 4.6 ft. Middle Pleistocene deposits that have stage IV calcrete are vertically offset by 4 ft. The average slip rate since the middle Pleistocene has been <0.01 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been about 125,000 to 250,000 yrs.

The Neal fault strikes northward at N10°W—N25°E, dips eastward, and consists of a main 8.4 mi long scarp and several associated en-echelon short scarps that are as much as 1.2 mi long. The main scarp has a distinct single slope with slope angles ranging between 14 and 22° and heights ranging between 5.2 and 15.7 ft. On the upthrown block the bedrock is shallow and locally exposed. Vertical offset of middle Pleistocene alluvial-fan deposits capped by a stage IV calcrete is at least 16.4 ft. The stage IV calcrete horizon or multiple, less-developed calcic horizons is/are presumed to be buried on the downthrown fault block. A possible upper Pleistocene—Holocene(?) alluvial surface that has a stage II calcic soil is vertically offset by at least 3 ft. The average slip rate since middle Pleistocene has been approximately <0.05 mm/yr. The average recurrence interval of surface ruptures since the middle Pleistocene has been approximately 60,000 to 125,000 yrs.

The Mayfield fault (fault 16b) strikes N30-55°W and dips northeastward. At one locality the fault dips 70 to 80° and striations preserved along the fault surface indicate that slip has been normal, parallel to the fault's dip. The Mayfield fault has a single-slope scarp, its scarp-slope angles ranging between 18 and 23° and heights between 13 and 23 ft. Similar to the Newal scarp, bedrock is shallow and locally crops out on the upthrown fault block. Vertical offset of middle Pleistocene alluvial-fan deposits capped by a stage IV calcrete is as much as 19.6 ft. Holocene(?) arroyo terrace deposits are not faulted. The fault's average slip rate since the middle Pleistocene has been <0.05 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been approximately 50,000 to 100,000 yrs.

The Sierra Vieja fault (fault 16c) strikes N30°W—N20°E, dips eastward, and consists of multiple en-echelon strands. Some of the strands have 15 ft high compound scarps that have steep scarp-slope angles of as much as 20°. Bedrock is shallow and locally crops out on the upthrown fault block. Vertical offset of possible middle Pleistocene alluvial-fan deposits is as much as 27 ft, and vertical offset of possible upper Pleistocene—Holocene(?) alluvial fan deposits is as much as 11.4 ft. The last surface rupture may have produced as much as 5 ft of vertical displacement if the steep part of the compound scarp was caused by a single rupture. Holocene(?) arroyo terraces are not displaced by the fault. Landslide deposits, including boulder-sized material, exist along the flank of Sierra Vieja, although whether the landslides were caused by seismic activity is not known. The average slip rate since the middle Pleistocene has been <0.1 mm/yr. The average recurrence interval of large surface ruptures since the middle Pleistocene has been about 35,000 to 70,000 yrs. The Sierra Vieja and Mayfield faults are distinct Quaternary faults closest to the 1931 Valentine earthquake, an MM intensity VII (M = 6.4) earthquake near Valentine, Texas (Dumas et al., 1980; Doser, 1987).

The Quaternary fault bounding the east side of Lobo Valley, the 12.4 mi long West Wylie Mountains fault (fault 17, Fig. 5), strikes N10-30°W and dips southwestward. Aerial-photograph studies indicate that two 0.6 mi long scarps are present. At one scarp, Tertiary—Quaternary(?) alluvium is faulted against Permian limestone. The other scarp cuts across Quaternary(?) alluvial-fan deposits.

Ryan Flat Basin (Fig. 4), southeast of Lobo Valley Basin, is about 31 mi long and 12.4 mi wide. Quaternary—Tertiary basin-fill deposits are probably mostly less than 1000 ft thick (Gates et al., 1980). Quaternary fault scarps remain unidentified in this basin.

Summary

1. Development of the late Cenozoic basins and associated normal faults has been at least partly influenced by zones of crustal weakness due to pre-late Cenozoic tectonism. Basin orientations and Quaternary fault strikes reflect the earlier structural grain.

2. The Hueco Bolson has been the most active Cenozoic basin, locally having as much as 9800 ft of fill. Other basins contain less than 3000 ft of Cenozoic basin fill, and several basins have less than 1000 ft of Cenozoic fill.

3. The Hueco Bolson contains the most active post-middle Pleistocene faults, which exhibit as much as 32 to 102 ft of vertical displacement across middle Pleistocene deposits. This basin also contains at least two faults that probably have had Holocene movement, although several faults associated with basins composing the Salt Basin Graben system and one fault bounding the southern Red Light Bolson also have had late Pleistocene to Holocene rupture.

Acknowledgments

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A look at carbonate rocks

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Abstract—Large volumes of oil and gas are produced from carbonate rocks on a worldwide basis. Reservoir types and productive capabilities are most often related to rock type and the facies to which the rock belongs.

The principal parameters of carbonate rocks are chemical composition, grade size, sorting, packing, identification of grains in the rock, cement, color, alteration or recrystallization, and porosity. Original porosity of carbonates depends on the kind and packing of original particles. Secondary porosity is reduced by infilling usually related to some particles or enhanced because some types of grains are dissolved. Carbonate sediments are organic detritus. The range of solubility of organic detritus is very large. Fossils present in the carbonates are clues to the source of the detritus. Additional research is needed on faunal relations of facies and rock types.

Ore recovery, well completion, and enhanced oil recovery are more successful when parameters of the carbonate rocks are extensively studied. A simplified approach to carbonate description is discussed.

Introduction

Important ores and large volumes of oil and gas are produced from carbonate rocks on a worldwide basis. Reservoir types and productive capability are most often related to rock type and the facies to which the rock belongs. Broad new understanding of carbonate rocks came with the publication of *Classification of Carbonate Rocks* by the American Association of Petroleum Geologists in 1962.

The principal parameters of carbonate rocks are chemical composition, grade size, sorting and packing, faunal and particulate content, cement, color, alteration or recrystallization, and porosity. Original porosity in carbonate rocks reflects the kind and packing of original particles. Secondary porosity is reduced by infilling that usually relates to some particles or is enhanced because some types of grains are dissolved. Carbonate sediments consist primarily of organic detritus. The range of solubility of organic particles is very large. Fossils present in the carbonates are clues to the source of the detritus. Additional research is needed on the study of faunal relations of facies and rock types.

Ore recovery, well completion, and enhanced oil recovery are more successful when parameters of the carbonate rocks are thoroughly described.

Interparticulate porosity characteristic of siliciclastic rocks also occurs in carbonate rocks. In addition, carbonate rocks exhibit unique pore geometry resulting from organic skeletal structure, organic bridging or binding, and dissolution. Carbonate grains commonly show much more open packing than do siliciclastic rocks.

The principal parameters of carbonate rocks are chemical composition, particle (grade) size, sorting and packing (fabric exclusive of grain size), faunal and particulate composition, cement, color, alteration, and recrystallization and porosity.

Chemical composition

Limestone and dolomite are the primary carbonates. Many carbonate particles originate as aragonite, which is rare in lithified carbonates because it is metastable and inverts to calcite in a very short time. Other organic detritus is a vast array of solid-solution calcites, which are crytalline phases with accessory minerals that originated as skeletal calcite of marine organisms. The solubility range of these compounds is often the clue to secondary porosity in carbonates. Solution porosity is commonly controlled by the type of organic calcite because of the great range of solubility of organic calcites.

Grade size

Grade size is one of the prime parameters of sedimentary rocks. The profession has long accepted the Wentworth (1922) grade scale as a standard for classification of detrital particles. The four main categories are gravel or rudite (> 2 mm), sand or arenite (2—h/16 mm), silt (^{1}/16-^{1}/256 mm), and clay or lutite (< ^{1}/256 mm).

Some carbonate rocks are so extensively recrystallized that the original fabric is obliterated. No published scale for crystal size has been widely accepted, although several workers have proposed such scales (DeFord, 1946; Folk, 1959).

Sorting and packing (exclusive of grain size)

Particles of carbonates exhibit the same characteristics of sorting and packing as quartzose sandstones, but they are usually not as closely packed. Shape and size of arenaceous particles relate closely to energy levels of the hydrodynamic regime, whereas those of carbonate particles characteristically depend on their biological origin (Fig. 1). Encrusting organic growths create textural types unique to carbonate rocks. Bioturbation and organic abrasion also create unique textural patterns.

Relations of matrix to aggregate in terms of skewness and kurtosis have long concerned petrologists. Recent works on carbonates manifest great concern for relations of matrix to aggregate. Amstrat in Canada and the Rocky Mountain area stressed the framework versus void-filler concept in carbonates during the late 1960s and the early 1970s. They significantly influenced the industrial use of the concept in exploration for carbonate reservoirs. Dunham (1962) influenced a majority of geologists with his approach to textural classification based upon the framework versus void-filler concept.

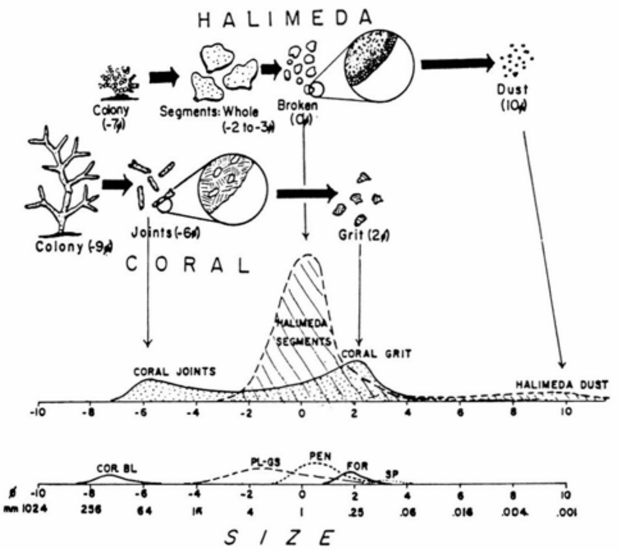

FIGURE 1—Carbonate sand, Isla Perez, Bahia de Campeche, Yucatan. The sand size grade illustrates that the control on the sediment results from the structure and architecture of the component organisms. The diameters of the particles are shown in millimeters and in Krumbein (1934) phi scale.

Faunal and particle content

Organic detritus constitutes the bulk of grains of most carbonate rocks (Fig. 1). Grabau (1913) used the term bioclastic for rocks that owe their essential character to organisms. Cayeux (1935) and Johnson (1951) based their classification of limestones on dominant organic remains, i.e. crinoidal, foraminiferal, oolitic, algal, etc. The organic detritus composing carbonate rocks holds important clues to depositional history and subsequent alteration that affect reservoir properties of the rocks. It is important that more attention be paid to the organic composition and fabric of these rocks. Classes of particles found in carbonates include organic fragments, lime mud, indeterminate calcitic fragments, pre-existing rock fragments, accessory minerals, non-carbonate organic matter, reworked fragments such as composite grains, lumps and grainstone, fecal and non-fecal pellets, organically coated grains such as oolites, pisolites, oncolites and oolitically coated fragments, and fragmental and non-fragmental skeletal material.

Cement

Calcite and dolomite are the common cementing minerals in carbonates. Anhydrite and gypsum cements are far more ubiquitous than realized; salt may also be common in cement. Chert occurs as cement in a great variety of carbonates. Siderite, ankerite, limonite, and other related minerals occur rarely as cement in carbonate rocks.

Fine to coarsely crystalline equant spar, bladed or fibrous spar, and aphanitic calcite are the most common calcite cements. Cement may be developed in optical continuity to grains (syntaxial) or as crusts showing no optical continuity to grains. It is often difficult to distinguish cement from recrystallized matrix in carbonate rocks.

Although dolomite is often cited as a cement in carbonates, recent work suggests that it occurs largely as an alteration product.

Color

Color is an important attribute of carbonate rocks. The GSA color chart is a most useful tool in determining colors.

Alteration

Processes of recrystallization (inversion of aragonite to calcite) or calcite to calcite (changing crystal size), dolomitization, and silicification are the common forms of alteration. Either process may change the carbonate with or without obliterating the original sedimentary texture. Anhydritization is also much more common than realized. Glauconite and phosphate are products of alteration. Void spaces created by dissolution are an important product of alteration. Importantly, alteration may deleteriously affect porosity. Just as importantly, alteration may increase porosity. All carbonate rocks show some degree of alteration (Fig. 2). Categorizing and classifying degrees of alteration has not been adequately solved. To a large extent, this is because alteration is commonly not pervasive but differentially related to types of organic grains. Therefore, alteration within a carbonate generally differs from grain type to grain type and among the constituents of the matrix.

Porosity

Interparticulate porosity is a common property of carbonates because they are detrital rocks, an attribute shared with siliclastic rocks. The amount of interparticulate porosity is a function of grade size, sorting, and packing. The shape of organic particles generally results in higher interparticulate porosity than in comparably shaped terrigenous particles. This is because of the "bridging" from concavo-convex shells and the shape and internal structure of highly irregular organic material. Void spaces within skeletal fragments also contribute porosity unique to carbonate rocks. Encrusting organisms such as foraminifera, bryozoans, and algae may grow with arched spaces that contribute to porosity, which is generally unique to carbonates.

Filling of void spaces by fine-grained matrix and by secondary crystal infilling, as cement, often deleteriously reduces porosity.

Dissolution within carbonate rocks produces interconnected voids and channels that may range from a few microns to several inches in diameter. Dissolution is a common feature in most producing carbonate reservoirs and greatly enhances the reservoir quality.

Fracturing is common in carbonates. Fractures contribute to the volume of production from carbonate reservoirs.

Classification

One of the earliest attempts at classification of carbonate rocks was Grabau's (1912) *Principles of Stratigraphy.* A growing interest in carbonate rocks led to publication in 1962 of the AAPG Memoir 1 on *Classification of Carbonate Rocks;* nine articles reviewed and

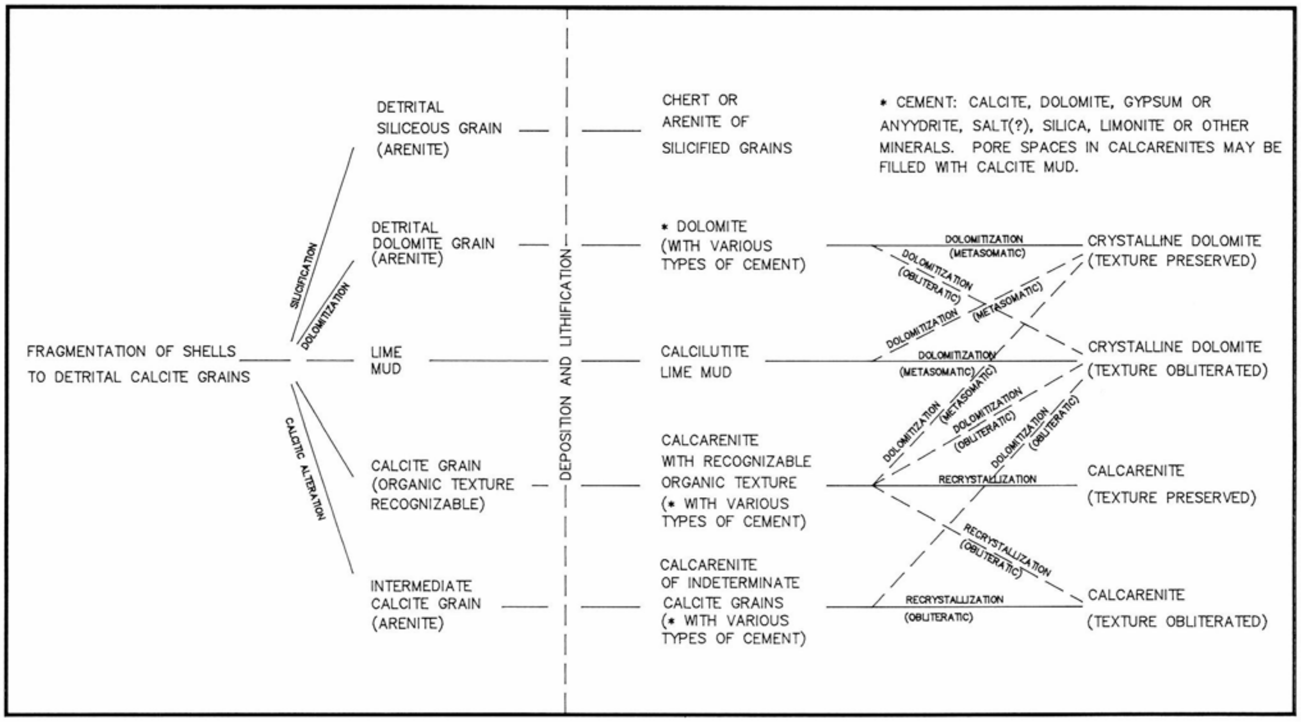

FIGURE 2—Simplified diagenesis of carbonate grains.

Descriptive (classific–ation)	Folk (1962)	Leighton et al. (1962)	Feray et al. (1962)	Dunham (1962)	Powers (1962)	Thomas (1962)	Nelson (1962)	Imbrie et al. (1962)	Plumley et al. (1962)
Framework	Interclastic Oolites Fossils Pellets	Detrital Ls Skeletal Ls Oolitic Ls Pellet Ls Lump Ls Algal encrusted Ls	Skeletal–Secretionary (shells) Nonskeletal Accretionary (Oolites)	Grainstone	Cse clastic Ls Calcarenite Calcarenitic Ls	Skeletal Nonskeletal Organic Lattice Congl Silt Ls Microgranular Micrograined	Fragmental Ls Shell debris Granular Ls Ls congl.	Oolite Oolitic Grapestone	Quiet water Slightly agit. Mod. agit. Strongly agit.
Inplace organisms	Biolith	Coralline Ls Algal Ls	Secretionary corals, etc.	Boundstone	Residual organic	Organic Lattice	Skeletal Ls	Coralgal	Quiet water
Mud–size constituents	Micrite and (Dismicrite)	Micrite	Nonskeletal particulate (paste)	Mudstone	Aphanitic Ls	Cryptograined Ls	Aphanitic Ls Cryptogranular Cryptoxln Calcilutite	Lime mud	Quiet water
Framework with organ. mud infilling	Intramicrite Oomicrite Biomicrite Pelmicrite	Detri. Micrite Skel. Micrite Ool. Micrite Lump Micrite	----	Packstone Wackestone	Calcarenitic Ls	Skeletal W> Microgranular Micrograined or Cryptoxln Mat.	----	Skeletal & pellet mud	Intermittently agitated
Cement (secondary)	Sparry calcite	----	nonskeletal particulate (paste)	----	----	----	Aphanitic fraction	----	----
Framework with cement infilling	Intrasparite Oosparite Biosparite	----	----	----	----	----	----	----	----

FIGURE 3—Comparison of classifications in AAPG Memoir 1.

gave classification for some aspects of carbonates. The classification of Folk (1959) was generally accepted by a majority of geologists. Dunham's (1962) *Classification of Carbonate Rocks According to Depositional Texture* has become the one most commonly accepted by geologists, but generally it is inadequate for the intended purpose. The nine schemes of classification in the AAPG Memoir 1 are based, for the most part, on a set of parameters known to each writer. A comparison of these schemes is shown in Fig. 3. Numerous classifications of carbonate rocks have been proposed, but some are too simple and some are so complex that they are not useful without serious modification. Most are primarily petrographic and fail to encompass the necessary concepts of sedimentary petrography, paleontology, biology, geochemistry, stratigraphy, and hydrology.

Classifications have been descriptive, genetic, or a combination of the two. Classifications that combine the genetic and descriptive approach have yielded mixed blessings and tribulations. Controversy as to the best approach began long ago and still continues.

Carbonate rocks are important to us as a tool in stratigraphic analysis. The explorationist's interest is not solely in the details of petrography or paleontology per se, but is directed to how carbonate rocks relate to the stratigraphic changes or facies spectrum. J. Wilson wrote extensively on *Carbonate Facies in Geologic History* (1975) without including a classification of carbonate rocks.

Carbonate rocks result from the accumulation of organic detritus which originates as aragonite or metastable calcitic (solid solution) compounds secreted by tissues of marine animals. The chemistry of the shell is controlled by the chemistry of the organism. There is a great difference in solubility index to organic calcite. However, as soon as the animal's shell becomes separate, it begins to change chemically.

Carbonate rocks and the particles of which they are composed are subject to a large number of chemical changes before the calcite becomes relatively stable. Some patterns of change are suggested in Fig. 3. It is obvious that the history of diagenesis of carbonate rocks can be, and in most cases is, very complex.

Carbonate reservoirs of the Ghwar Oil and Gas Field in Saudi Arabia are oolites or calcarenite grainstones without matrix and with a minimum of cement. The Dayton Abo Reef in Chaves County, New Mexico, produces oil from dolomites from which anhydrite has been dissolved. The Permian dolomites of the East Pampa Oil and Gas Field in the Texas Panhandle have most of their abundant fusulinids dissolved to create extensive porosity. Many other examples of porosity related to internal constituents of carbonate rocks can

		grade scale		alteration	gmc-grains mat/cem	type cement	type grains	porosity		color
		detrital	crystalline					grade	type	
LIMESTONE	DOLOMITE	rudite >2mm	coarsely crystalline >2mm	moderately altered, strongly altered, relic texture only; original texture obliterated	boundstone, grainstone, wackestone, mudstone*; kurtosis, skewness, sorting index, etc.; *(Applies only in siltite and lutite)	spar, fn xln, organic, anhydrite/gypsum, fe, etc calcite, dolomite	pellets, ooliths, terrigenous detrital, reworked, fossils, etc.	tight, slight, moderate, very porous (or percent)	interparticulate, intergranular, fossilomoldic, dissolution, etc.	Wide range of color (See GSA Color Chart)
		arenite 2.0–0.06 mm (vc, c, m, f, vf)	medium crystalline 2.0–0.06 mm							
		siltite 0.06–0.004 mm	finely crystalline 0.06–0.004 mm							
		lutite <0.004mm	very finely crystalline <0.004mm							

FIGURE 4—A plan for describing carbonate rocks.

be listed. Composition and diagenetic history of carbonate rocks are also important in localizing ore deposits or oil reservoirs.

The most effective plan for describing carbonates is one that takes into account the fundamental properties of the carbonates as detrital particles that are chemically unstable. A plan for describing carbonates is outlined in Fig. 4.

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The role of diagenetic studies in flow-unit modeling: San Andres Formation, Yoakum County, Texas

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Abstract—The Permian San Andres Formation represents one of the most prolific hydrocarbon-producing intervals of the Permian Basin. Dolostone lithofacies intercalated with thin evaporites accommodate highly compartmentalized reservoirs resulting from complex depositional and diagenetic histories. This compartmentalization often facilitates the use of these reservoirs in flow-unit studies. Perhaps more important than the relationship of productive intervals to depositional facies is the degree to which diagenetic processes have influenced reservoir properties.

Detailed petrographic evaluation of the reservoir in question, though often overlooked, should be an integral part of flow-unit studies. Once a diagenetic sequence is established, the information may be incorporated into the fades model in order to better understand how to subdivide the reservoir. Such an investigation has been conducted on the San Andres Formation in Reeves Field of southeastern Yoakum County, Texas. Here, multi-stage diagenetic overprints are superimposed on depositional fades that vary in degree of lateral extent, thereby complicating the geometries of individual productive zones within the reservoir.

Analysis of the reservoir reveals that Reeves San Andres sediments were subjected to dominant diagenetic processes including dolomitization and sulfate emplacement, both of which are major factors in porosity evolution and preservation, and a variety of minor processes that have had little effect on reservoir quality. The recognition of diagenetic fades, an understanding of the processes that have created them, and identification of the implications of these processes on reservoir properties are vital to any flow-unit study.

Introduction

The Permian San Andres Formation represents one of the most prolific hydrocarbon-producing intervals of the Permian Basin. Peritidal dolostone lithofacies intercalated with thin evaporite deposits create a classic example of the layer-cake stratigraphy. Reservoirs within these strata often are highly compartmentalized, having resulted from complex depositional and diagenetic histories. This compartmentalization frequently facilitates the use of these reservoirs in flow-unit studies. Perhaps more important than the relationship of productive intervals to depositional facies, however, is the degree to which diagenetic processes have enhanced or diminished reservoir properties.

Detailed petrographic evaluation of the reservoir in question, though often overlooked, should be an integral part of flow-unit studies. Once a diagenetic sequence is established, the information may be incorporated into the facies model in order to better understand how to subdivide the reservoir. Concepts developed in a recent study of the Reeves San Andres Field (Henderson, 1992) are currently being applied there in an effort to define flow units. Reeves Field, located in extreme southeastern Yoakum County, Texas (Fig. 1), is a mature Northern Shelf San Andres play that has been subjected to waterflood for nearly 30 years. Discovered in 1957, Reeves Field, as of 1992, has produced roughly 26 million barrels of oil, exceeding initial reserve projections of 20 million barrels (Chuber and Pusey, 1969). Within Reeves Field, multi-stage diagenetic overprints are superimposed on depositional facies that vary in degree of lateral extent, thereby complicating the geometries of individual productive zones within the reservoir.

This investigation focuses on the Reeves Unit which occupies a large portion of the total field area (approximately 6800 acres). A detailed study of six cored wells within the Reeves Unit provides a basis for development of depositional and diagenetic models. The applicability of these models is extended throughout the study area by incorporating core and petrophysical data from additional 95 wells. Of particular interest are the diagenetic processes that have induced major changes in reservoir characteristics. Petrographic analysis reveals that the Reeves San Andres sediments were subjected to cyclic invasions of dolomitizing, sulfate-emplacing, and low-salinity fluids. The recognition of diagenetic facies, an understanding of the processes that have created them, and identification of the implications of these processes on reservoir properties are vital to any flow-unit study.

Reservoir facies

Reeves San Andres sediments were deposited in peritidal marine environments on a shallow, pro-

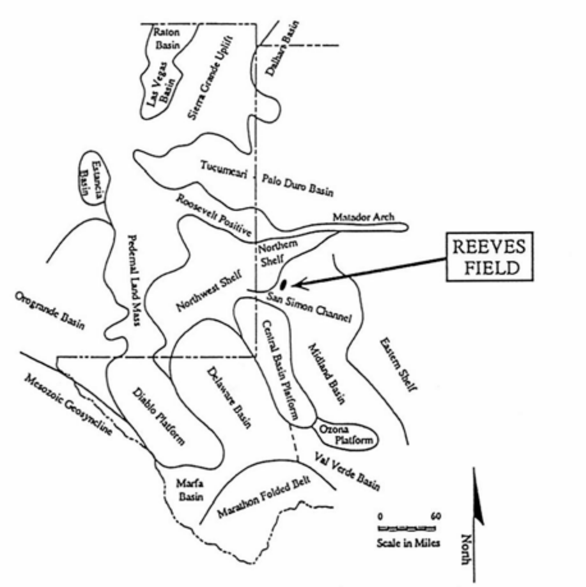

FIGURE 1—Geologic setting of west Texas and eastern New Mexico illustrating location of Reeves Field.

grading shelf. The facies spectrum includes, in a seaward direction, supratidal sabkha, intertidal flat, and shallow-marine fades (Fig. 2). Topography along a nonlinear and prograding shoreline influenced the lateral distribution of depositional facies.

Depositional facies are arranged in repetitive upward-shoaling sequences, or hemicycles (Wilson, 1975), the most complete of which contain a vertical succession of subtidal, intertidal, and supratidal deposits. Supratidal deposits, however, commonly are absent. Within the cored interval of this study, at least 20 such depositional cycles are recorded in a less than 200 ft interval (Fig. 3). Unfortunately, apart from being able to identify supratidal facies on the basis of log responses to sulfates, there exists no relationship that facilitates the determination of depositional facies from logs.

From a reservoir perspective, subtidal deposits are the most important. Subtidal deposits may include, in an upward succession, basal shaley mudstone/wackestone, wackestone, and packstone/grainstone subfacies (Fig. 2). Each subfacies is not necessarily present in all depositional cycles. Practically all subtidal facies are characterized by abundant secondary intercrystalline porosity due to pervasive neomorphic dolomitization. This porosity is best preserved in the wackestone subfacies (Fig. 4A) and, together with lesser amounts of secondary and tertiary moldic porosity, creates the best reservoir facies.

Subtidal wackestones comprise most of total thickness of the Reeves San Andres section. Thicknesses of these subfacies range from less than one to more than 40 ft. Subtidal packstone/grainstone subfacies (Fig. 4B) contain lesser amounts of intercrystalline porosity, but some primary intergranular and secondary and tertiary moldic porosity. Moldic porosity, where preserved, is largely isolated and contributes to effective porosity only through the intercrystalline network. Where large amounts of primary intergranular pores are unoccluded by dolomite and sulfate cements, packstone/grainstone subfacies may approach reservoir potential. Isolated intervals of tertiary intracrystalline porosity may be present in the form of hollow dolomite rhombs in both wackestone and packstone or grainstone subfacies (Fig. 5A, B), often resulting in unusually high values of porosity and permeability. The basal mudstone/wackestone subfacies consists of dense, shaley dolomite with minor amounts of intercrystalline porosity and no moldic porosity.

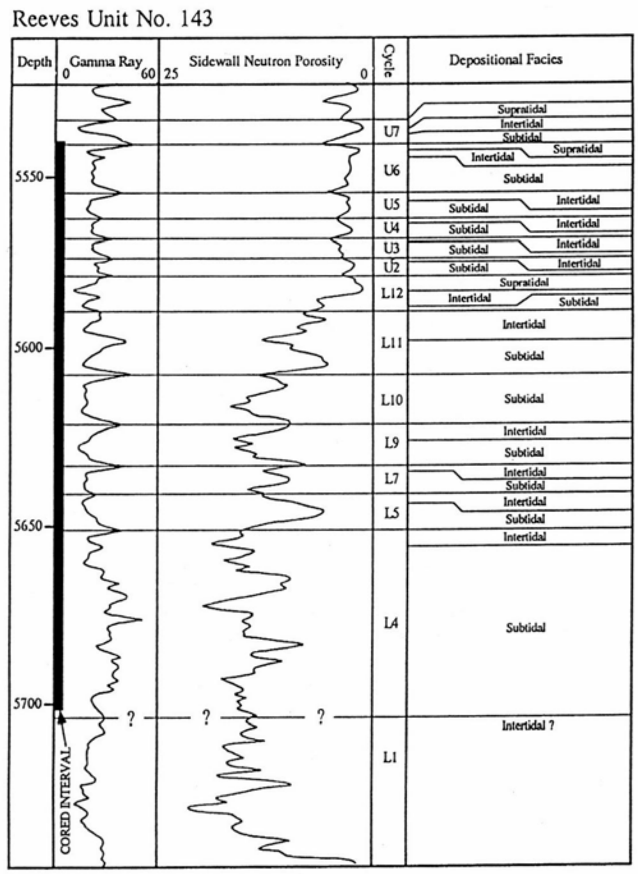

FIGURE 3—Type log of lower San Andres section in Reeves Field illustrating depositional cycles and facies described in core.

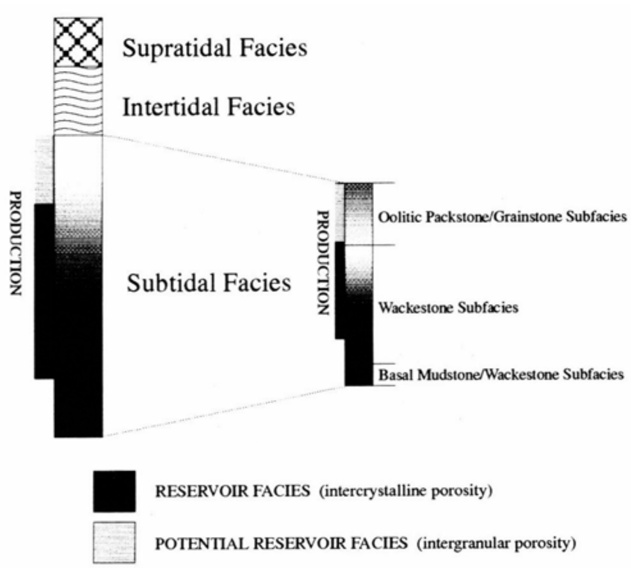

FIGURE 2—Depositional facies and subfacies observed in core of the Reeves San Andres section and their relationship to depositional cycles and productive intervals.

Diagenesis and effects on reservoir properties

The purpose of this study is neither to embrace nor propose any specific mechanism of diagenesis, but rather to discuss the cause and effect relationship of those processes having significant impact on reservoir quality. For a comprehensive review of models of dolomitization, the reader is referred to Hardie (1987). A number of papers concerning diagenetic mechanisms in the San Andres Formation is included in Bebout and Harris (1990). Models invoked to explain multi-stage diagenetic overprints within the Reeves section are discussed in detail by Henderson (1992).

San Andres sediments of Reeves Field were subjected to a variety of diagenetic processes, most of which had some influence on reservoir properties. Dominant diagenetic events that had significant effects on porosity and permeability include dolomitization and sulfate emplacement. A host of minor diagenetic processes, including silicification and the emplacement of kaolinite/dickite and fluorite, had little effect on reservoir quality.

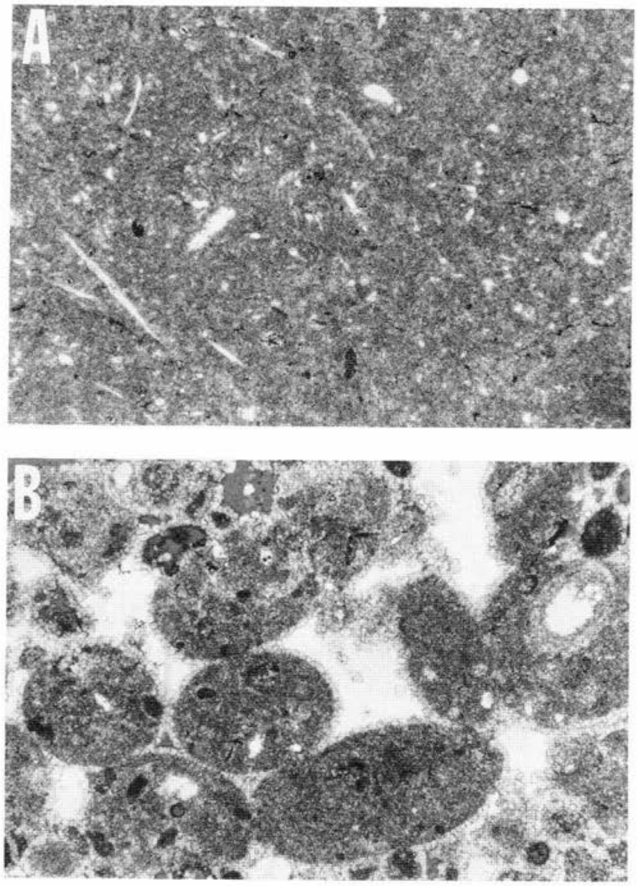

FIGURE 4—Subtidal depositional facies of the Reeves San Andres section. **A**, Wackestone subfacies: This subfacies, consistently the best reservoir facies, is characterized by finely crystalline dolostone with abundant secondary intercrystalline porosity. Moldic porosity, created by dissolution of skeletal material, is important in the lower reaches of the subfacies. **B**, Upper packstone/grainstone subfacies: Thin rims of coarsely crystalline dolomite cement surround allochems. Larger intergranular voids generally are occluded by anhydrite cement. Subfacies may approach reservoir quality where primary intergranular porosity is preserved. Field of view is 1.8 mm wide.

Observation of the paragenetic relationships between crystals of diagenetic minerals (primarily dolomite and anhydrite) and pore space allows the ordering of diagenetic processes into a chronological sequence. Many similar investigations of San Andres fields have been undertaken during the past two decades (Welsh, 1982; Glenn, 1985; Leary and Vogt, 1990). The diagenetic sequence observed in the Reeves San Andres section reflects the invasion of dolomitizing, sulfate-emplacing, and low-salinity fluids. Furthermore, subtle differences in the diagenetic sequences observed in different depositional cycles indicate that these invasions were of a cyclic nature.

Dolomitization

Pervasive dolomitization of the Reeves San Andres had the most extensive effects on reservoir properties. The entire cored inteval has been completely neomorphically dolomitized, a process by which the dolomite is thought to have replaced original aragonitic muds (Jacka, 1975). The principal effect of dolomitization is the creation of abundant secondary intercrystalline porosity present in practically all

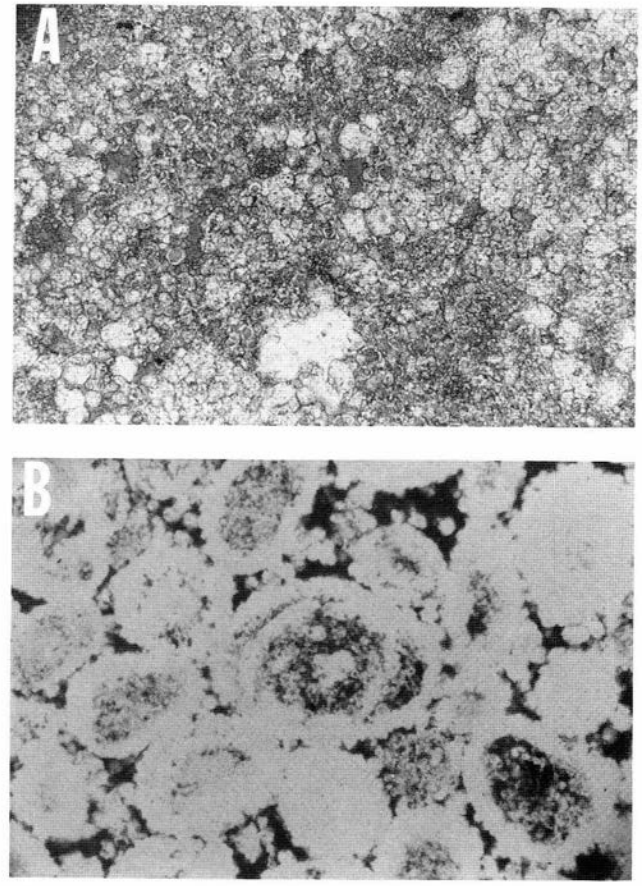

FIGURE 5—Tertiary intracrystalline porosity of Reeves San Andres section. **A**, Subtidal wackestone characterized by abundant hollow dolomite rhombs. Core analysis of this sample yields porosity of 24% and permeability of 7.0 md. **B**, Hollow dolomite rhombs within core of partially dissolved ooid and intergranular voids of grainstone subfacies. Pillbox structures are more apparent under reflected light. Field of view is 1.0 mm wide.

depositional fades. Minor amounts of biomoldic porosity have been generated, primarily in wackestone and some grainstone subfacies, as the result of penecontemporaneous dissolution of aragonitic, calcitic, and siliceous skeletal material.

With the replacement of mud-sized sediments by dolomite, there will be an enhancement of reservoir-flow characteristics because of an increase in particle size (Lucia, 1990). This generally translates into an increase in permeability by way of the "rearrangement" of porosity in the reservoir. Therefore, it is essential to consider the relationship of dolostone fabrics to depositional facies when defining flow units in the San Andres Formation. Productive fades of the Reeves section are characterized by idiotopic to hypidiotopic dolostone fabrics in which relatively large amounts of intercrystalline porosity are preserved (Fig. 6). Within a depositional cycle there generally is an upward change from idiotopic and hypidiotopic fabrics (more porous) in the subtidal wackestone and packstone/grainstone subfacies, to xenotopic fabrics (tight) in overlying intertidal fades.

The effect of dolomitization within grainstone intervals generally is represented by a slight reduction in porosity due to cementation. Unlike dolomitized muddy sediments, flow characteristics within grain-

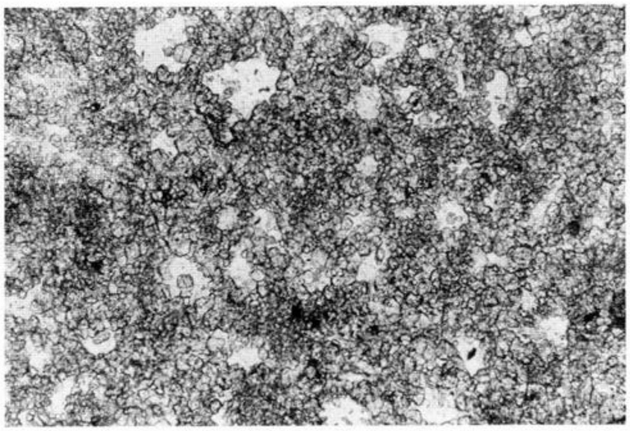

FIGURE 6—Idiotopic to hypidiotopic dolostone fabric of wackestone subfacies. Preserved secondary intercrystalline porosity is characteristic of productive facies within Reeves Field. Field of view is 1.0 mm wide.

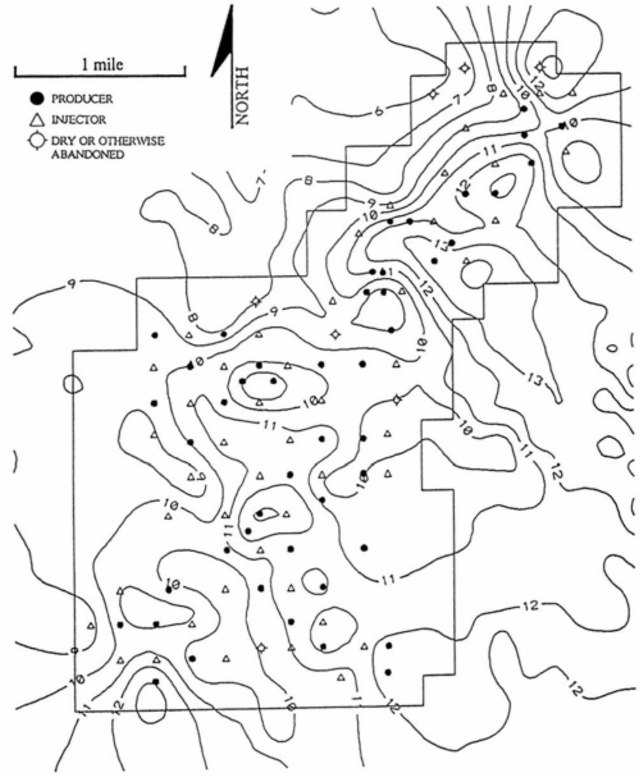

FIGURE 7—Computer-generated average-porosity map of Reeves Unit Main Pay. Data are from core analyses of 101 wells. Contour interval is 1% porosity.

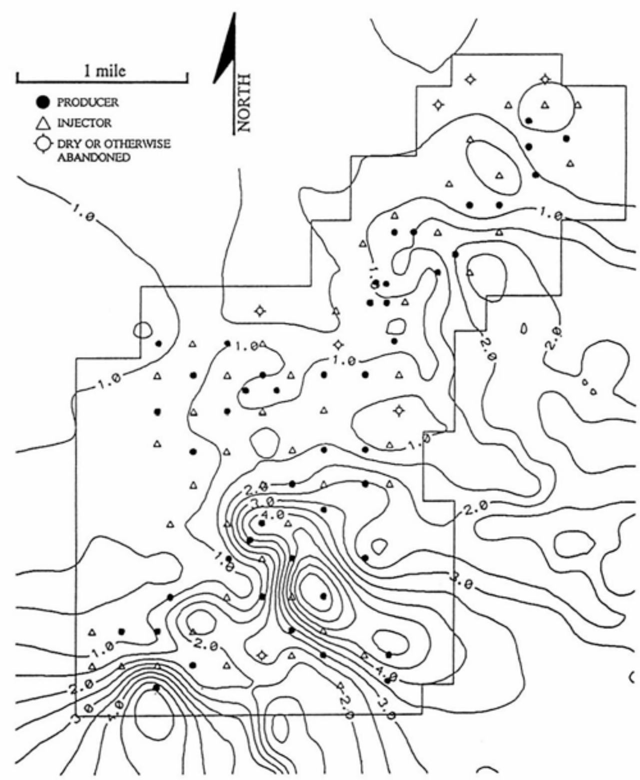

FIGURE 8—Computer-generated average-permeability map of Reeves Unit Main Pay. Data are from core analyses of 101 wells. Contour interval is 0.5 md.

stone intervals generally are not enhanced because of original particle sizes that are greater than the size of replacive dolomite crystals (Lucia, 1990). Dolomite cements occur as primary rims around grains in grainstones and, less frequently, intergranular void fills. Subtidal grainstone intervals commonly are cemented by isopachous intergranular rims of relatively coarse, translucent rhombs (Fig. 4B).

Dolomitization has resulted in basinward increases in porosity and permeability as illustrated in Figs. 7 and 8. These increases may be attributed to a distal increase in flow characteristics resulting from a corresponding increase in crystal size, and may reflect the direction in which diagenetic fluids migrated. Welsh (1982) recorded a basinward increase in dolomite rhomb size from 1 to 20 µm within supratidal/interidal facies, and from 25 to 310 µm in subtidal fades over a distance of nearly 60 mi within the lower San Andres in the Tucumcari Basin. However, the maximum shelfto-basin transect in Reeves Field is only 2.9 mi. An increase in rhomb size similar to that noted by Welsh (1982) may not be discernible over such a short distance. It may be that such a direction increase simply reflects a higher percentage of porous subtidal facies that thicken subtly to the southeast. A more ominous proposition is the possibility that diagenesis may be controlled by structure—a notion that could be argued for on the basis of the similarity between average porosity and permeability maps (Figs. 7, 8) and structure on top of the lower San Andres (Fig. 9). This apparent relation remains a topic of interest in Reeves Field.

Though flow units tend to be on the same scale as the depositional cycles described in this study, detailed core description reveals that the reservoir is actually compartmentalized on a scale far below the resolution of any wireline log. Intervals that range from a few inches to more than 3 ft thick within each depositional cycle may readily absorb water applied to slabbed core. Twelve such porous and permeable intervals were observed in one subtidal fades approximately 10 ft thick. The permeability barriers separating these porous streaks often consist of dense hypidiotopic to xenotopic dolomite fabrics with little

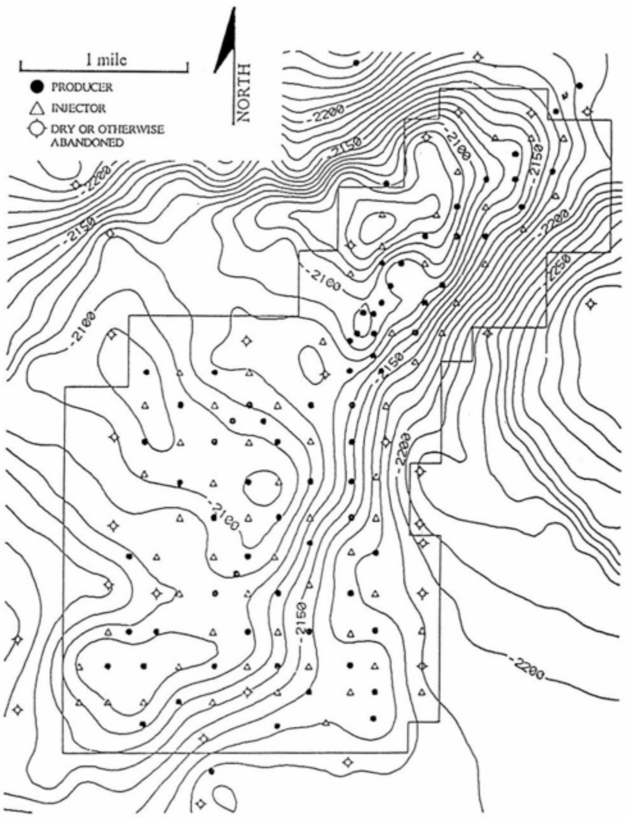

FIGURE 9—Computer-generated structure-contour map of Reeves Field developed on top of Main Pay. Contour interval is 10 ft. Note similarity of structure-contour map to average-porosity and average-permeability maps. Does this imply a connection between structure and diagenesis?

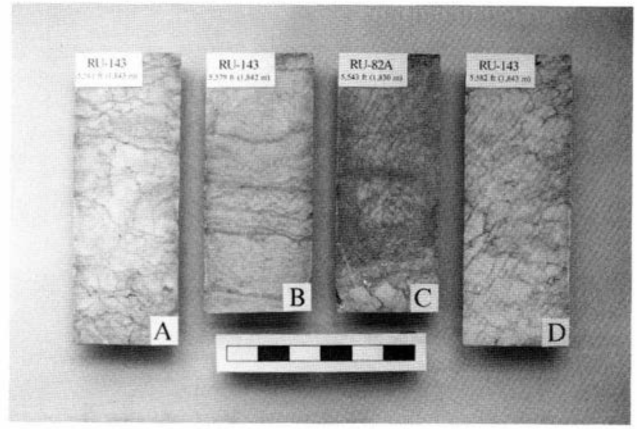

FIGURE 10—Morphologies of supratidal sulfate observed in Reeves San Andres. **A**, Nodular mosaic (chickenwire) anhydrite. **B**, Enterolithic (ptygmatic) anhydrite. **C** and **D**, Possible anhydrite pseudomorphs after subvertically oriented gypsum crystals.

or no intercrystalline porosity. It has not been determined whether, though it appears possible that, these small-scale porous streaks or corresponding tight streaks may be correlated from one well to another within Reeves Field.

Initial sulfate emplacement

Two stages of sulfate emplacement, the timings of which are somewhat problematic, have occurred in the San Andres section of Reeves Field. Sulfate emplacement is responsible for the reduction, although minor, of all types of porosity and has occurred in all depositional facies, though there is a tendency for the amount of sulfate to increase upward within a depositional cycle. The initial stage of sulfate emplacement will be discussed here, with the second stage addressed in a following section.

Initial sulfate emplacement is thought to have occurred during or immediately following dolomitization. Magnesium-charged brines that infiltrated the sediments resulted from Mg/Ca ratios elevated due to the loss of Ca by evaporative concentration and precipitation of gypsum and anhydrite (Kinsman, 1969; Patterson and Kinsman, 1982). Primary gypsum was replaced by anhydrite with continued progradation of the sabkha. Supratidal sulfate morphologies include individual anhydrite nodules, enterolithic anhydrite, nodular mosaic (chickenwire) anhydrite, and anhydrite pseudomorphs after gypsum (Fig. 10). Supratidal sulfate emplacement has had no impact on reservoir properties, though the resulting morphologies may be important as seals.

Occurring penecontemporaneously with dolomitization and supratidal precipitation of sulfate minerals was the replacement of dolomitized matrix and allochems by poikilotopic anhydrite crystals, or "porphyroblasts," recognized on the basis of stairstepped margins or rectangular reentrants between the replacive anhydrite and dolomite matrix. This process had only very minor effects on reservoir properties. Porphyroblast emplacement was primarily a one-stage process involving only the replacement of matrix (Fig. 11A). However, some porphyroblasts originated as mold-filling cements with subsequent matrix replacement (Fig. 11B). Anhydrite crystals nucleated in shell molds created by dissolution during dolomitization. When pore-filling was completed, centrifugal replacement of the matrix surrounding the filled mold began. Though apparently thought by some authors to have occurred during deep burial (White, 1984), evidence suggests that porphyroblast emplacement occurred rather early in the diagenetic history of Reeves San Andres sediments.

Meteoric (fresh-water) diagenesis

Authigenic silica, kaolinite/dickite, and fluorite are present in limited amounts throughout the Reeves section and reflect the influx of lower-salinity fluids at shallow depths of burial. Because these minerals exhibit some fades specificity and are in many instances replaced by a second generation of anhydrite, it is inferred that they were emplaced relatively early in the diagenetic history of the San Andres. However, it is impossible to acertain by petrographic evidence whether these minerals formed as the result of more than one stage of fresh-water influx.

Authigenic quartz is present in subtidal and intertidal facies as megaquartz rosettes and chalcedony. Megaquartz rosettes (Fig. 12A) are the most common morphology and are present only within felted-lath sulfate nodules of the subtidal and intertidal facies. Chalcedony is observed in only one instance where it is entirely replacive of a burrow-filling sulfate nod-

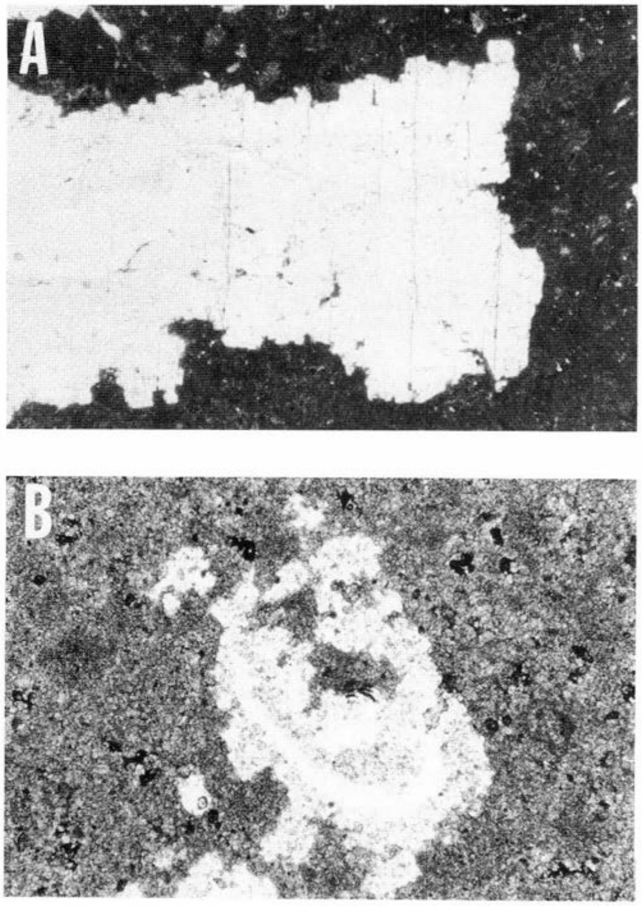

FIGURE 11—Poikilotopic anhydrite crystals (porphyroblasts) resulting from: **A**, matrix replacement during initial sulfate emplacement (field of view = 1.8 mm), and **B**, cementation of skeletal mold with subsequent replacement of surrounding matrix (field of view = 1.0 mm).

ule in the subtidal facies. Silica is notably absent in the supratidal deposits of Reeves Field, thus suggesting that silicification was a phreatic, rather than vadose, diagenetic process. This is in contrast to other studies of San Andres diagenesis that attribute silicification to burial diagenesis (Leary and Vogt, 1990).

Dutton and On (1986) indicated that Tertiary uplift of the Guadalupian section in west Texas and eastern New Mexico created a meteoric recharge zone and sufficient eastward dip to allow the migration of meteoric fluids into the subsurface. Leary and Vogt (1990) cited this model as the cause for deep burial silicification and precipitation of kaolinite in the San Andres of some Central Basin Platform fields. One problem inherent to this model is that silicification and associated diagenetic processes would surely be wholesale and exhibit no evidence of facies specificity. This is absolutely not the case in Reeves sediments because silica is limited to only subtidal and, rarely, intertidal deposits. Kaolinite/dickite and fluorite (Fig. 12B, C) are observed only in subtidal deposits and are of such rarity that they are not readily apparent in core or thin sections. Another problem with the model suggested by Leary and Vogt (1990) concerns the timing of these meteoric diagenetic processes. They conclude that silicification is a late-stage, deep-burial event. However, in the Reeves San Andres practically all

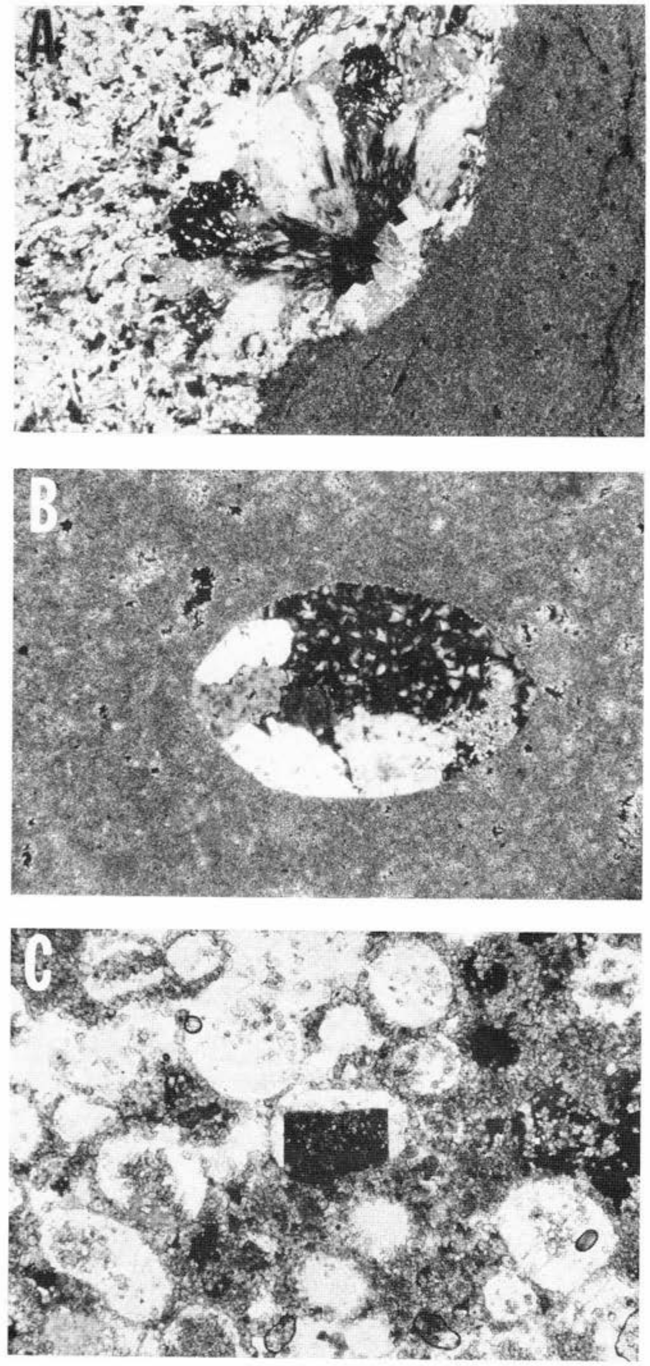

FIGURE 12—Evidence of meteoric diagenesis within Reeves San Andres section. **A**, Megaquartz rosettes replacing felted-lath anhydrite nodule. Rosette is subsequently replaced by second-generation anhydrite porphyroblasts. **B**, Kaolinite/dickite precipitated as cement in ostracode mold. **C**, Cubic fluorite crystal precipitated in oomold. Remaining pore space subsequently occluded by second-generation anhydrite cement. Field of view is 1.0 mm wide.

examples of silica, whether megaquartz or chalcedony, are partially replaced by the second stage of anhydrite (to be discussed later).

The invasion of meteoric fluids also caused the dissolution of much initial sulfate, which must be inferred on the basis of indirect evidence. In isolated instances, porphyroblasts contain inclusion-free felted-lath fabrics surrounded by minor amounts of monocrystalline anhydrite. Because felted-lath sulfates cannot form the rectangular reentrants of these porphyroblasts, it is concluded that the initial anhydrite crystals were subjected to at least partial dissolution and the resulting voids occluded by a second generation of sulfate cement.

Anhydrite porphyroblasts commonly are dissolved to produce crystal-moldic porosity which generally is among the most common pore types in some San Andres reservoirs (Welsh, 1982; Glenn, 1985); however, such porphyroblast molds are not preserved in the Reeves San Andres. The lack of molds indicates that porphyroblasts may not have been subjected to complete dissolution, or any molds simply were occluded by the second-generation sulfate.

Hollow dolomite rhombs, a form of tertiary intracrystalline porosity, are recognized both in idiotopic, or sucrosic, subtidal dolostones (Fig. 5A) and within cores of dissolved ooids (Fig. 5B) in grainstone subfacies. Jacka (1984) attributed this phenomenon to the preferential replacement of the organic-rich cores of some dolomite rhombs. Intracrystalline porosity was produced by subsequent dissolution of this anhydrite. However, hollow dolomite rhombs may also be associated with the development of limpid dolomite overgrowths on original replacive dolomite rhombs with later dissolution of the original rhombs (Leary and Vogt, 1990). Tertiary intracrystalline porosity is often overlooked as an important pore type in many San Andres fields though, as within Reeves Field, hollow dolomite rhombs may significantly increase porosity and permeability (Fig 5A).

Second sulfate emplacement

The second stage of sulfate emplacement was largely a process of cementation, though some placement did occur. Anhydrite and barite/celestite were precipitated as cement in skeletal molds and oomolds, porphyroblast molds, intergranular voids, and fenestral voids. Anhydrite also is replacive of silica and kaolinite/dickite. The primary reservoir effect of this second stage of sulfate emplacement is the reduction of primary intergranular porosity in subtidal-grainstone subfacies.

Moldic cement is the most common representation of the second-generation sulfate. Intergranular anhydrite cements are characteristic of subtidal-grainstone subfacies (Fig. 4B). These cements are commonly poikilotopic and may be replacive of the allochems that they cement. Anhydrite may be partially to completely replacive of mold-filling dickite. In addition, anhydrite porphyroblasts may replace authigenic megaquartz rosettes centripetally (Fig. 12A).

The lack of preserved sabkha fades that form aquacludes prohibiting the vertical migration of diagenetic fluids may have allowed the deposits of a given depositional cycle to be influenced by diagenetic events taking place during or following deposition of overlying younger strata. It is inferred that the second generation of sulfate in a given cycle is related to the invasion of dolomitizing/sulfate-emplacing (initial) fluids in overlying successive cycles. However, second-generation sulfate is observed within cycles that are capped with a supratidal aquaclude. This might suggest that sulfate-emplacing fluids were in part derived from dissolution of the evaporitic aquaclude itself.

Discussion and conclusion

Diagenetic studies should be an integral part of any flow-unit modeling study, particularly in formations like the San Andres in which reservoirs may exhibit a great degree of diagenetic heterogeneity. Compartmentalization generally is closely related not only to the distribution of depositional facies but to the influence of diagenetic overprints as well.

Detailed analysis of the Reeves San Andres indicates that the reservoir was subjected to a variety of diagenetic processes, some of which have affected reservoir properties and thereby complicated the geometry of individual productive zones. Dolomitization has been the dominant diagenetic process and has modified the reservoir through the creation of abundant secondary intercrystalline porosity which increases effective porosity of the reservoir. Minor amounts of moldic porosity were developed penecontemporaneously with dolomitization. Cementation by dolomite in grainstone facies was negligible. The initial emplacement of sulfate within the Reeves San Andres was primarily a replacement phenomenon within subtidal reservoir facies. Here the initial stage is manifested by the presence of poikilotopic anhydrite porphyroblasts that have replaced the matrix and occluded minor amounts of moldic pores. The most significant consequence of initial sulfate emplacement is the precipitation of supratidal sulfate forms which serve as reservoir seals. Major enhancement of porosity and permeability in isolated intervals was caused by meteoric dissolution which produced hollow dolomite rhombs and "recreated" some previously occluded secondary moldic pores. Although there are two documented mechanisms by which these "pillbox" crystals may form, each involves dissolution. Hollow dolomite rhombs are often overlooked as important pore types within the San Andres Formation. Other meteoric processes have had insignificant effects on reservoir properties. Large-scale porosity occlusion occurred during the second emplacement of sulfate. Most moldic porosity and some primary intergranular pores were occluded by poikilotopic anhydrite cements. Occlusion of secondary intercrystalline porosity was trivial.

Detailed petrographic analysis not only can help create a fades model for a particular field but can also aid in establishing a diagenetic sequence. This is accomplished through simply observing the paragenetic relationships between pore space and diagenetic minerals. More important are the changes in reservoir properties that these diagenetic processes have induced, and how the chronological sequence has influenced the evolution and occlusion of porosity. The information gained can then be incorporated into what is known about facies distribution to get a comprehensive model of the reservoir.

Acknowledgments

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Variations in cementation exponent (m) and fracture porosity, Permian Delaware Mountain Group Sandstones, Reeves and Culberson Counties, Texas

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Abstract—In order to calculate accurate volumetric oil reserves in the Permian Delaware Mountain Group, reliable values for cementation exponent (m) are required in addition to the other reservoir parameters. The porosity in these siltstone and very fine-grained sandstone reservoirs is intergranular and therefore cementation exponent should be approximately 2.0. However, crossplots of core-derived porosity versus formation-resistivity factor (Fr) indicate an average cementation exponent (m) of 1.80. The lower cementation exponent is a result of minor amounts of fracture porosity. Comparison of the Delaware Mountain Group porosity versus Fr crossplot with the laboratory data of Rasmus (1987) reveals a similar decrease in Fr with a decrease in porosity due to the presence of 1% fracture porosity.

The lower cementation exponent (1.80) results in the calculation of substantially lower water saturations, which increases the amount of volumetric oil reserves. Analysis of three zones in the Bell Canyon and Cherry Canyon Formations of the Delaware Mountain Group using standard methods of calculating water saturation resulted in volumetric oil reserves (based on 40 acre drainage) of 1.37 to 1.42 million barrels. However, using a cementation exponent of 1.80 resulted in volumetric oil reserves of 1.55 million barrels. The 9-13% increase in volumetric oil reserves from only three zones in the Bell Canyon and Cherry Canyon Formations illustrates the critical importance of combining core analysis with log analysis when doing volumetric reserve calculations.

Introduction

The Permian Delaware Mountain Group of west Texas and southeastern New Mexico is subdivided into the Bell Canyon, Cherry Canyon, and Brushy Canyon Formations. The Delaware Mountain Group consists of up to 3000 ft of multiple siltstones and very fine-grained sandstones interbedded with minor thin limestones and organic-rich shaly siltstones. The siltstone and sandstone facies represent deep-water turbidites deposited in the Delaware Basin (Gardner, 1992). The interbedded limestones and organic-rich shaly siltstones represent non-turbidite basin sedimentation and constitute the reservoir seals (Gardner, 1992).

In the Delaware Basin are numerous fields that produce from the Delaware Mountain Group (Fig. 1), and active exploration is still ongoing. For example, in 1989 the Hat Mesa Delaware Field, which has estimated recoverable reserves of 1.2 million barrels, was discovered as a result of a re-entry of an older Pennsylvanian Morrow gas well (Thomerson and Asquith, 1992).

In the study area of the Screwbean and Geraldine Fields (Fig. 1) the Bell Canyon and Cherry Canyon reservoir facies consist of siltstones (Mz = 0.05-0.06 mm) and very fine-grained sandstones (Mz = 0.080.10 mm) with porosities ranging from 10 to 22%. The porosity in these reservoirs is intergranular and the cementation exponent (m) thus should be approximately 2.00 (Focke and Munn, 1987).

Core analysis and petrography

Forty-six one and one-half inch diameter core plugs from both the Bell and Cherry Canyon Formations were selected for core analyses. The analyses were performed at the Center for Applied Petrophysical Studies (CAPS) at Texas Tech University and consisted of porosity and permeability measurements together with the determination of cementation exponent (m). All Ro (wet resistivity) values were measured at confining stress and then used to calculate formation re-

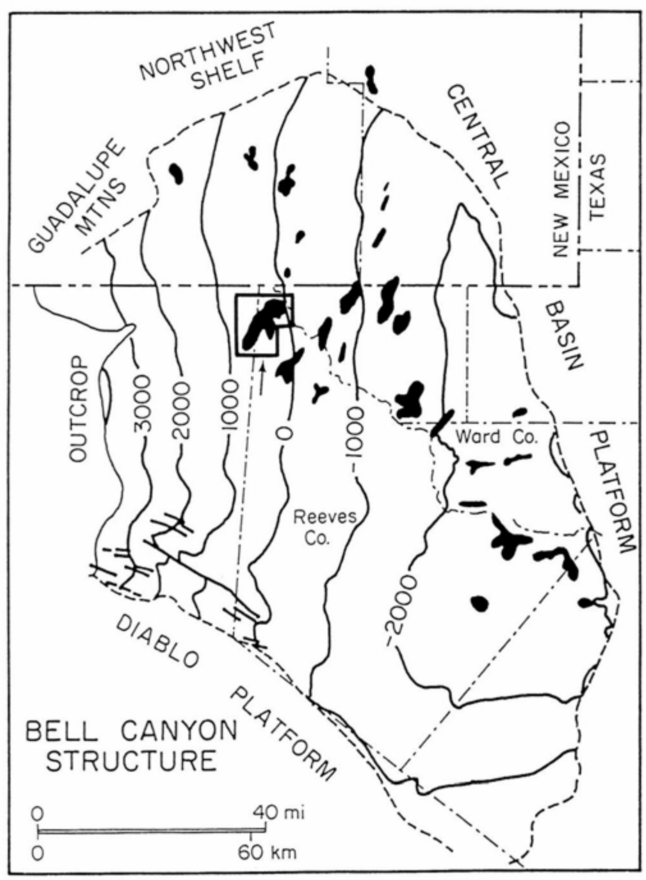

FIGURE 1—Index map of study area in the Screwbean and Geraldine Fields, Reeves and Culberson Counties, Texas. Black areas are Permian Delaware Mountain Group fields. The most northward field is the Hat Mesa Delaware Field in Lea County, New Mexico (modified after Berg, 1979).

sistivity factor (Fr = Ro/Rw). A crossplot (Fig. 2) of porosity versus formation resistivity factor (Fr) data for the Bell and Cherry Canyon sands has a slope of 1.80, indicating an average cementation exponent of 1.80. The question is why is the cementation exponent less than 2.00 for these siltstone and very fine-grained sandstone reservoirs?

Fig. 3 is a porosity versus Fr crossplot of Bell and Cherry Canyon data over a porosity range of 1.8-22%. The porosities below 10% are non-reservoir due to the presence of dolomite cement and/or clay matrix. Note in Fig. 3 that the Bell and Cherry Canyon data

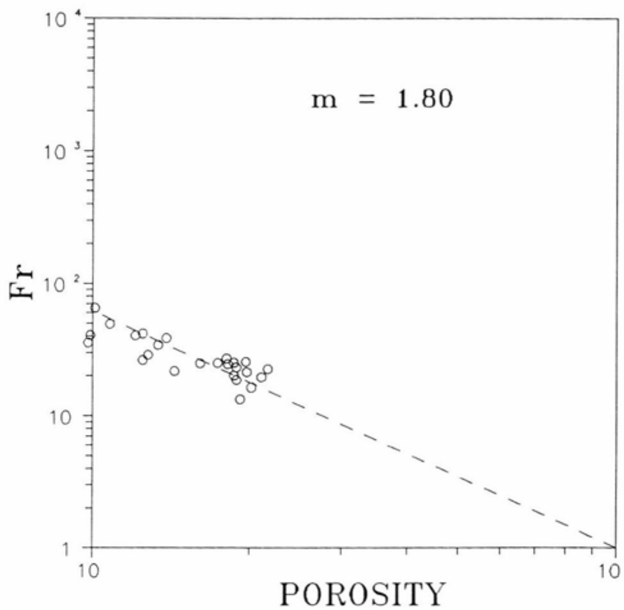

FIGURE 2—Crossplot of porosity versus formation resistivity factc (Fr) for the Bell and Cherry Canyon reservoirs, Screwbean an Geraldine Fields, Reeves and Culberson Counties, Texas. The slop of the best-fit line (1.80) is the average value for cementation e› ponent (m).

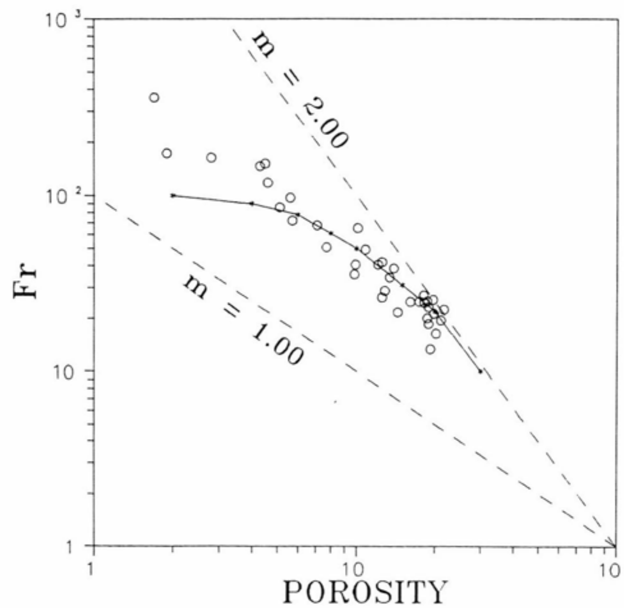

FIGURE 3—Crossplot of porosity versus formation resistivity facto (Fr) for the Bell and Cherry Canyon Formations (open circles). Th solid curved line represents Fr values calculated by the Rasmu (1987) equation for water-filled intergranular porosity with 1% wa ter-filled fracture porosity.

cluster between the m values of 2.00 (intergranular porosity) and 1.00 (plane fracture porosity) and that Fr decreases (lower m) as porosity decreases. A similar decrease in m with a decrease in porosity was first noted by Borai (1987). Also included in Fig. 3 are Fr values calculated by the Rasmus (1987) formula for reservoirs with water-filled fracture and intergranular porosity (i.e. solid curved line):

$$Fr = \frac{Ro}{Rw} = \frac{1}{(1-\phi f) * \phi ig\hat{\ }mig + \phi f\hat{\ }mf}$$

Where:

- Fr = formation resistivity factor,
- Ro = wet resistivity,
- Rw = formation water resistivity,
- ϕf = percent fracture porosity in Fig. 3 (ϕf = 1%),
- mf = cementation exponent for fracture porosity in Fig. 3 (mf = 1.0),
- ϕig = percent intergranular porosity in Fig. 3 (ϕig varies from 1 to 29%),
- mig = cementation exponent for intergranular porosity in Fig. 3 (mig = 2.0).

Assumed: All the porosity is water-filled (Swig = Swf = 1.0).

The numbers on the solid curved line represent the percentage of the porosity that is fracture porosity (Fig. 3). The concomitant Fr values for the solid curved line were calculated by the Rasmus (1987) equation with the assumptions listed above. Note how well the trend in Bell and Cherry Canyon data (open circles), follows the trend in the calculated Fr values down to a porosity of 4% (Fig. 3). This similarity between the Bell and Cherry Canyon Fr data with the calculated Fr values using the Rasmus (1987) formula suggests that the lower m values for the Bell and Cherry Canyon siltstones and very fine-grained sandstones are the result of minor amounts of fracture porosity.

Petrographic analyses of thin sections cut from the core plugs reveal the presence of microfractures in most of the core plugs. Photomicrographs (Fig. 4A, B) illustrate the minor fracture porosity in addition to the dominant intergranular porosity. The presence of these microfractures lowers the value for cementation exponent (m) because fractures decrease the tortuosity of the pore geometry.

Economic importance

Because the presence of minor amounts of micro-fracture porosity in a reservoir with intergranular porosity lowers cementation exponent (m), Archie water saturations are also lower. Therefore, when volumetric hydrocarbon reserves are calculated, the results can be significant. Fig. 5 illustrates two net-pay summaries for two potential behind-pipe pay zones in both the Bell and Cherry Canyon Formations. Fig. 6 illustrates a potential pay zone in a well that is presently plugged and abandoned. The water saturations for all three of these potentially productive zones were calculated with a cementation exponent (m) of 1.80 (Figs. 5, 6). Table 1 is a comparison of calculated oil reserves for the three Bell and Cherry Canyon zones illustrated in Figs. 5 and 6. Note in Table 1 that using a cementation exponent (m) of 1.80 results in a 9-13% increase in oil reserves compared

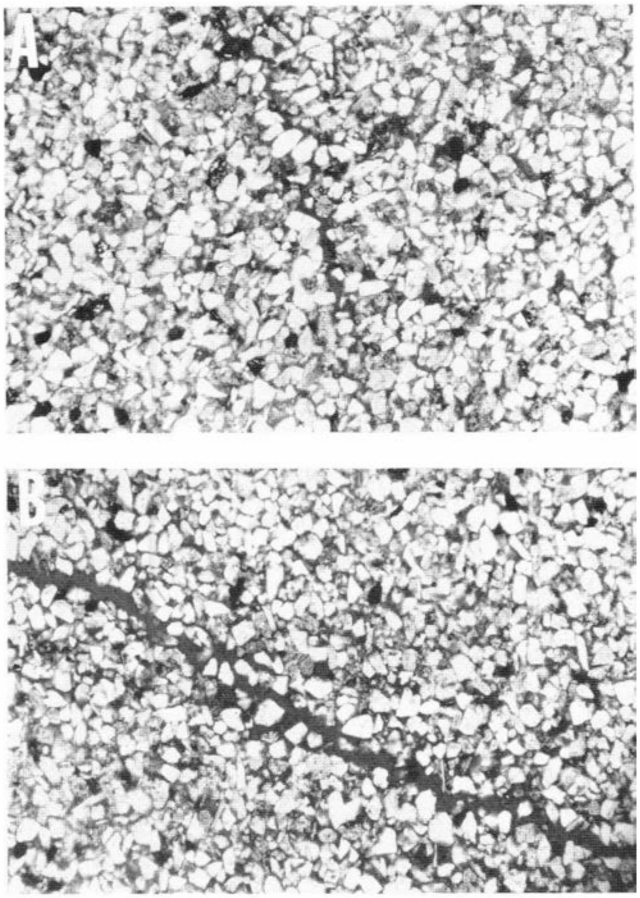

FIGURE 4—**A**, Photomicrograph of Bell Canyon siltstone illustrating abundant intergranular porosity and minor microfracture porosity. Porosity = 19.8%, permeability = 9.05 md. **B**, Photomicrograph of Cherry Canyon siltstone illustrating abundant intergranular porosity and minor microfracture porosity. Porosity = 18.9%, permeability = 4.5 md.

to the two standard methods (i.e. F = 0.62/Φ^2.15 and 0.81/(Φ^2).

Summary

A crossplot of porosity versus formation resistivity factor (Fr) for Bell and Cherry Canyon siltstones and sandstones of the Screwbean and Geraldine Fields in Reeves and Culberson Counties, west Texas, indicates a cementation exponent of 1.80. A comparison of the porosity and Fr data from the Bell and Cherry Canyon Formations with Fr values calculated by the Rasmus (1987) equation for intergranular porosity with 1% fracture porosity results in similar trends. Petrographic analysis reveals the presence of microfractures in most of the core plugs, thus suggesting that the lower m value (i.e. 1.80) is due to the minor fracture porosity decreasing the tortuosity of the inter-granular porosity.

The lower value for cementation exponent (m) results in a 9-13% increase in volumetric reserves for only three potentially productive Bell and Cherry Canyon zones when compared to reserves calculated for standard methods (i.e. F = 0.62/Φ^2.15 and 0.81/ Φ^2). This substantial increase in volumetric reserves is a function of both the lower water saturations and greater net-pay thicknesses using the lower m value.

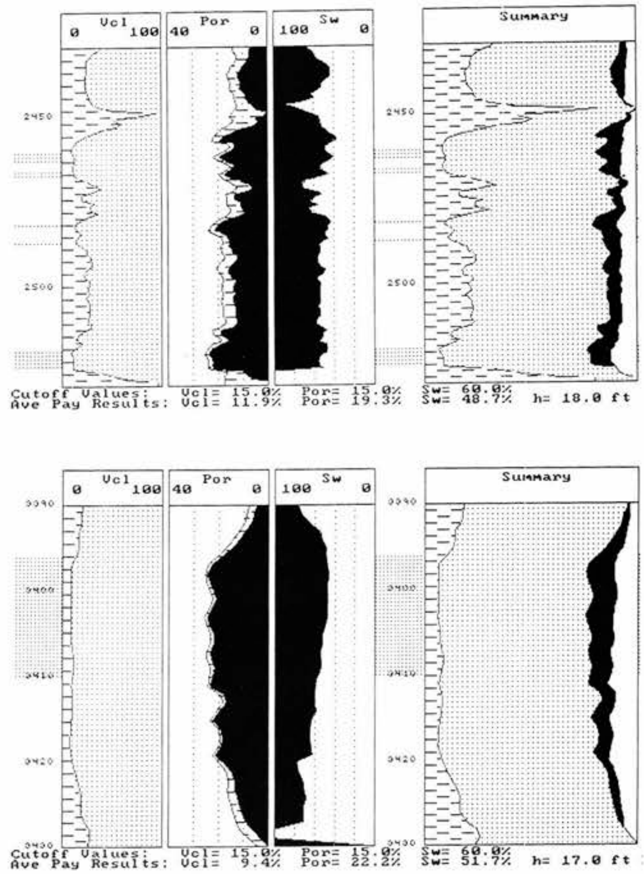

FIGURE 5—Net-pay summaries for two potential behind-pipe pay zones in well #1. The water saturations were calculated using a cementation exponent (m) of 1.80. Upper zone = Bell Canyon, Lower zone = Cherry Canyon.

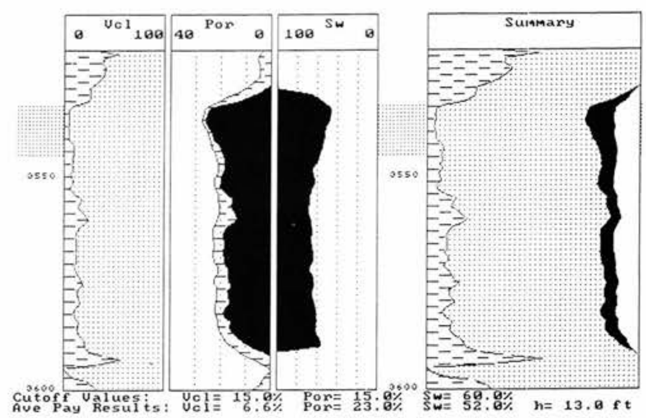

FIGURE 6—Net-pay summary for a Bell Canyon potential pay zone in well #2 which is presently plugged and abandoned. The water saturations were calculated using a cementation exponent (m) of 1.80.

TABLE 1—Oil-reserves changes with changes in cementation exponent (m) for three Bell Canyon and Cherry Canyon potential pay zones, Reeves and Culberson Counties, Texas.

Method	OOIP (40 ac.)	Recoverable reserves (17% R.F.)
F = 1/ϕ^1.80	1.55 million	263,000
F = 0.62/ϕ^2.15	1.42 million	241,000
F = 0.81/ϕ^2.00	1.37 million	233,000

Acknowledgments

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The effects of residual-oil saturations on the interpretation of water versus oil-productive Delaware sandstones

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Abstract—Delaware sandstones in west Texas and southeastern New Mexico that have excellent hydrocarbon shows and calculated water saturations of 60% or less sometimes produce only water. The problem with these siltstone to very fine-grained sandstone reservoirs is whether or not the hydrocarbons in these reservoirs are movable. Using net-pay cut-offs of Vcl >15%, effective porosity <15%, and Archie water saturation <60%, Bell Canyon and Brushy Canyon example zones contained 18 and 22 ft of net pay, respectively. However, when these two zones were tested, the Bell Canyon zone produced only water and the Brushy Canyon zone produced 125 BOPD and some water.

A series of crossplots that include (1) shallow resistivity porosity versus deep resistivity porosity, (2) Archie water saturation versus Ratio water saturation, and (3) Rxo/Rmf versus Rt/Rw (Dew Plot) were used to differentiate movable and residual oil. On all three crossplots the Bell Canyon example exhibited almost no movable oil, whereas the Brushy Canyon example exhibited a higher proportion of movable oil. Thus, using these crossplots, the oil-productive versus water-productive Delaware sandstones were differentiated by determining what proportion of the oil was movable.

Introduction

The siltstone and very fine-grained sandstone reservoirs of the Permian Delaware Mountain Group often contain several zones that have shows of both oil and gas. When these zones are tested some are oil-productive with some water and others produce only water. The reason for these often excellent shows is the low permeability of these very fine-grained reservoirs, which results in a low degree of hydrocarbon movability. It is therefore important to recognize which of these zones are oil-productive.

One method that can be utilized to differentiate oil-productive from water-productive Delaware sandstones is to determine which of the zones with oil and gas shows have movable hydrocarbons and will thus produce oil, and which contain only immovable hydrocarbons and will produce only water.

In order to determine the degree of hydrocarbon movability in these low-permeability sandstones, a series of crossplots can be used (Thomerson, 1992; Thomerson and Asquith, 1992). These crossplots include (1) shallow resistivity (Rxo) porosity versus deep resistivity (Rt) porosity, (2) Archie water saturation versus Ratio water saturation, and (3) Rxo/Rmf versus Rt/Rw (Dew Plot). Hydrocarbon-productive zones should exhibit movable hydrocarbons, whereas an oil-bearing water-productive zone should exhibit a lack of movable hydrocarbons (i.e. Kro = 0).

Well #1: Water-productive Bell Canyon sandstone

The first example (Fig. 1) is a Bell Canyon sandstone. During the drilling of this zone a 100-150 total-gas increase was noted with C1 through C5 hydrocarbons liberated. In addition, the samples had a pale-yellow fluorescence with a slow, weak cut when wet. Later core analysis of rotary sidewall cores indicated oil saturations that ranged from 12 to 22%. Core porosities varied from 14 to 21.7%, with permeabilities from 1.5 to 28.6 md.

The original log analysis was done using an Rw of 0.035 ohm-m and the following net-pay cut-offs: (1) Vcl <15%, (2) effective porosity >15%, and (3) Sw <60%. Using these net-pay cut-offs, 53 ft of net pay was present in the Bell Canyon zone. When the zone was perforated and tested, only water with a slight show of oil and gas was produced. The water recovered from this zone had an Rw of 0.058 ohm-m at 75°F, which at formation temperature reduced to 0.048 ohm-m. Net pay was then recalculated using an Rw of 0.048 ohm-m and the same net-pay cut-offs used in the original analysis (Fig. 2). Note in Fig. 2 that even when the correct Rw is used there is still 18 ft of net pay, indicating the Bell Canyon should be oil-productive.

An examination of three log-analysis crossplots reveals why this Bell Canyon sandstone produced water. These crossplots are (1) Rxo porosity versus Rt porosity (Fig. 3), (2) Archie water saturation versus Ratio water saturation (Fig. 4), and (3) Rxo/Rmf versus Rt/Rw (Fig. 5; Dew plot). Note in Fig. 3 that the resistivity porosity calculated with Rxo and Rt is the

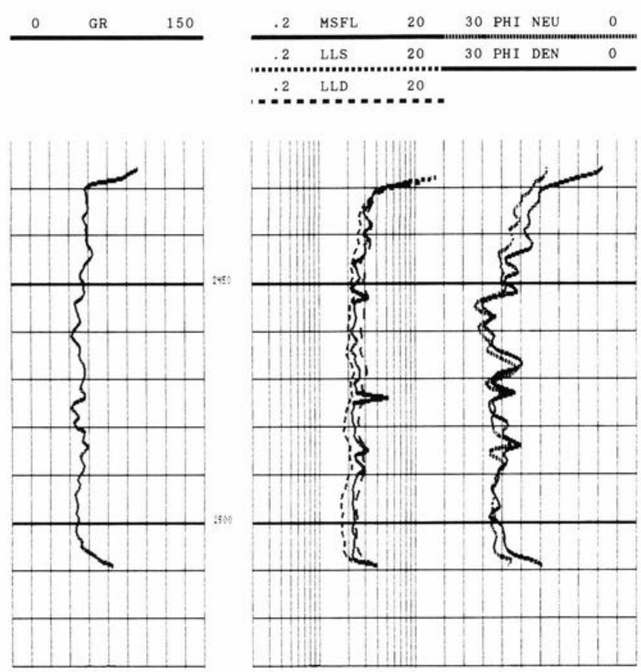

FIGURE 1—Dual laterolog – Rxo log with neutron–density (lime matrix) porosity log through the Bell Canyon (example #1).

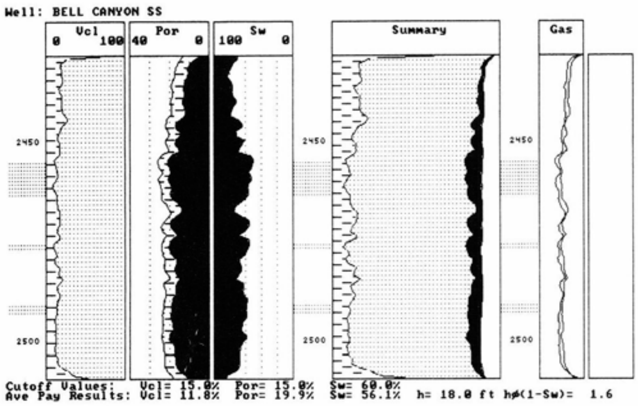

FIGURE 2—Net-pay summary for the Bell Canyon (example #1).

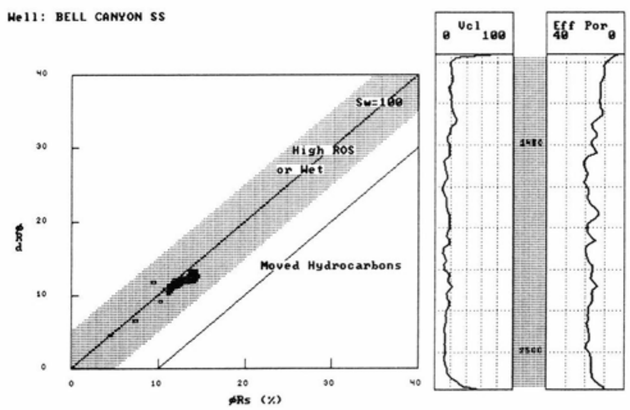

FIGURE 3—Crossplot of Rxo porosity versus Rt porosity for the Bell Canyon (example #1). Note that both the porosities are the same, which indicates that the water saturations in both the flushed and invaded zones are the same. Hydrocarbons therefore are immovable.

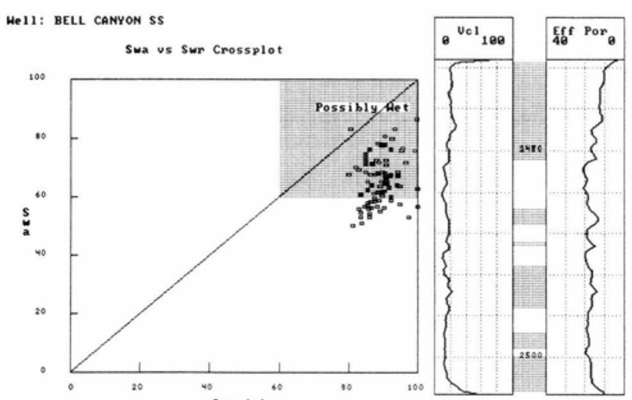

FIGURE 4—Crossplot of Archie versus Ratio water saturations for the Bell Canyon (example #1). Note that Ratio water saturation is much higher than Archie water saturation, which indicates that the Bell Canyon has a high residual-oil saturation.

same. This indicates that the hydrocarbon saturations are the same in both the flushed zone and the uninvaded zone because the hydrocarbons are immovable. Therefore, the hydrocarbons are residual and the zone should produce only water.

The Archie water saturation versus Ratio water saturation crossplot (Fig. 4) indicates that Ratio water

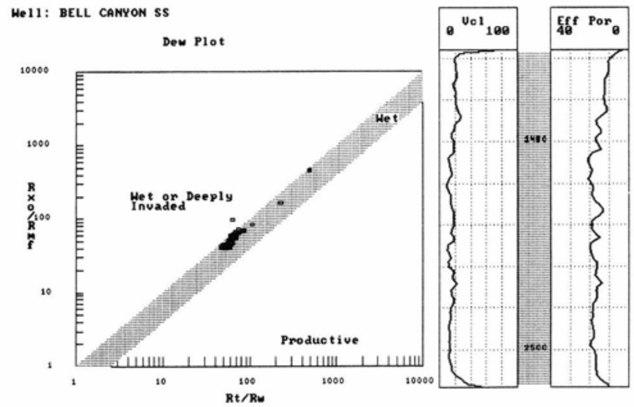

FIGURE 5—Crossplot of Rxo/Rmf versus Rt/Rw (Dew Plot) for the Bell Canyon (example #1). Note that all the data cluster in or above the dotted pattern, which indicates that the movable-hydrocarbon index (Sw/Sxo) is higher than 0.7 and the hydrocarbons have a low movability.

saturation is much greater than Archie water saturation, which is a result of the lack of moved hydrocarbons (Asquith, 1984). The data for the Bell Canyon sandstone all plot in or above the dotted pattern on the Dew Plot (Fig. 5), indicating a movable-hydrocarbon index (Sw/Sxo) higher than 0.7. Reservoirs that have Sw/Sxo values >0.7 indicate a lack of movable-hydrocarbons (Schlumberger, 1972). The Dew Plot and the Archie versus Ratio water-saturation crossplots of the data from the Bell Canyon sandstone thus support the conclusion reached from the Rxo porosity versus Rt porosity crossplot (Fig. 3), that the hydrocarbons are immovable (i.e. Kro = 0). The Bell Canyon zone should therefore produce water. The lack of movable hydrocarbons in a zone (example #1) with water saturations less than 60% may indicate that the zone is oil-wet or the oil is degraded.

Well #2: Oil-productive Brushy Canyon sandstone

The second example (Fig. 6) is a Brushy Canyon sandstone. Like in the Bell Canyon example, both oil and gas shows were noted in this zone during drilling. These shows included a 75-240 unit total-gas increase (Cl through C5) and pale-yellow fluorescence with a fast milky cut dry and a fast cut when wet. Oil saturations from sidewall core analysis ranged from 9.8 to 12.5%. Core porosities ranged from 9 to 16.3%, with permeabilities from 0.06 to 17.5 md. Using an Rw of 0.038 ohm-m and the same net-pay cutoffs as in the Bell Canyon example, 22 ft of net-pay was noted (Fig. 7). When this Brushy Canyon zone was perforated, it had an initial production of 125 BOPD with minor water.

An examination of the Rxo porosity versus Rt porosity crossplot for the Brushy Canyon zone (Fig. 8) reveals that Rt porosity is less than Rxo porosity. This loss of resistivity porosity between Rt- and Rxo-derived porosities is a result of the movement of hydrocarbons out of the flushed zone due to invasion. Remember that the greater the hydrocarbon saturation, the less the resistivity porosity.

A comparison of Archie and Ratio water saturations (Fig. 9) illustrates that the values of both water sat-

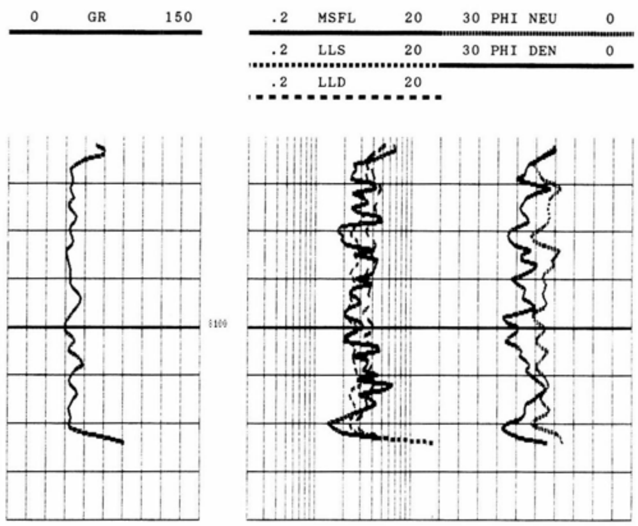

FIGURE 6—Dual laterolog – Rxo log with neutron–density (lime matrix) porosity log through the Brushy Canyon (example #2).

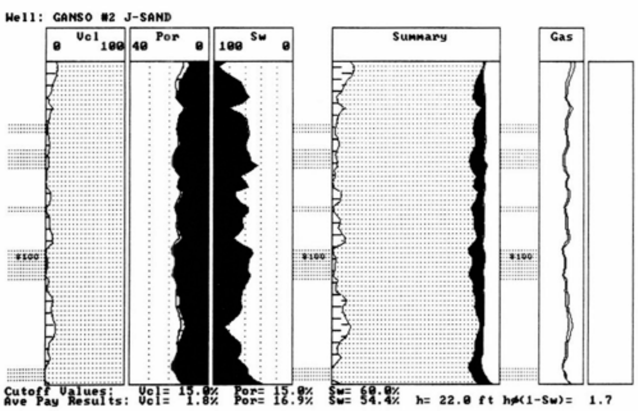

FIGURE 7—Net-pay summary for the Brushy Canyon (example #2).

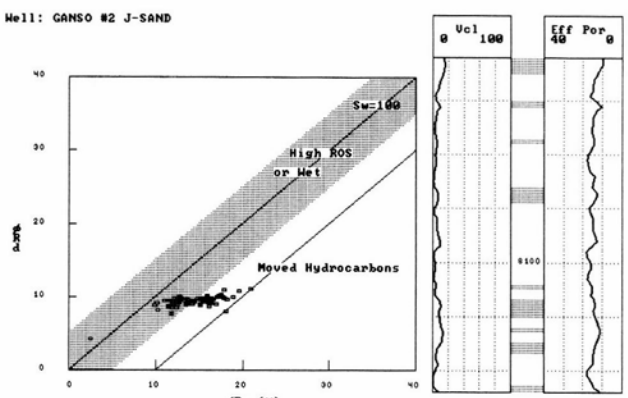

FIGURE 8—Crossplot of Rxo porosity versus Rt porosity for the Brushy Canyon (example #2). Note that Rxo porosity is much less than Rt porosity, which indicates that the water saturation in the flushed zone (Rxo) is higher than the water saturation in the uninvaded zone (Rt). The hydrocarbons therefore are movable.

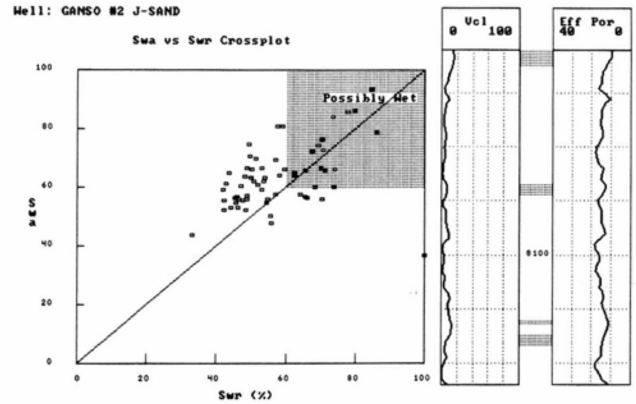

FIGURE 9—Crossplot of Archie versus Ratio water saturations for the Brushy Canyon (example #2). Note that Archie and Ratio water saturations are approximately equal, which indicates less residual-oil saturation than in the Bell Canyon (example #1).

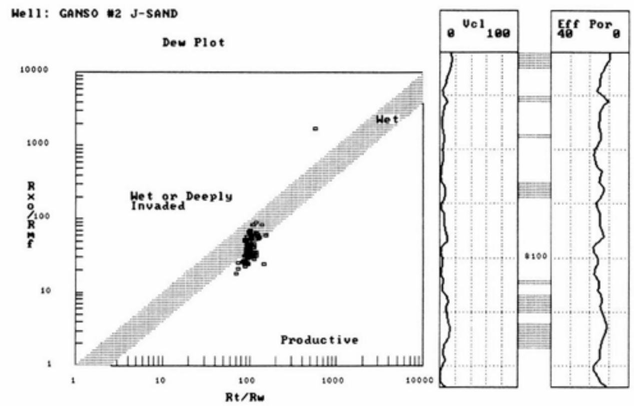

FIGURE 10—Crossplot of Rxo/Rmf versus Rt/Rw (Dew Plot) for the Brushy Canyon (example #2). Note that some of the data plot below the dotted pattern, which indicates a movable-hydrocarbon index (Sw/Sxo) lower than 0.7. A portion of the oil is therefore movable.

urations are similar, which indicates a degree of movement of the hydrocarbons from the flushed zone. On the Dew Plot (Fig. 10) some of the data from the Brushy Canyon plot below the dotted pattern indicate a movable-hydrocarbon index (Sw/Sxo) of less than 0.7, which is characteristic of reservoirs with movable hydrocarbons (Schlumberger, 1972). Therefore, unlike the Bell Canyon in example #1, the Brushy Canyon contains movable hydrocarbons and is oil-productive.

Summary

One of the major problems in the log analysis of reservoirs in the Delaware Mountain Group is the presence of residual oil in both oil-productive and water-productive zones. The key to the interpretation of these high-porosity-low-permeability reservoirs is the determination of presence of movable hydrocarbons. If the hydrocarbons are immovable as in the Bell Canyon sandstone (example #1), the zone will produce oil. However, if a portion of the hydrocarbons is movable as in the Brushy Canyon (example #2), then the zone should produce oil.

The method used to detect the movability of hydrocarbons in the examples is a series of logging crossplots. These crossplots are (1) Rxo porosity versus Rt porosity, (2) Archie versus Ratio water saturations, and (3) Rxo/Rmf versus Rt/Rw (Dew Plot). All of these crossplots detect the presence of movable hydrocarbons by the difference in water saturations between the flushed zone and the uninvaded zone. The greater the difference between the water saturations in the flushed zone and the uninvaded zone, the greater the amount of hydrocarbons that have been moved by the invasion of mud filtrate.

Acknowledgments

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Triassic stratigraphy and correlations, southern High Plains of New Mexico—Texas

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Abstract—Nonmarine Upper Triassic strata of the Chinle Group exposed in east-central New Mexico (principally San Miguel, Guadalupe and Quay Counties) and west Texas (from Oldham to Mitchell Counties) are readily correlated using lithostratigraphy and biostratigraphy. In east-central New Mexico, Chinle Group strata rest disconformably on Middle Triassic red beds of the Moenkopi Formation (Anton Chico Member), which are mostly grayish-red litharenites and mudstones of fluvial origin. These Moenkopi strata can be correlated lithostratigraphically across northern New Mexico to the Holbrook Member of the Moenkopi Formation in northeastern Arizona, a correlation supported biostratigraphically. However, no Moenkopi strata or correlative rocks are present in west Texas.

The lowermost portion of the Chinle Group in east-central New Mexico is the Santa Rosa Formation consisting of (ascending) the Tecolotito (mostly quartzarenite), Los Esteros (mostly variegated bentonitic mudstone) and Tres Lagunas (mostly quartzarenite) Members. The overlying Garita Creek Formation is red-bed mudstones, sandstones and intraformational conglomerates. Fossil plants and vertebrates indicate a late Carnian age for the Santa Rosa and Garita Creek Formations. Lithostratigraphy and biostratigraphy indicate that their west Texas correlatives are the Camp Springs, Iatan and Tecovas Members of the Dockum Formation: Camp Springs = Tecolotito, Iatan = part of Los Esteros, and Tecovas = part of Los Esteros, Tres Lagunas and at least part of Garita Creek. Lithology and thickness differences allow ready distinction of the New Mexico and Texas units, thus justifying their separate lithostratigraphic names.

The upper part of the Chinle Group in east-central New Mexico consists of sandstones and intrabasinal conglomerates of the Trujillo Formation, which disconformably overlies older Chinle Group strata. It is readily traced into west Texas as the Trujillo Member of the Dockum Formation. Fossil plants and vertebrates indicate a latest Carnian–earliest Norian age for the Trujillo in east-central New Mexico and west Texas. Suggestions that it is correlative to the late Carnian Santa Rosa Formation or Camp Springs Member are refuted by lithostratigraphic correlations and biostratigraphy. The Bull Canyon Formation (lower–middle Norian) of east-central New Mexico conformably overlies the Trujillo, and this thick red-bed sequence of mudstones and sandstones can be traced into west Texas as the Bull Canyon Member of the Dockum (Cooper Canyon Member is an unnecessary synonym). The youngest Chinle Group strata in east-central New Mexico are cyclically bedded siltstones and sandstones of the Rhaetian Redonda Formation. They have no correlative in west Texas.

Introduction

Triassic strata of nonmarine origin are widely exposed on the southern High Plains of eastern New Mexico and west Texas (Fig. 1). These rocks pertain to two lithostratigraphic units that represent two distinct tectonosequences: (1) Middle Triassic (lower Anisian) Moenkopi Formation, and (2) Upper Triassic (upper Carnian—Rhaetian) Chinle Group. Since 1983 we have undertaken extensive studies of these Triassic strata. Our purpose here is to review the results of these studies and respond to the critique of our conclusions offered by Lehman (this volume). Although we have studied the Triassic strata exposed throughout eastern New Mexico and west Texas, our summary emphasizes east-central New Mexico (San Miguel, Harding, Guadalupe and Quay Counties) and the Texas Panhandle, as these areas are most relevant to the issues raised by Lehman.

Moenkopi tectonosequence

The oldest Triassic strata exposed in east-central New Mexico are fluvial red beds as much as 41 m thick and dominated by trough-crossbedded, micaceous litharenites and lithic graywackes. In a preliminary review of Triassic stratigraphy of east-central New Mexico, Lucas et al. (1985) followed Gorman and Robeck (1946) and others (e.g. Finch et al., 1976; Lupe, 1977; Granata, 1981; Finch and Wright, 1983; McGowen et al., 1979, 1983) in identifying these strata as the lowermost member of the Santa Rosa Formation. Gorman and Robeck (1946) mapped this unit (at the approximate scale of 1 inch = 1 mile) throughout its outcrop belt in much of Guadalupe County, although Johnson (1974) included these strata in the Middle Permian (Guadalupian) "Bernal" Formation in part of San Miguel County (Lucas and Hayden, 1991). A skull of the amphibian *Eocyclotosaurus* indicates that the lowermost member of the Santa Rosa Formation, as then identified, is of Middle Triassic (early Anisian) age (Lucas and Morales, 1985).

Subsequent field work in east-central New Mexico supported removal of the lowermost member from the Santa Rosa Formation as a distinct formation for the following reasons: (1) it is lithologically very distinct from the overlying Santa Rosa, which is characterized by relatively mature quartzarenites and bentonitic mudstones variegated purple, green and red; (2) a profound erosional unconformity separates the lowermost member from overlying Santa Rosa strata; and (3), as Gorman and Robeck (1946) ably demonstrated, the lowermost member can be mapped as a unit distinct from the remainder of the Santa Rosa Formation. In recognition of these observations, Lucas and Hunt (1987) renamed the lowermost member of the Santa Rosa Formation the Anton Chico Formation, after a village in San Miguel County near the type section of the unit they designated and described.

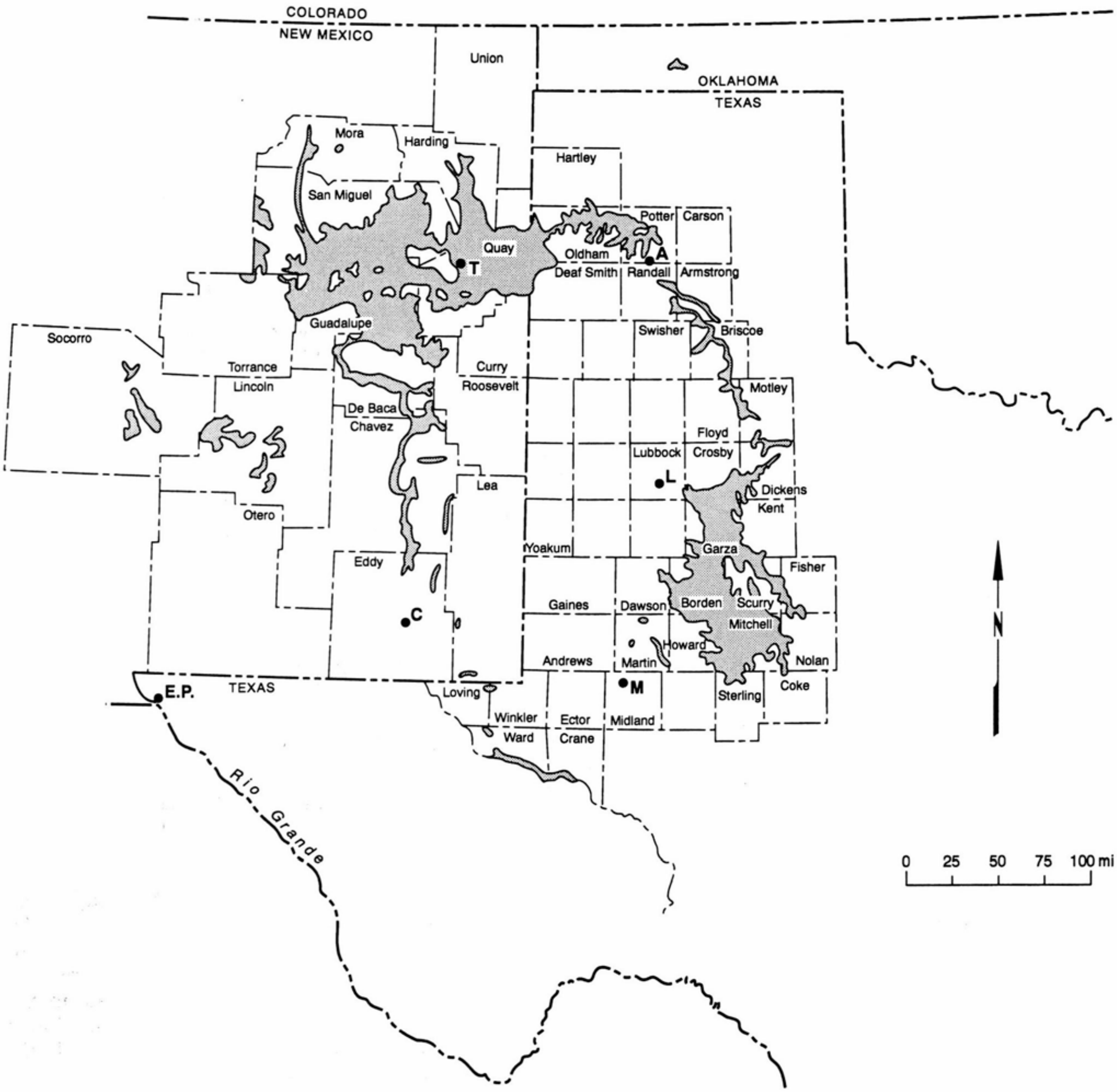


FIGURE 1—Index map showing distribution of Triassic strata on the southern High Plains and adjacent areas of eastern New Mexico and west Texas.

Lucas and Hunt (1987) were familiar with Anton Chico outcrops only in east-central New Mexico. They recognized the correlation (based on the shared amphibian *Eocyclotosaurus)* of Anton Chico Formation strata in east-central New Mexico with the Holbrook Member of the Moenkopi Formation in eastern Arizona (also see Morales, 1987). However, Lucas and Hunt (1987) were not convinced about continuity of Moenkopi strata between eastern Arizona and east-central New Mexico, and so believed that deposition of the Anton Chico Formation took place in a basin separate from the Moenkopi basin of deposition.

The reason for this error stemmed from a longstanding failure to recognize Moenkopi strata throughout west-central and north-central New Mexico. This began with McKee's (1954) classic and highly influential monograph on Moenkopi Formation stratigraphy in northern Arizona. McKee (1954) documented the thinning of the Moenkopi Formation eastward across northern Arizona and its zero isopach in the Defiance uplift along the Arizona—New Mexico border. He therefore concluded that Moenkopi strata are not present in west-central New Mexico. However, Cooley (1957, 1959) subsequently identified a thin interval at the base of the Triassic section as Moenkopi(?) Formation as far east as Grants in Cibola County. Stewart et al. (1972) further extended this interval of possible Moenkopi strata to the Sevilleta Grant in Socorro County, southeast of the Colorado Plateau edge. However, to the north, in Sandoval, Bernalillo and Santa Fe Counties, no Moenkopi strata were recognized, and the red beds between the Guadalupian San Andres/Glorieta Formations and the base of the Upper Triassic Chinle strata were long mapped as

Permian "Bernal" Formation (e.g. Wood and Northrop, 1946; Stewart et al.,1972; Kelley and Northrop, 1975; Woodward, 1987). In parts of Valencia and Cibola Counties the Chinle was mapped lying directly on the San Andres or Glorieta Formations (e.g. Kelley and Wood, 1946). Thus in 1987 Lucas and Hunt did not suspect continuity of the Moenkopi Formation across west-central and north-central New Mexico.

Further work by Lucas, Hunt, S. N. Hayden, B. Allen and K. K. Kietzke, however, demonstrated otherwise. These workers recognized that strata in west-central and north-central New Mexico previously identified as Moenkopi(?) Formation or "Bernal" Formation pertain to a single lithostratigraphic unit. This unit is as much as 68 m thick and is mostly trough-crossbedded, micaceous litharenite and lithic graywacke. Fossils of charophytes, ostracodes, tetrapod footprints and amphibians indicate that these strata are of Middle Triassic (early Anisian) age. Furthermore, these strata disconformably overlie Guadalupian strata of the San Andres or Glorieta Formations and are disconformably overlain by basal Chinle Group strata. For these reasons Lucas and Hunt (1989) reduced the rank of the Anton Chico Formation and recognized it across northern New Mexico as the Anton Chico Member of the Moenkopi Formation. Detailed lithostratigraphy, much of it published (Hayden and Lucas, 1988a, b, 1989; Hunt and Lucas, 1987; Lucas and Hayden, 1989a, b, 1991; Lucas, 1991a, b; Lucas and Hunt, 1993b) supports this stratigraphic assignment. Biostratigraphy (Morales, 1987; Kietzke, 1988, 1989a, b; Lucas and Morales, 1985; Lucas and Hayden, 1989a; Hunt and Lucas, 1993) indicates that the Anton Chico Member is the correlative of the Holbrook Member of the Moenkopi Formation in eastern Arizona. Magnetic-polarity stratigraphy also supports a Holbrook—Anton Chico correlation (Steiner and Lucas, 1992; Steiner et al., 1993). Holbrook Member outcrops are present in eastern Arizona as far east as St. Johns, about 80 km west of Upper Nutria on the Zuni Pueblo of New Mexico where the westernmost Anton Chico Member outcrops are present. A higher percentage of mudstone and the presence of nodular gypsum in the Holbrook Member (McKee, 1954; Lucas, 1993b) distinguish it from the Anton Chico Member.

In eastern New Mexico the Anton Chico Member of the Moenkopi Formation is present as far south as Bull Gap near Carrizozo in Lincoln County (Lucas, 1991b; Lucas et al., 1991). South and east of that point, and throughout west Texas, Upper Triassic strata rest directly on Upper Permian (Ochoan) strata of the Quartermaster (= Dewey Lake or Pierce Canyon) Formation (Lucas and Anderson, 1993a, b).

McGowen et al. (1979, 1983) assigned an Early Triassic age to the Bissett Conglomerate in the Glass Mountains of west Texas, but that unit contains Early Cretaceous fossils of the dinosaur *Iguanodon* (Lucas, 1992). May (1988), May and Lehman (1989) and Lehman (1992) identified an "eolianite" beneath the Upper Triassic strata in the Texas Panhandle and suggested that it is correlative with the Anton Chico Member of the Moenkopi Formation. Our examination (Lucas and Anderson, 1993b) of this "eolianite," however, suggests that it is a fluvial-sand complex of the upper Quartermaster Formation, like those documented by Schiel (1988) in southeastern New Mexico.

We thus conclude that a wealth of detailed lithostratigraphic and biostratigraphic data supports recognition of the Anton Chico Member of the Moenkopi Formation across much of northern and eastern New Mexico. This conclusion has been accepted and supported by other workers (e.g. Morales, 1987; Ochev and Shishkin, 1989; Steiner et al., 1993). We also conclude that no Lower or Middle Triassic strata are present in west Texas, a conclusion long advocated by biostratigraphers (e.g. Case, 1914; Colbert and Gregory, 1957; Gregory, 1957; Chatterjee, 1986).

Chinle tectonosequence

Santa Rosa Formation

Rich (1921) and Darton (1922) first used the term Santa Rosa Sandstone. Rich (1921, p. 295) referred to the unit as a "coarse gray sandstone, conglomeratic at base," and Darton (1922, p. 183) described it as a "resistant, massive sandstone" that "appears to occur at about the horizon of the Shinarump conglomerate." As noted above, Gorman and Robeck (1946) mapped four distinct members of the Santa Rosa Sandstone in much of Guadalupe County, New Mexico. Lucas and Hunt (1987), for reasons explained above, removed the lowermost member from the Santa Rosa Sandstone. Lucas and Hunt (1987) referred to the Santa Rosa as the Santa Rosa Formation because it contains significant amounts of mudstone, siltstone and conglomerate in addition to sandstone. Furthermore, Lucas and Hunt (1987) assigned formal names to the three remaining members of the Santa Rosa mapped by Gorman and Robeck (1946): Tecolotito (lower), Los Esteros (middle) and Tres Lagunas (upper) Members. These units were distinguished lithologically and were recognized as informal units by Gorman and Robeck (1946), Finch et al. (1976a), Lupe (1977), McGowen et al. (1979, 1983), Granata (1981), Finch and Wright (1983) and Broadhead (1984, 1985). Assigning them formal names was only a logical step in the development of a precise, formal nomenclature for the Upper Triassic strata in east-central New Mexico.

The Tecolotito Member is a quartzarenite—sandstone-dominated interval (Fig. 2A) that rests disconformably on strata of the Anton Chico Member of the Moenkopi Formation or on older, Guadalupian rocks. It contains extrabasinal conglomerates of quartzite, chert, petrified-wood fragments and novaculitic chert or Paleozoic limestone cobbles. However, no age-diagnostic fossils are known from the Tecolotito Member of the Santa Rosa Formation.

The overlying mudstone-dominated Los Esteros Member (Fig. 2C) contains fossil plants at Santa Rosa (Ash, 1987) of Ash's (1980) late Carnian *Dinophyton* floral zone. The tripartite Santa Rosa Formation can be recognized as far west as Lamy in Santa Fe County, New Mexico (Allen and Lucas, 1988; Lucas, 1991a), where the Los Esteros Member contains an extensive vertebrate fossil assemblage of late Carnian age (Hunt and Lucas, 1988a, b). The thickest (as much as 45 m) and most extensively exposed member of the Santa

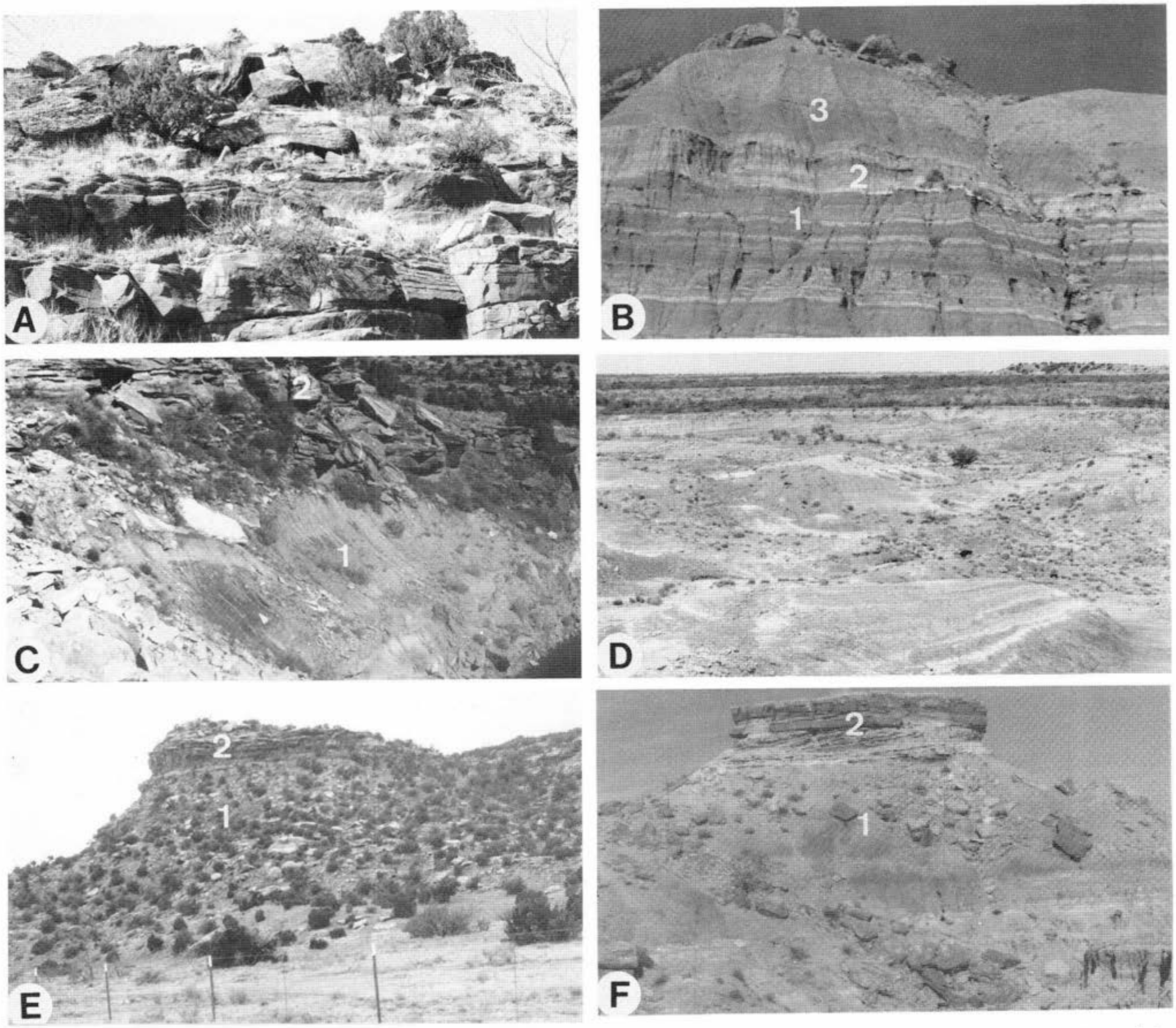


FIGURE 2—Selected outcrops of the Santa Rosa Formation, Garita Creek Formation, and Camp Springs and Tecovas Members of the Dockum Formation. **A–B**, In east-central New Mexico the Tecolotito Member of the Santa Rosa Formation (A, near Alamogordo Reservoir, DeBaca County, New Mexico) is conglomerate and quartzarenite that typically form prominent benches and defend bold escarpments. In west Texas the Camp Springs Member of the Dockum Formation (unit 2 in B at Palo Duro Canyon, Randall County, Texas) often is a thin, pebbly and sandy zone above the Upper Permian Quartermaster Formation (unit 1 in B) and below the bentonitic mudstone slopes of the Tecovas Member of the Dockum Formation (unit 3 in B). **C–D**, In east-central New Mexico the Los Esteros Member of the Santa Rosa Formation (unit 1 in C, at Los Esteros Reservoir, Guadalupe County) is mostly variegated bentonitic mudstone and minor sandstone. The overlying Tres Lagunas Member of the Santa Rosa Formation (unit 2 in C) is a ledge- and bench-forming interval of sandstone and conglomerate. In contrast, the partially correlative strata of the Tecovas Member of the Dockum Formation in west Texas (D) are a mudstone-dominated sequence that lacks prominent resistant and persistent sandstones, so it weathers to low badlands like these along the south fork of Home Creek in Crosby County, Texas. **E–F**, The Trujillo Formation (unit 2 in E) overlies the Garita Creek Formation (unit 1 in E) in east-central New Mexico, much as the Trujillo Member of the Dockum Formation (unit 2 in F) overlies the Tecovas Member of the Dockum (unit 1 in F) in west Texas. Thickness and lithology of the Trujillo vary little across the Texas–New Mexico line. However, the Tecovas Member is equivalent to the Los Esteros–Tres Lagunas–Garita Creek interval in New Mexico, a much thicker and sandier sequence (compare B, D and F to C and E; also see Fig. 7). E is near Trementina in San Miguel County, New Mexico; F is along Sierrita de la Cruz Creek, Oldham County, Texas.

Rosa Formation, the Tres Lagunas Member, is mostly quartzarenite (Fig. 2C) and lacks age-diagnostic fossils.

In west Texas the Tecovas Member of the Dockum Formation contains most of the plants and vertebrates found in the Los Esteros Member of the Santa Rosa Formation in New Mexico (Murry, 1986, 1987, 1989). This indicates that the Tecovas Member is at least partly correlative with the Los Esteros Member, a correlation supported by stratigraphic position (see below). Correlation of part of the Los Esteros Member with the Iatan Member in west Texas also is probable (see below). On the Colorado Plateau, fossil vertebrates and plants support broad correlation of the lower part of the Chinle Group (Monitor Butte Formation and Blue Mesa Member of Petrified Forest Formation) with the Los Esteros Member (Lucas, 1993a, 1994).

Camp Springs Member of Dockum Formation

The base of the Upper Triassic section throughout west Texas, except along the Canadian River drainage in the northern Panhandle, consists of conglomerate and conglomeratic sandstone (Fig. 3). The oldest available stratigraphic name for this unit is the Camp Springs Conglomerate of Beede and Christner (1926). The lectostratotype section of the Camp Springs designated by Lucas and Anderson (1993a) is in Scurry County near the village of Camp Springs, where the member is 13.2 m thick, disconformably overlies laminar reddish-brown sandstone and siltstone of the Permian Quartermaster Formation and is overlain by grayish-red bentonitic mudstone of the Tecovas Member of the Dockum Formation. Although Beede and Christner (1926) did not properly define the Camp Springs Conglomerate by the standards of today's stratigraphic code, the name was used by subsequent workers (e.g. Adkins, 1932; Van Siclen, 1957; Finch et al. 1976b; Murry, 1986); however, the nature and distribution of the unit so named was not always well understood. This lack of understanding is the result of the long-persistent but erroneous notion that the base of the Upper Triassic section in west Texas is a mudstone or a siltstone (e.g. Page and Adams, 1940; McGowen et al., 1979, 1983). This error likely originated with Gould's (1907) highly influential work on Upper Triassic stratigraphy in the northern Texas Panhandle. Gould (1907) indicated that the base of the Upper Triassic section is a "lavender shale" at the bottom of his Tecovas Formation, but a closer examination reveals that this is not everywhere the case (Fig. 3). Gould's (1907) observations were very good for his day, and most subsequent workers merely tried to project his northern Texas Panhandle stratigraphy to the south (Adkins, 1932, is an excellent example; but see Adams, 1929, for a different approach). However, careful outcrop stratigraphy reveals the base of the Upper Triassic section from Palo Duro Canyon southward to be conglomerate and conglomeratic sandstone (Figs. 2B, 3).

The Camp Springs Member in west Texas is readily recognized and traced based on its lithology and stratigraphic position. Throughout its outcrop belt from Champion Creek Lake in Mitchell County to Palo Duro Canyon in Randall County it is extrabasinal conglomerate consisting of silica pebbles and siltstone/sandstone rip-ups from underlying Permian strata, often in a "granite wash" (micaceous arkose of biotite grains in a microcline/quartz groundmass) matrix. Trough crossbeds are the dominant bedform, and maximum thickness is 15 m. The Camp Springs Member disconformably overlies the Upper Permian Quartermaster Formation and is conformably overlain by mudstones of the Tecovas or the Iatan Members (Fig. 4).

In Randall, Scurry and Crosby Counties, Texas, skulls of the phytosaur *Paleorhinus* have been collected from the Camp Springs Member (Langston, 1949; Hunt and Lucas, 1991a). *Paleorhinus* is the most primitive phytosaur and is known from late Carnian strata in Arizona, Wyoming, Germany, Austria, Morocco and India. Particularly significant is its presence in marine late Carnian strata in Austria (Opponitzer Schichten), which provides an important cross-correlation of non-marine Late Triassic biochronology to the Late Triassic SGCS (standard global chronostratigraphic scale). Its presence in the Camp Springs Member demonstrates that this unit is as old as the oldest Chinle Group strata elsewhere in the western United States (Lucas, 1993a).

Correlation of the Camp Springs Member with Upper Triassic strata in eastern New Mexico is supported by stratigraphic position, lithology and paleontology. The Los Esteros Member of the Santa Rosa Formation contains the more advanced phytosaur *Rutiodon* and no *Paleorhinus,* as does the Tecovas Member above the Camp Springs. The stratigraphic position and extrabasinal conglomerates of the Camp Springs and Tecolotito Member of the Santa Rosa Formation are very similar. This supports their correlation, which Lehman (this volume) accepts, although he uses the name Santa Rosa for Camp Springs in west Texas.

Iatan Member of Dockum Formation

About 70-100 m of Upper Triassic strata are exposed above the Camp Springs Member in Howard and Mitchell Counties, Texas. As Grover (1984) first observed, these strata consist of four persistent beds of sandstone intercalated with four persistent slope-forming intervals of mudstone. The sandstones are trough-crossbedded, micaceous and subarkosic and locally contain lenses of clay-ball conglomerates, especially at their bases. The mudstones are dark reddish brown to grayish red and bentonitic. The persistent sandstone intervals are 10 m thick or less, whereas the mudstone intervals are thicker. Intercalated thin sandstone and thick mudstone intervals are not present in the Tecovas Member of the Dockum Formation to the north, which occupies the same stratigraphic position as the strata above the Camp Springs Member in Howard and Mitchell Counties. These strata are also lithologically distinct from the Trujillo and Bull Canyon Members to the north. For this reason Lucas and Anderson (1993c) named these strata in Howard and Mitchell Counties the Iatan Member of the Dockum Formation, after the defunct railroad siding of Iatan in Mitchell County near where the type section was designated and described. Nevertheless, the low relief of the rolling plains of Howard and Mitchell Counties makes it impossible to measure a single complete section of the latan Member. Its estimated thickness of 80-100 m is based on a composite of several stratigraphic sections along a 40 km traverse from Champion Creek Lake in Mitchell County to Signal Peak in Howard County (Lucas and Anderson, 1993c). This thickness is confirmed by subsurface well logs in this area, which indicate the Iatan Member is 70-100 m thick (Shamburger, 1967, fig. 9) (Fig. 5).

Some earlier workers (e.g. Adams, 1929; Adkins, 1932; Page and Adams, 1940; Shamburger, 1967) have referred to the combined Camp Springs and latan Members in Howard and Mitchell Counties as the Santa Rosa Formation (Sandstone), overlain by the "Chinle Formation." This nomenclature well reflects Hoots' (1925, p. 89) observation that in this area the Upper Triassic section "is divisible into two more or less distinct formations—a lower one with a maximum thickness of 275 feet, characterized by red clay and numerous beds of massive gray crossbedded sandstone (= Camp Springs and Iatan Members of

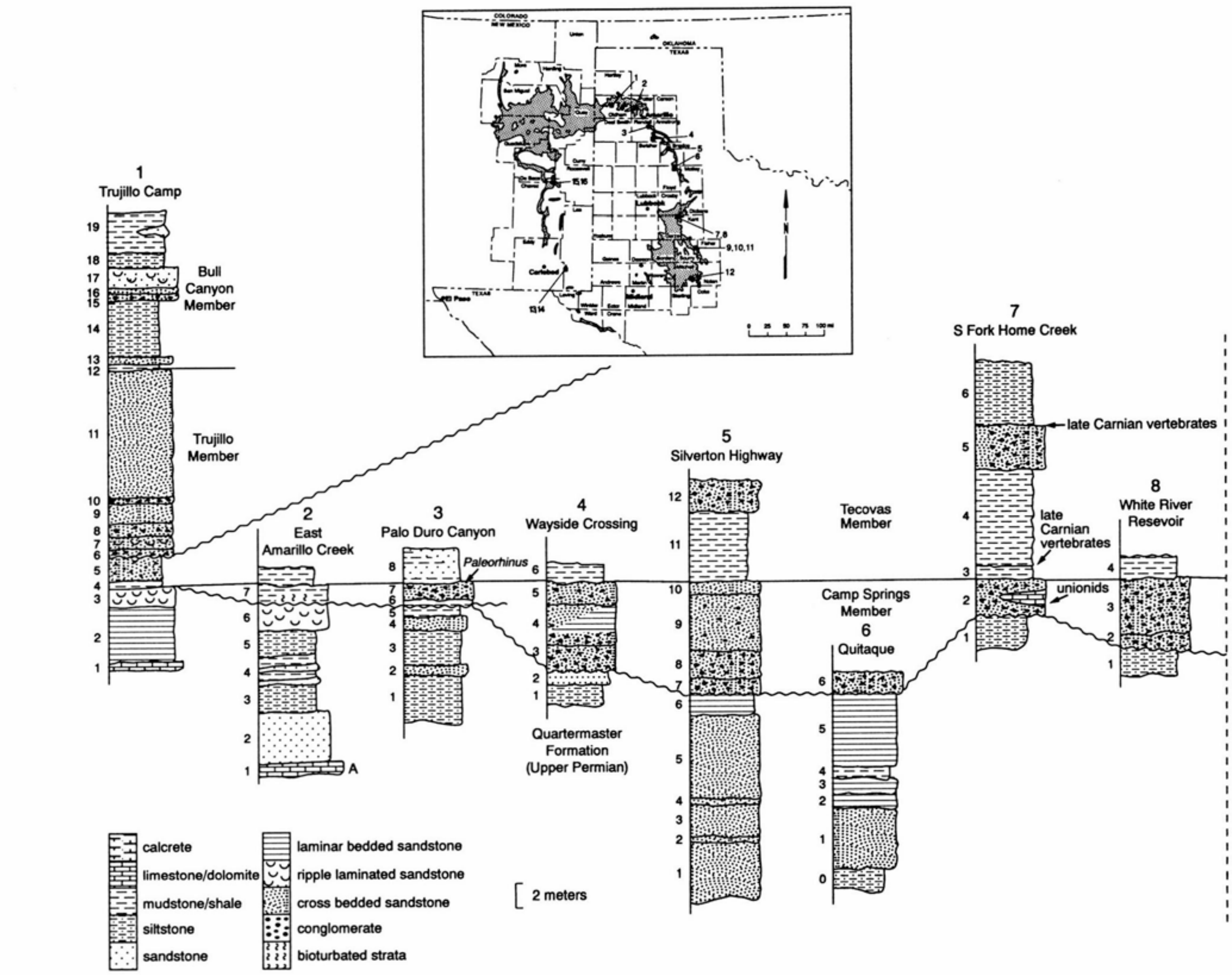


FIGURE 3—Measured stratigraphic sections across the Permian–Triassic boundary in west Texas and southeastern New Mexico. See Lucas and Anderson (1993b) for further explanation.

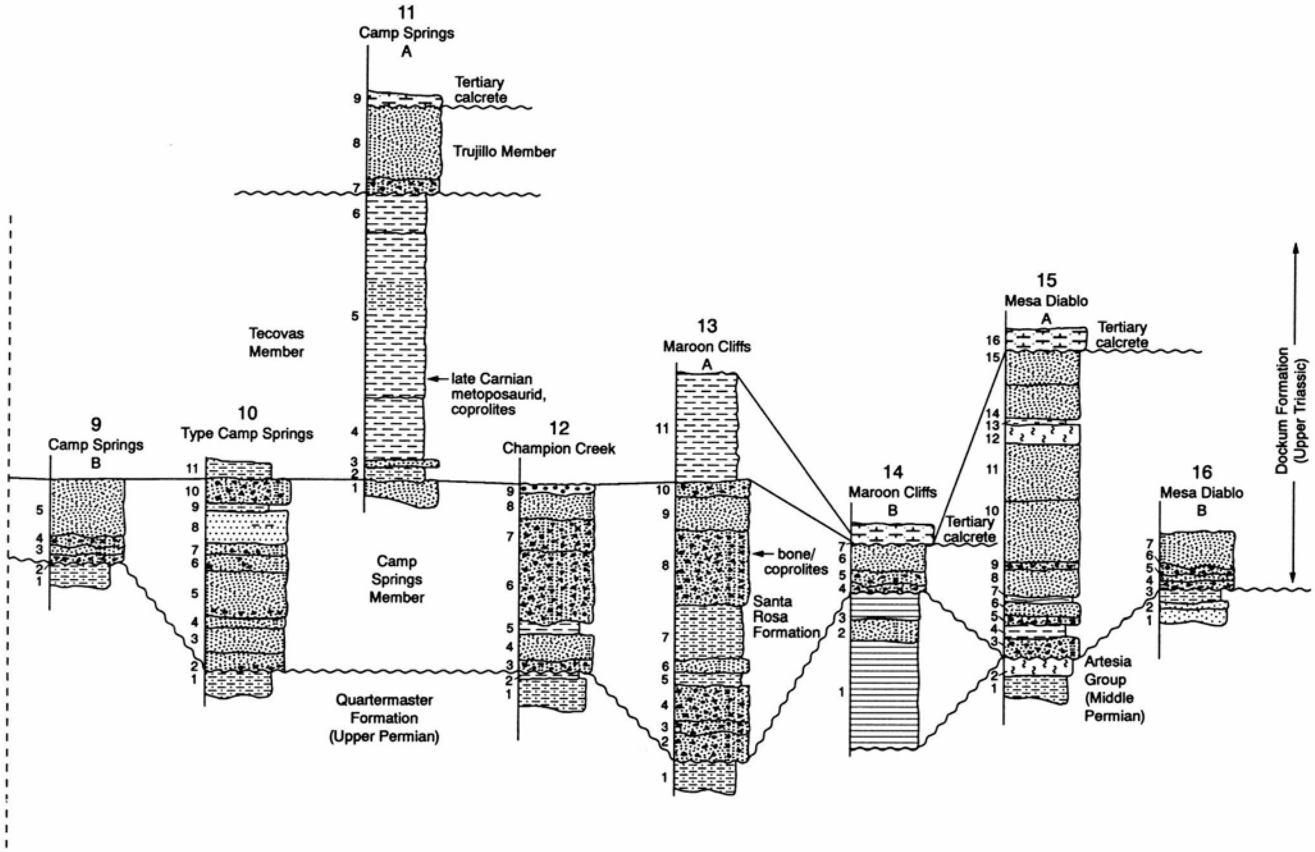
Dockum Formation of our usage) and an upper one with a maximum thickness of 175 feet or more consisting almost entirely of red clay" (= Tecovas Member of Dockum Formation of our usage). However, the Iatan Member is a distinct lithosome overlain by the Tecovas Member (Fig. 5) and should not be assigned to the Santa Rosa Formation. Nor should it be assigned to the Tecovas, Trujillo or Bull Canyon Members of the Dockum Formation as indicated by Lehman (this volume). Earlier workers (e.g. Drake, 1892; Adams, 1929; Shamburger, 1967) recognized that this is not a correct assignment for the Dockum strata exposed in Howard and Mitchell Counties. Our work supports their conclusions.

Correlation of the Iatan Member with Dockum strata to the north is aided by biostratigraphy. A large vertebrate assemblage containing *Paleorhinus* is present in about the middle of the member (Lucas et al., 1993). This indicates that the lower half of the Iatan Member is older than the vertebrate-bearing strata of the Tecovas Member. Iatan-equivalent strata to the north of Howard and Mitchell Counties thus are a relatively thin interval of the lower part of the Tecovas Member.

San Pedro Arroyo Formation

Triassic strata exposed in Socorro and Lincoln Counties, New Mexico, are the Anton Chico Member of the Moenkopi Formation (as much as 102 m thick) overlain by a Chinle Group section up to 149 m thick (Lucas, 1991b). The lowermost 6-26 m of the Chinle Group section here is trough-crossbedded silica-pebble conglomerate and micaceous subarkose. In Lincoln County these strata are assigned to the Santa Rosa Formation (undivided), whereas in Socorro County they are termed Shinarump Formation (Lucas, 1991b). These differing name assignments are based on (1) proximity of the Socorro County strata to the Colorado Plateau edge, where Shinarump is used for correlative rocks, and (2) previous usage of Santa Rosa in Lincoln County for these oldest, Chinle strata. In an earlier work Lucas (1991b, p. 245) noted that ". . . use of Shinarump or Santa Rosa for this interval is somewhat arbitrary . . . however, it is important to recognize the temporal and depositional equivalence of Shinarump and Santa Rosa strata across south-central New Mexico."

Lucas (1991b) introduced the name San Pedro Ar-



royo Formation for Chinle Group strata above the Shinarump—Santa Rosa interval in south-central New Mexico. The San Pedro Arroyo Formation is as much as 123 m thick and consists of variegated bentonitic mudstone and minor conglomerate, sandstone, siltstone and limestone. Its lowermost strata contain a late Carnian vertebrate and ostracode fauna that indicate broad correlation with the Los Esteros—Garita Creek interval in east-central New Mexico. Recently published magnetostratigraphy (Molina-Garza et al., 1993) refines this correlation, indicating that the lower part of the San Pedro Arroyo Formation is the correlative of the Los Esteros Member of the Santa Rosa Formation. However, no fossils that allow an age assignment below the level of Late Triassic are known from the remainder of the San Pedro Arroyo Formation.

Lithologically, the San Pedro Arroyo Formation cannot be precisely matched to any stratigraphic unit in east-central New Mexico or on the southern Colorado Plateau. Near its base the San Pedro Arroyo Formation contains a distinctive limestone interval (Ojo Huelos Member of Lucas, 1991b) not present outside of Socorro and Valencia Counties. Numerous thin, commonly lenticular sandstones and conglomerates intercalated with mudstones are not matched by Chinle Group strata to the north. To recognize their lithologic distinctiveness, Lucas (1991) coined the name San Pedro Arroyo Formation for the unit previously mapped in Socorro and Lincoln Counties as "Chinle Formation" by Wilpolt and Wanek (1951), Budding (1964), Smith (1964), Weber (1964), Haines (1968), Ryberg (1968), Kelley (1971) and others.

Garita Creek Formation

Above the Santa Rosa Formation in east-central New Mexico are red-bed mudstones and sandstones as much as 152 m thick (Fig. 2E). Kelley (1972a, b) referred to this unit as the "lower shale member of the Chinle Formation" and mapped its distribution throughout east-central New Mexico. Granata (1981), McGowen et al. (1983) and Broadhead (1984, 1985), among others, also recognized this unit, as had Darton (1928) much earlier. Lucas and Hunt (1989) formalized this mapped, lithologically distinctive unit as the Garita Creek Formation, naming it for a small creek in San

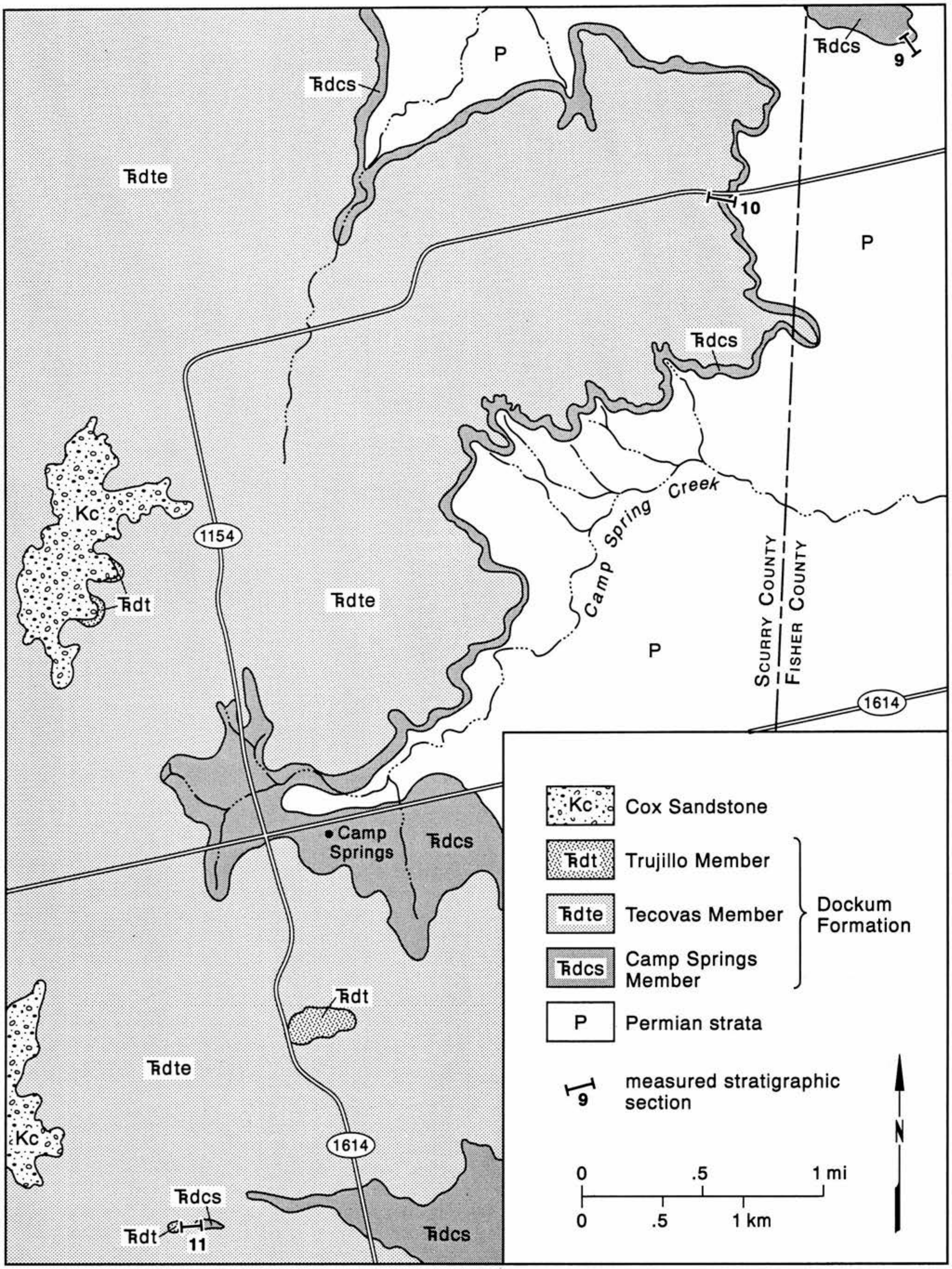


FIGURE 4—Reconnaissance geologic map of the Camp Springs area in west Texas. The mapping is of parts of the Inadale NW and Camp Springs 7.5 minute maps. Three of the measured sections in Fig. 3 are located on this map.

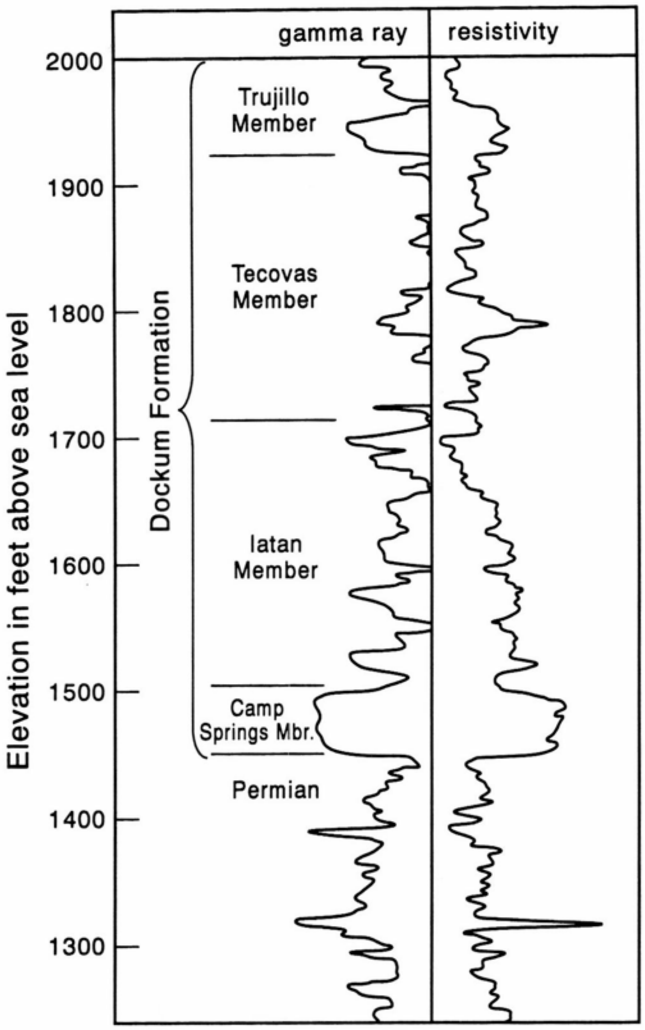


FIGURE 5—This well-log from just west of Westbrook in Mitchell County, Texas, allows clear recognition of the Camp Springs, Iatan, Tecovas and Trujillo Members of the Dockum Formation in the subsurface (well 28-47-603; see Shamburger, 1967).

Miguel County near the type section they designated and described.

The Garita Creek Formation, as Kelley's (1972a, b) mapping demonstrates, is present throughout much of San Miguel, Guadalupe and De Baca Counties. It is also present as far west as Lamy in Santa Fe County (Allen and Lucas, 1988; Lucas, 1991a). In Santa Fe and San Miguel Counties the Garita Creek Formation contains vertebrates of late Carnian age (Hunt et al., 1989). Although demonstrably younger, by superposition, than the late Carnian vertebrates of the Los Esteros Member of Santa Rosa Formation, the Garita Creek and Los Esteros faunas are similar (Fig. 6). They are part of a broadly constrained late Carnian vertebrate fauna from the Chinle Group that is the basis of the Adamanian land-vertebrate faunachron of Lucas and Hunt (1993a). Further work is needed to make finer biostratigraphicalfbiochronological distinctions using vertebrates in this time interval, if such distinctions are possible. Currently only one vertebrate assemblage of late Carnian age can be recognized, and it is present in both the Los Esteros Member and the Garita Creek Formation.

The same assemblage is confined to the Tecovas Member of the Dockum Formation in west Texas (e.g. Murry, 1986, 1989) (Fig. 6). This indicates correlation of the Los Esteros—Garita Creek interval with the Tecovas Member, a correlation in part supported by fossil plants shared by the Los Esteros and Tecovas (see above). No palynomorphs have yet been recovered from the Los Esteros Member or the Garita Creek Formation. However, Tecovas palynomorphs indicate a late Carnian age (Dunay and Fisher, 1974, 1979; Litwin et al., 1991; Cornet, 1993) and are the same as those found in upper Carnian Chinle Group strata on the Colorado Plateau that contain the Adamanian vertebrate assemblage. Unionid bivalves from the Tecovas Member and Colorado Plateau Adamanian units also support this correlation (Good, 1993a, b), as do ostracodes (Kietzke, 1989b; Kietzke and Lucas, 1991). Furthermore, the stratigraphic position of the Los Esteros—Garita Creek and Tecovas strata is the same; they are sandwiched between correlative units, the Tecolotito—Camp Springs below and the Trujillo above. Correlation of the Los Esteros—Garita Creek and the Tecovas intervals thus is beyond question, and it is the most precise correlation that can be attempted at present, as Lehman (this volume) indicates. However, in attempting this correlation, one finds major lithologic and thickness changes between east-central New Mexico and west Texas (Fig. 7), a fact not considered by Lehman (1994) and discussed below.

Tecovas Member of Dockum Formation

Gould (1907) named the Tecovas Formation of the Dockum Group for mudstone-dominated strata north-

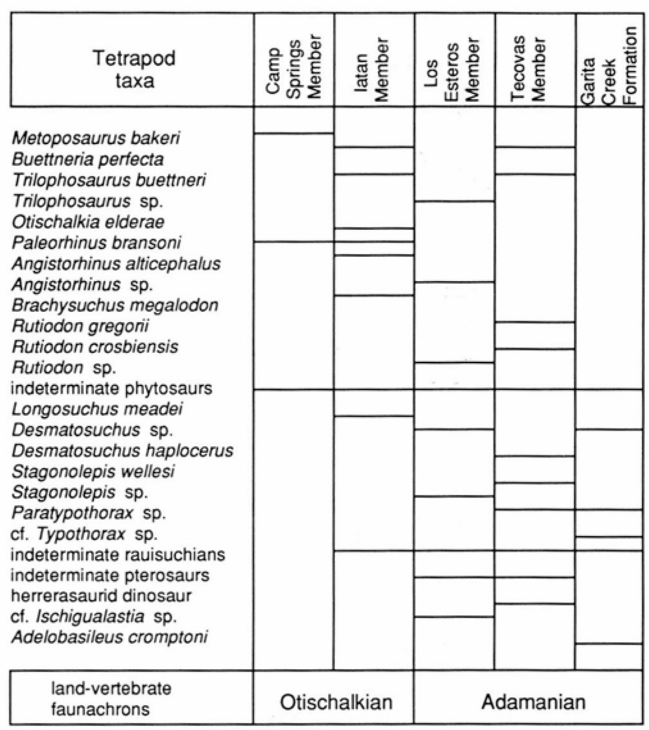


FIGURE 6—Stratigraphic distribution of tetrapods in upper Carnian strata of east-central New Mexico and west Texas (based on data in Murry, 1986, 1987, 1989; Hunt and Lucas, 1991a, b; Lucas et al., 1993; and other sources).

west of Amarillo in Potter County, Texas. Lucas and Anderson (1992) designated his section on West Amarillo Creek in Potter County the lectostratotype. The Tecovas Member has a maximum thickness of 67 m, and it is dominantly a fine-grained sequence of variegated red, yellow, purple and green bentonitic mudstone with some trough-crossbedded sandstones (Figs. 2B, D, F). It is present throughout the Texas Panhandle Upper Triassic outcrop belt.

Correlation of the Tecovas Member with the Los

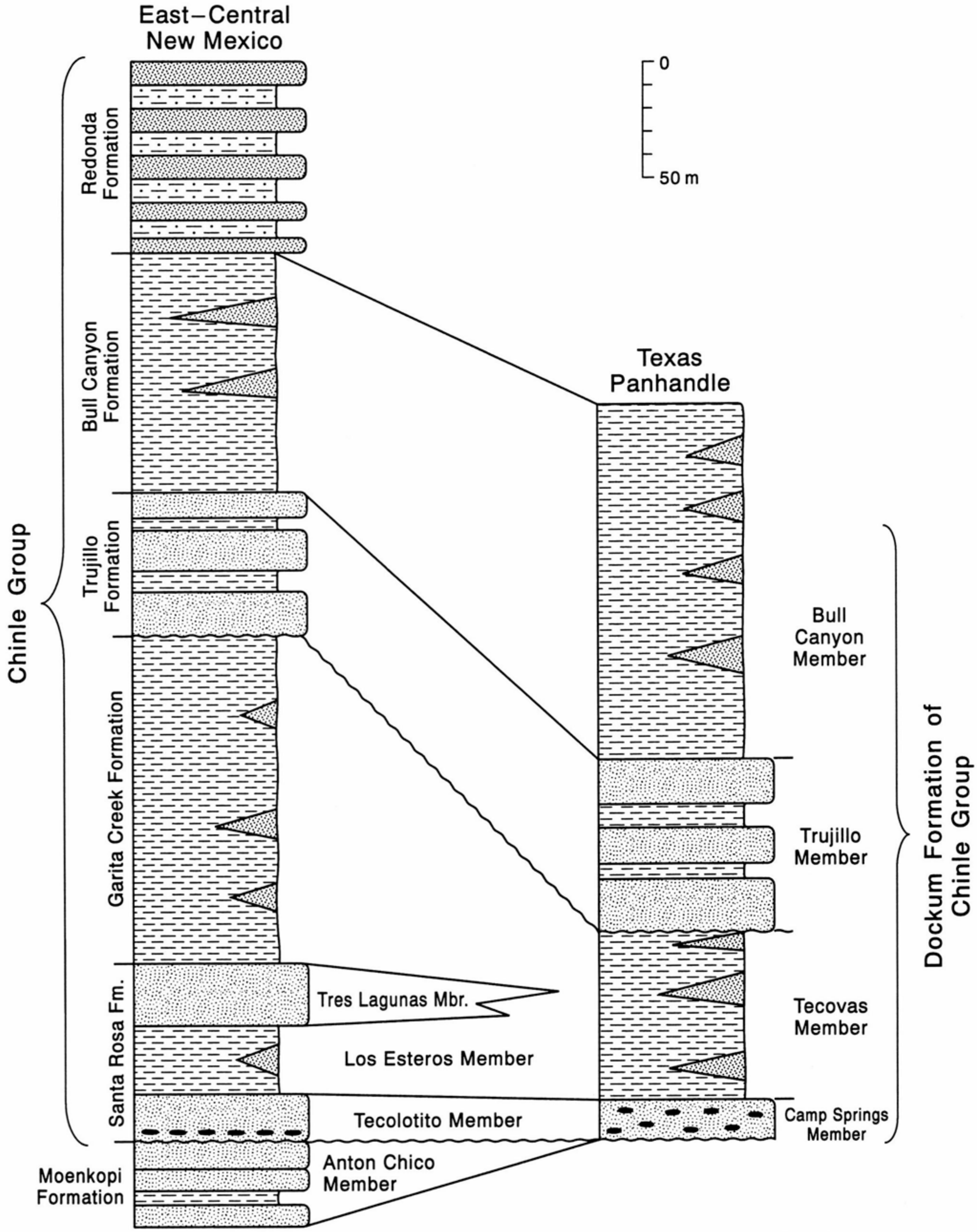


FIGURE 7—Correlation of lithostratigraphic units between east-central New Mexico and the Texas Panhandle. Lithology is somewhat simplified, and the thicknesses indicated are maximum reported thicknesses. Note the extent of thickness and lithofacies changes between the correlative Los Esteros–Garita Creek and Tecovas intervals.

Esteros-Garita Creek interval in east-central New Mexico was elaborated above. Lehman (1994) accepts this correlation but wants to apply the term Tecovas to the entire east-central New Mexico interval. In so doing he not only ignores the clear thickness and lithologic differences between the Tecovas Member and the Los Esteros-Garita Creek interval (Figs. 2, 7), but is the first worker (other than Spiegel, 1972) to suggest the name Tecovas be used in New Mexico.

The Los Esteros-Garita Creek interval has a maximum thickness of 251 m in east-central New Mexico, whereas the maximum Tecovas Member thickness is 67 m in west Texas. The Los Esteros Member is up to 44 m of mostly red, gray and purple mudstone overlain by up to 45 m of mostly quartzarenites of the Tres Lagunas Member, in turn overlain by up to 152 m of red-bed mudstones and sandstones of the Garita Creek Formation. This contrasts markedly with the variegated red, yellow, purple and green mudstones and minor sandstones of the much thinner Tecovas Member in west Texas (Figs. 3, 6). Indeed, the Tres Lagunas Member alone is about as thick as the entire Tecovas Member. This indicates just how misleading Leh-man's (this volume, fig. 1) cross section is.

Lehman (this volume) criticizes us "for a lack of regard for earlier generations of geologists," yet he wants us to ignore all previous work on the Upper Triassic stratigraphy of east-central New Mexico—by Darton, Gorman and Robeck, Kelley and others—by bringing the name Tecovas into the state. His only claim to precedence for this is Spiegel's (1972) unsupported (and, significantly, unheeded) suggestion to bring the term Tecovas into east-central New Mexico.

One of the most challenging stratigraphic problems that faces us in understanding the Upper Triassic of the southern High Plains is relating the Los EsterosGarita Creek interval to the Tecovas interval. Where does the Tres Lagunas Member pinch out? Is the Tecovas actually equivalent to all, or only part, of the correlative interval in east-central New Mexico as now understood? What are the exact facies changes that take place in this interval between east-central New Mexico and west Texas that have led to such contrasting lithologies and thicknesses? Only answering these and other questions will enhance understanding of the Late Triassic depositional system in this area. Applying the term Tecovas to the Los EsterosGarita Creek interval in east-central New Mexico thus (1) runs counter to long and well-accepted strati-graphic practice, and (2) obscures obvious thickness and lithologic differences between correlative strata in east-central New Mexico and west Texas.

Trujillo Formation and Trujillo Member of Dockum Formation

To most previous workers the Santa Rosa Formation was the most obvious, laterally persistent, sandstone-dominated unit in east-central New Mexico. On the other side of the border, the Trujillo Member of the Dockum Formation was the most obvious, laterally persistent, sandstone-dominated Upper Triassic unit in west Texas. In the absence of detailed lithostratigraphy and biostratigraphy there thus was some logic to correlating the two units. The Santa Rosa (New Mexico) = Trujillo (Texas) correlation became well entrenched in the literature and was one of the most widely cited stratigraphic misconceptions concerning the Upper Triassic of the southern High Plains (e.g. Adams, 1929; Bates, 1942; Nicholson et al., 1955; Hills and Kottlowski, 1983). As Lucas and Hunt (1989) concluded, the miscorrelation of the Santa Rosa and Trujillo had been readily refuted by detailed lithostratigraphy, mapping and biostratigraphy, as Lehman (this volume) acknowledges.

Darton (1928, fig. 143) recognized a thick sandstone-dominated interval above the Santa Rosa in the Upper Triassic section of east-central New Mexico. Subsequent mapping by Northrop et al. (1946), Griggs and Hendrickson (1951), Wanek (1962) and Trauger and Bushman (1964), among others, recognized this interval as a mappable, informal stratigraphic unit. Kelley (1972a, b) assigned the formal name Cuervo Sandstone Member of Chinle Formation to this unit and mapped its distribution throughout east-central New Mexico.

Recognition of the nature and extent of the Cuervo Sandstone Member increased the confusion over correlation of the Santa Rosa Formation with the Trujillo Member of the Dockum Formation. This confusion was best revealed at Ute Dam on the Canadian River just west of the New Mexico-Texas border in Quay County. The thick sandstone sequence at the dam was identified as (1) Santa Rosa Sandstone (Dane and Bachman, 1965), (2) Cuervo equivalent to Trujillo (Spiegel, 1972), (3) both Santa Rosa and Cuervo (Finch et al., 1976a), and (4) Logan Sandstone, a new name informally proposed to sidestep the problem (Trauger et al., 1972). Gould's (1907) type Trujillo is only about 45 km east of Ute Dam, at Trujillo Camp in a tributary of the Canadian River in Oldham County, Texas. Gould (1907) had correctly traced it, over a nearly continous outcrop, to the New Mexico-Texas border on the Canadian River downstream from Ute Dam. Clearly, the sandstones exposed at Ute Dam are Trujillo equivalent.

Because of lack of exposure, the sandstones at Ute Dam cannot be traced up the Canadian River into Guadalupe County, where the river has cut down through the Santa Rosa Formation. Here arose much of the uncertainty about the correlation of the Ute Dam sandstones westward. However, the stratigraphic position of these sandstones is readily determined by tracing them both north, up Ute Creek toward the Canadian escarpment, and south, down Revuelto Creek toward the Llano Estacado. These traverses indicate that the Bull Canyon Formation followed by the Redonda Formation are the Upper Triassic strata that overlie the sandstones at Ute Dam. This means that the Ute Dam sandstones occupy the same stratigraphic position as Kelley's Cuervo Sandstone farther west (the Santa Rosa is much lower in the section), which supports correlation of Gould's Trujillo and Kelley's Cuervo. Both occupy the same stratigraphic position and are of similar thickness and essentially identical lithology, being dominantly composed of trough-crossbedded micaceous litharenites and intrabasinal (clasts of calcrete, mudstone and siltstone rip-ups) conglomerates with interbeds of red-bed mudstones, siltstones and finer-grained sandstones. Furthermore, correlation of Kelley's Cuervo and Gould's Trujillo is supported by biostratigraphy (see below).

Based on the above considerations, Lucas and Hunt (1989) abandoned Kelley's term Cuervo and replaced it with Gould's term Trujillo, as the Trujillo Formation. Lehman (this volume) accepts this correlation and nomenclature with one minor modification: he terms the unit Trujillo Sandstone, even though it contains significant amounts of conglomerate, mudstone and siltstone.

The age of the Trujillo in west Texas has been established by palynomorphs, plant megafossils and vertebrates as lying just above or across the Carnian-Norian boundary. The controversial plant *Sanmiguelia* (a possible angiosperm) is known from the Trujillo Member in Palo Duro Canyon, Texas (Ash, 1976; Cornet, 1986). This indicates Ash's (1987) *Sanmiguelia* floral zone of Norian age. However, palynomorphs from various Trujillo outcrops and from a borehole in west Texas indicate that its lower part is locally of latest Carnian age (Dunay and Fisher, 1974, 1979; Litwin et al., 1991; Cornet, 1993). Vertebrates from the Trujillo at Revuelto Creek, Quay County, New Mexico, include the aetosaur *Typothorax* and indicate an early Norian age (Hunt, 1991). These biostratigraphic indicators support correlation of the Trujillo of the southern High Plains with medial Chinle Group sandstone/conglomerate complexes on the Colorado Plateau termed Sonsela, Moss Back and Agua Zarca (Lucas, 1991a, 1993a; Lucas and Luo, 1993).

This correlation further underscores the wide age difference between the *Paleorhinus-bearing* late Carnian Camp Springs Member in west Texas and the latest Carnian-early Norian Trujillo Member. As much as 67 m of Tecovas strata separate these two units in the northern Texas Panhandle, and the base of the Trujillo is an erosional unconformity that represents a hiatus equivalent to part of the latest Carnian. It is therefore not possible to accept Lehman's (1992) claim that the type Camp Springs is the same unit as the Trujillo. His current map (Lehman, this volume, fig. 1) shows the type Camp Springs east of the town of Camp Springs as the Santa Rosa Sandstone, which is his name for the Camp Springs Member of our usage. Lithology, stratigraphic position and biostratigraphy document the clear and easy separation of the Camp Springs and Trujillo in west Texas (Figs. 3, 7).

Bull Canyon Formation and Bull Canyon Member of Dockum Formation

The red-bed-mudstone-dominated interval above the Trujillo Formation in east-central New Mexico is as much as 110 m thick. These strata were recognized already by Darton (1928), and Dobrovolny and Summerson *(in* Dobrovolny et al., 1946) mapped them through much of Quay County as an unnamed member of the Chinle Formation. Kelley (1972a, b) mapped this unit through most of east-central New Mexico as the upper shale member of the Chinle Formation. Lucas and Hunt (1989) named this unit the Bull Canyon Formation for Bull Canyon in eastern Guadalupe County where the type section was designated and described.

Gould (1907) recognized an upper mudstone-dominated interval of the Trujillo Member of the Dockum in the Texas Panhandle. Chatterjee (1986) subsequently named this interval the Cooper Member of the Dockum Formation. However, as noted by Lehman et al. (1992), the name Cooper is preoccupied by several other stratigraphic names, including the Tertiary Cooper Marl of South Carolina and Georgia. Furthermore, Chatterjee's (1986) type section of his Cooper Member is about 16 m thick and represents only a tiny fraction of the upper-mudstone dominated Dockum interval. Clearly, this is not an adequate type section for the upper mudstone-dominated interval of the Dockum originally recognized by Gould (1907).

Because the name Cooper was preoccupied when Chatterjee (1986) introduced it, this name should not be used for a Dockum Formation stratigraphic unit despite our (Lucas and Hunt, 1987; Lucas and Anderson, 1992) use of it in regional correlation charts. In stating this, we stress that: (1) ours was the only published use of Chatterjee's term Cooper, no Texas geologist used it between 1986 and 1992; (2) our use preceded our work in west Texas and realization that Cooper, when proposed by Chatterjee (1986), was a preoccupied name; and (3) our use of the name Cooper was only in a regional correlation chart and thus was the type of matter-of-fact usage that appears in any article attempting a regional correlation based, in part, on units in the literature.

To solve the problem that the incorrect proposal of Cooper Member created, we extended Lucas and Hunt's (1989) term Bull Canyon Formation from east-central New Mexico into west Texas, giving it a new rank there as a member of the Dockum Formation (Lucas and Anderson, 1993a). Bull Canyon was not a preoccupied name when introduced by Lucas and Hunt (1989), and it has a properly defined type section. Recent work on physical stratigraphy and biostratigraphy (Lucas and Hunt, 1989; Lucas and Anderson, 1992; Lehman et al., 1992) supports extension of the term Bull Canyon into west Texas. From Quay County, New Mexico, the unit can be traced directly, with a few outcrop breaks, into Oldham County, west Texas. Also, the verebrate faunas of the Bull Canyon Formation in east-central New Mexico and in mudstone-dominated strata above the Trujillo near Post in Garza County, Texas, overlap in age (Chatterjee, 1986; Lucas and Hunt, 1989).

Lehman et al. (1992) and Lehman (this volume) present an alternative solution to the stratigraphic nomenclature problem created by Chatterjee (1986). They propose to rename the Cooper Member the Cooper Canyon Formation (of the Dockum Group) and describe a new type section-161.5 m thick. Furthermore, Lehman et al. (1992) argue that their Cooper Canyon Formation should take precedence over the term Bull Canyon Formation in east-central New Mexico. Lehman et al.'s (1992) proposals violate all rules of accepted stratigraphic procedure by redefining and renaming an ill-defined and improperly named stratigraphic unit then claiming that the newly created unit (Cooper Canyon Formation) has priority over a name

(Bull Canyon Formation) properly defined and named three years earlier. In fact, the Cooper Canyon formation of Lehman et al. (1992) is simply a synonym of Bull Canyon Formation of Lucas and Hunt (1989).

The Bull Canyon Formation is mostly reddish-brown mudstone with lesser amounts of siltstone and ledgy sandstone. The sandstones are commonly ripple-laminated, but trough crossbedding and planar laminations are also present. The maximum reported thickness of the Bull Canyon Member in west Texas is 161.5 m near Post in Garza County (Lehman et al., 1992), but this thickness is largely determined by post-Triassic erosion because no Triassic strata overlie the Bull Canyon Member in west Texas. Fossil vertebrates indicate that the Bull Canyon Member is of early Norian age (Chatterjee, 1986; Lucas and Hunt, 1989).

Redonda Formation

Dobrovolny and Summerson *(in* Dobrovolny et al., 1946) named the youngest strata of the Chinle tectonosequence in east-central New Mexico the Redonda Member of the Chinle Formation. It was raised to formational rank by Griggs and Read (1959). Since Lucas and Hunt (1989), we have followed that suggestion (contrary to the preliminary report of Lucas et al., 1985) by recognizing the Redonda as a unit of formational rank.

The Redonda Formation is confined to east-central New Mexico, is as much as 140 m thick, and consists mostly of cyclically bedded siltstone and sandstone (Lucas et al., 1985; Hester, 1988). Its extensive vertebrate fauna suggests a latest Triassic (Rhaetian) age (Lucas, 1993a, 1994; Lucas and Hunt, 1993a).

The terms Dockum and Chinle

On the southern High Plains the terms Chink and Dockum have been used in a variety of ways to identify Upper Triassic strata. Both terms have been accorded either formational or group rank and have usually subsumed most or all of the Upper Triassic section. Any review of previous usage of these terms clearly indicates a certain amount of disagreement over what Chinle and Dockum should encompass as lithostratigraphic units. The solution advocated by Lehman (this volume) is to call all the Upper Triassic strata on the southern High Plains the Dockum Group. This is a relatively new use of the term Dockum Group, not one advocated by any recent worker.

To properly understand the original Cummins' (1890, p. 189-190) proposal of the term "Dockum Beds," we quote his full description:

> A few miles before reaching Dockum, situated in the western edge of Dickens County, I came upon a bed of conglomerate sandstone and red clay, resting unconformably upon the clays and sandstones of the upper Permian, entirely unlike anything I have heretofore seen in Texas. This formation lies along the foot of the Staked Plains in a narrow belt. Because of its extensive occurrence in the vicinity of Dockum, I gave the formation the name of Dockum Beds, but will not for the present attempt to determine their correlation. I have found everywhere on the beds of the Permian belt pieces of conglomerate and large pebbles of white quartz that did not belong to the Trinity sands of the Cretaceous which were supposed to overlie the Permian to the westward, and it is a matter of interest to know where this drift came from. The fragments of conglomerate increased in size as we traveled westward until we came upon the beds of that material in the vicinity of Dockum, and the question was solved as to the origin of the fragments of conglomerate and the quartz pebbles.
>
> In the conglomerate are many silicified trunks of trees, some of them of great length. In the red clay above the conglomerate are fossil remains of large reptiles, whose species I was unable to determine in the field. In the upper sandstone were many casts of a *Unio* that I have provisionally called *Unio documensis.* In most places that fossil occurs only as casts, and in one place only did I find specimens of both valves, and they were so badly encrusted with carbonate of lime that the peculiar markings of the shell could not be seen. The sandstone was everywhere full of scales of mica, some of the scales being one-sixteenth of an inch square. The whole thickness of this formation in this vicinity is about 150 feet. These beds extend under the Staked Plains. I traced them up Blanco Canyon to the falls of White River, where they pass out of sight under the beds of the overlying strata.
>
> There are a great many springs of clear pure water flowing from these beds, and wherever the formation has been penetrated by wells, an abundance of good water has been obtained.

Clearly, this proposal, not based on "tested mappability" and lacking a type section, does not meet modern standards imposed by the NACSN (1983) for the proper proposal of a new stratigraphic term. Despite this, Dockum as a formation or group gained wide usage in west Texas and somewhat less wide usage in eastern New Mexico.

Cummins' (1890) description makes it clear what strata pertain to his "Dockum Beds"; these are the Camp Springs, Tecovas and Trujillo Members of the Dockum Formation of our usage (Fig. 8). However, few modern (post-World War **II)** workers seem to have concerned themselves with what strata composed the original Dockum of Cummins (1890). This perhaps explains the wide variety of usages of the term Dockum, many of which included strata in the Dockum that are clearly not equivalent to strata of Cummins' original Dockum.

Three solutions to the problem this has created (i.e. Dockum, as used by most workers, is a very imprecise and confusing stratigraphic term) are possible:

1. The term Dockum could be abandoned. The NASC (North American Stratigraphic Code) certainly allows for this by stating (Article 20a) that "widespread misuse in diverse ways which compound confusion" may justify abandonment of a stratigraphic name. Dockum has been so misused. Nevertheless, this name is well entrenched in the literature, especially that of Texas geology, and is so unlikely to be abandoned that this solution seems untenable.
2. The term Dockum Group could be used to refer to all Upper Triassic strata in eastern New Mexico and west Texas. Lehman (this volume) advocates this solution, as did a few early workers (e.g. Darton, 1928; Gorman and Robeck, 1946). This greatly expands Cummins' (1980) original concept of the Dockum to include, among other strata, a. thick post-Trujillo section (Bull Canyon and Redonda Formations) in east-central New Mexico. It also raises the question what are the westward and northward limits of the Dockum Group? Given that all Upper Triassic nonmarine strata from the Colorado Plateau to west Texas represent one integrated depositional system that produced a single, complex lithosome, what should these strata be named? On

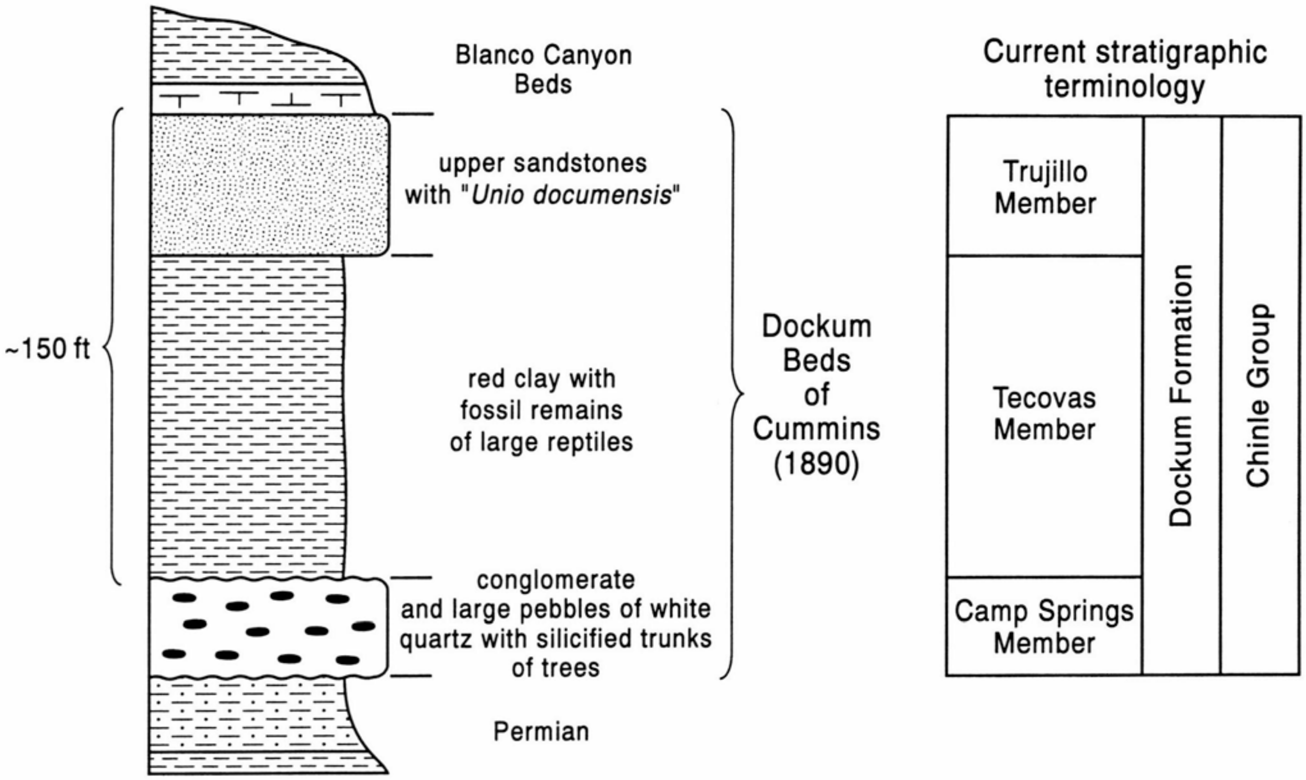


FIGURE 8—Stratigraphic interpretation of Cummins' (1890) original description of the "Dockum Beds."

the Colorado Plateau they are the Chinle Formation of most authors. The Chinle had a well defined type section when Gregory (1916, 1917) named it, one that encompasses almost all of the Upper Triassic lithosome throughout the American Southwest. Chinle has long been used in a precise and consistent manner in a voluminous literature and a myriad of geologic maps. Furthermore, the term has been used both in eastern New Mexico and west Texas by several workers. For this reason we prefer to assign all Upper Triassic nonmarine strata in the American Southwest to the Chinle Group (Lucas, 1993a). Dockum admittedly has priority over Chinle (as do the names Dolores and Popo Agie: Lucas, 1993a), but Chinle is a much more widely used name with a type section that represents much more of the Chinle Group section than does the original Dockum section of Cummins.

3. By recognizing all Upper Triassic nonmarine strata in west Texas as the Chinle Group, it might seem advisable to abandon the term Dockum althogether, as discussed above. Instead, we prefer to use the term Dockum in a precise way consistent with virtually all previous usages in west Texas. Thus, we identify the Dockum Formation as consisting of four members—Camp Springs, Tecovas, Trujillo and Bull Canyon. This expands Cummins' original Dockum to include the post-Trujillo strata of the Bull Canyon Member, but this expansion in west Texas dates back to Gould (1907) and has been accepted by most subsequent workers.

Our usage creates the problem that it restricts the term Dockum to west Texas simply as a concession to Texas usage. Certainly the Dockum strata continue into eastern New Mexico; there is no "state-line fault." Lithofacies changes merit some nomenclature changes across the Texas–New Mexico state line, as discussed above. Other units that do not undergo lithofacies changes merely change rank from member (in Texas) to formation (in New Mexico). The only way to avoid this, and avoid the problems that led to Chinle Group discussed above, is to abandon the name Dockum altogether and raise its four west Texas members tc formation rank in the Chinle Group. We like this solution but doubt that Dockum will ever be abandoned as a stratigraphic term in Texas. Therefore, we advocate a stratigraphically precise and geographically restricted use of the term Dockum Formation consistent with most of previous usage.

Lehman's critique

Lehman (this volume) presents a critique of much of the stratigraphic nomenclature and some of the correlations discussed above. However, his all-encompassing condemnation of our work masks some key areas of agreement while highlighting other areas of disagreement.

Areas of agreement

We agree with Lehman that a single depositional system produced the Upper Triassic strata in west Texas and eastern New Mexico. There should be no "state-line fault" between west Texas and eastern New Mexico that merits separate consideration of the Upper Triassic strata on both sides of the border. (But see Finch and Wright [1983] for an unsupportable claim that a fault actually does offset Triassic strata on the Texas–New Mexico line along the Canadian River.)

The correlation of Upper Triassic strata between west Texas and eastern New Mexico proposed by Lehman (this volume) does not differ significantly from the correlations we have published. We agree that the Redonda Formation is confined to east-central New Mexico, that the Bull Canyon and Trujillo Formations of east-central New Mexico can be traced directly into west Texas, that the Tecovas Member of the Dockum Formation in west Texas is correlative with the Los Esteros and Tres Lagunas Members of the Santa Rosa Formation and the Garita Creek Formation in east-central New Mexico, and that the Camp Springs Member of the Dockum Formation in west Texas is correlative to the Tecolotito Member of the Santa Rosa Formation in east-central New Mexico. Lehman's support of these correlations and of the unity of Late Triassic deposition in Texas–New Mexico represents his acceptance of major points we have worked on and published for years. Where Lehman disagrees with us is on what stratigraphic nomenclature should be applied to Upper Triassic strata in eastern New Mexico and west Texas and (most critically) on some Upper Triassic stratigraphic relationships in west Texas.

Areas of disagreement

Definition of stratigraphic units—Lehman's (this volume) discussion makes it clear that he does not understand the procedures and practices attendant to naming new stratigraphic units. First, he applies modern standards for naming units to much earlier workers, but only in those cases in which he wishes to abandon the names they proposed. Thus he notes Beede and Christner's (1926) failure to meet modern standards when naming the Camp Springs Conglomerate, but fails to mention that Cummins' (1890) proposal of the Dockum Beds also failed to meet these standards. The difference here is not the way in which Camp Springs and Dockum were proposed, but the fact that Lehman wants to abandon the name Camp Springs and use (and actually greatly expand the use of) the term Dockum.

Similarly, Chatterjee's (1986) proposal of the term Cooper Member of Dockum formation did not meet modern standards of definition, even though it was published three years after the most recent version of the NASC (NACSN, 1983). The name Cooper was preoccupied many times over when proposed, and no geologist working in Texas mapped the unit or used the name in print since its proposal. Indeed, our usages of Cooper in regional correlation charts seem to be the only published references to this unit since its proposal. Yet, Lehman (this volume; Lehman et al., 1992) wants to rename and redefine the Cooper Member as the Cooper Canyon Formation and have it take precedence over Bull Canyon Formation, a name properly defined in 1989. In the same article, however, Lehman does not approve of our (Lucas and Anderson, 1993a) identification of a Camp Springs Member type section to properly define that unit, because he stresses the improper (by today's standards) original definition of the Camp Springs by Beede and Christner (1926). We conclude that the stratigraphic standard to which Lehman adheres is a double standard: names he wishes to use need not have been properly introduced, but an improper introduction (by today's standards) of a stratigraphic name is a reason to abandon that name if Lehman does not wish to use it.

Another misconception embodied in Lehman's (this volume) critique of our work is the idea that to name a new lithostratigraphic unit you must map that unit. The NASC (Article 24[d]) states that: "The proposal of a new formation must be based on tested mappability. Well-established formations commonly are divisible into several widely recognizable lithostratigraphic units; where formal recognition of these smaller units serves a useful purpose, they may be established as members and beds, for which the requirement of mappability is not mandatory. A unit formally recognized as a formation in one area may be treated elsewhere as a group, or as a member of another formation, without change of name."

Every new formation-rank unit we have proposed, and every unit we have elevated to formational rank, has been "based on tested mappability," as the above summary shows. Indeed, the new member names we proposed for the Santa Rosa Formation also meet the criterion of tested mappability (see above). Ironically, Chatterjee's (1986) proposal of Cooper Member did not meet the criterion of tested mappability, simply because that unit had never been mapped before 1986, nor did Chatterjee map it then. Because Cooper was proposed by Chatterjee as a member, it need not have met the mappability criterion. Now, Lehman et al. (1992) and Lehman (this volume) wish to recognize a Cooper Canyon Formation as a redefinition of Chatterjee's Cooper Member. This is a mappable unit, and the first published mapping of it appeared in Lehman et al. (1992) and Lehman (this volume). Clearly, Lehman believes that "tested mappability" means that a unit can be mapped anytime after it is proposed, which is not how we interpret Article 24(d) of the NASC quoted above.

Lehman also presents an argument for the preservation and priority of the name Cooper Member of Chatterjee (1986) as Cooper Canyon Formation, even though as we have indicated that (1) the name was preoccupied when proposed, (2) it was not mapped until 1992, (3) it was not used by anyone except us in summaries of regional Upper Triassic correlation, (4) Chatterjee's original Cooper type section represents about 10% of the total unit thickness, and (5) the name Cooper Canyon Formation of Lehman et al. (1992) clearly is a synonym of Bull Canyon Formation of Lucas and Hunt (1989). A large part of Lehman's (this volume) argument for preserving Chatterjee's (1986) term Cooper is based on the assertion that it is not a preoccupied name (i.e. a homonym in terms of the NASC). Thus Lehman posed the question "was the name Cooper Formation [actually it was Cooper *Member]* preoccupied? [when proposed in 1986]. Strictly speaking, no; the lithologic modifier was different." Yet, Lehman et al. (1992) claimed the name Cooper was preoccupied, which was why they modified it to Cooper Canyon.

We conclude that Cooper was a preoccupied name when Chatterjee (1986) first used it because, for example, the term "Cooper marl" has long been used in South Carolina and is accepted as 4 formal term by the U.S. Geological Survey (e.g. Wilmarth, 1938, p. 512). Lehman's (this volume) claim that this does not preoccupy Chatterjee's Cooper Member indicates that he misunderstands Article 7 of the NASC. This article makes it clear that a difference in lithologic descriptor is not relevant to homonymy of stratigraphic names; it is the homonymy of the geographic name that is critical. Cooper had been used as the geographic name in several stratigraphic names long before Chatterjee used it, and so Chatterjee introduced Cooper as a homonym, which is a legitimate reason to abandon it (NASC, Article 20[a]). There is no basis in the NASC for preserving Chatterjee's name Cooper, despite Lehman's claims to the contrary.

Previous work—Lehman (this volume) presents a very incomplete, inaccurate and misleading review of our work and the stratigraphic work of earlier geologists. From his article it would appear that we have made more than 50 errors, too many to address here. Instead, we focus on the major problems his review creates.

Lehman's review is designed to create the impression the Upper Triassic stratigraphy in west Texas was well understood early in this century, and that the nomenclature he advocates is consistent with that of earlier workers. This is clearly not the case, as an accurate review of stratigraphic work in west Texas between 1890 and 1993 reveals. Our Figure 9, of the nomenclature used by major workers on the Upper Triassic of west Texas, contrasts with Lehman's (this volume) figure 2. For example, his figure suggests long, extensive usage of Santa Rosa for the basal Dockum in west Texas. However, a careful review of the literature reveals quite the opposite, with much evident uncertainty and disagreement about use of the term Santa Rosa in Texas.

We conclude that Lehman's review of previous work on the Upper Triassic of west Texas, especially his figure 2, is neither comprehensive nor correct. Instead, it is largely a misrepresentation intended to mislead the reader into believing Lehman is advancing a long-recognized stratigraphic framework and its attendant nomenclature. In fact, no other geologist who worked in west Texas has used Lehman's Triassic nomenclature. It has appeared in none of the many reports or. maps published by the Texas Bureau of Economic Geology. Significantly, it does not appear on the newest version of the state geologic map of Texas (Barnes, 1992). Lehman's proposed nomenclature for the Upper Triassic of west Texas thus not only lacks the historical precedence he claims for it; it has never been advocated by any other geologist.

Lehman's presentation of the development of Upper Triassic stratigraphic nomenclature in eastern New Mexico, especially his figure 2, is largely taken from Lucas et al. (1985) and is somewhat more accurate that his historical summary of the west Texas nomenclature, as comparison of his figure 2 with our Figure 10 shows. Nevertheless, here his goals are to present our work as confusing and unnecessary, and this leads him to misrepresentation. An example is

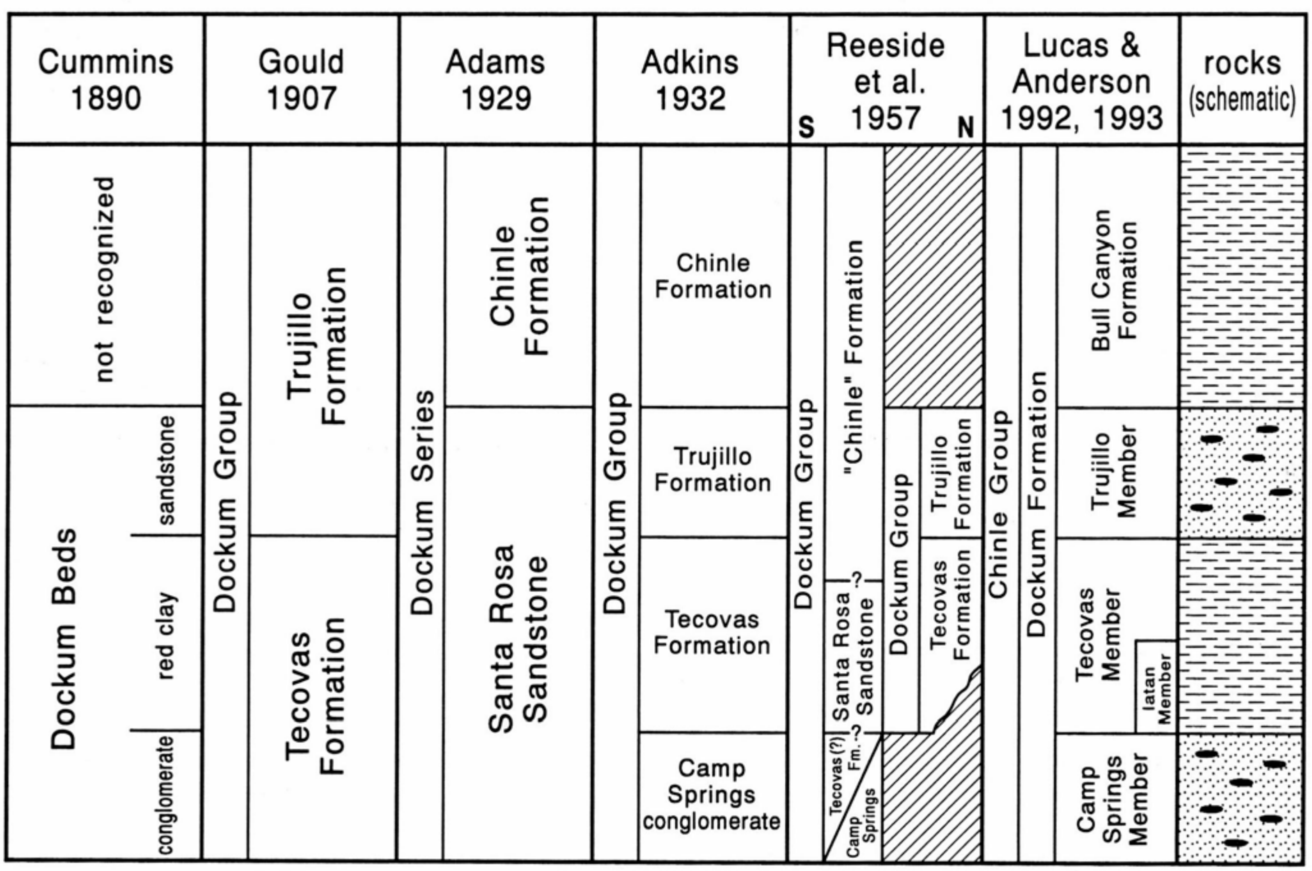


FIGURE 9—Development of Upper Triassic stratigraphic nomenclature in west Texas.

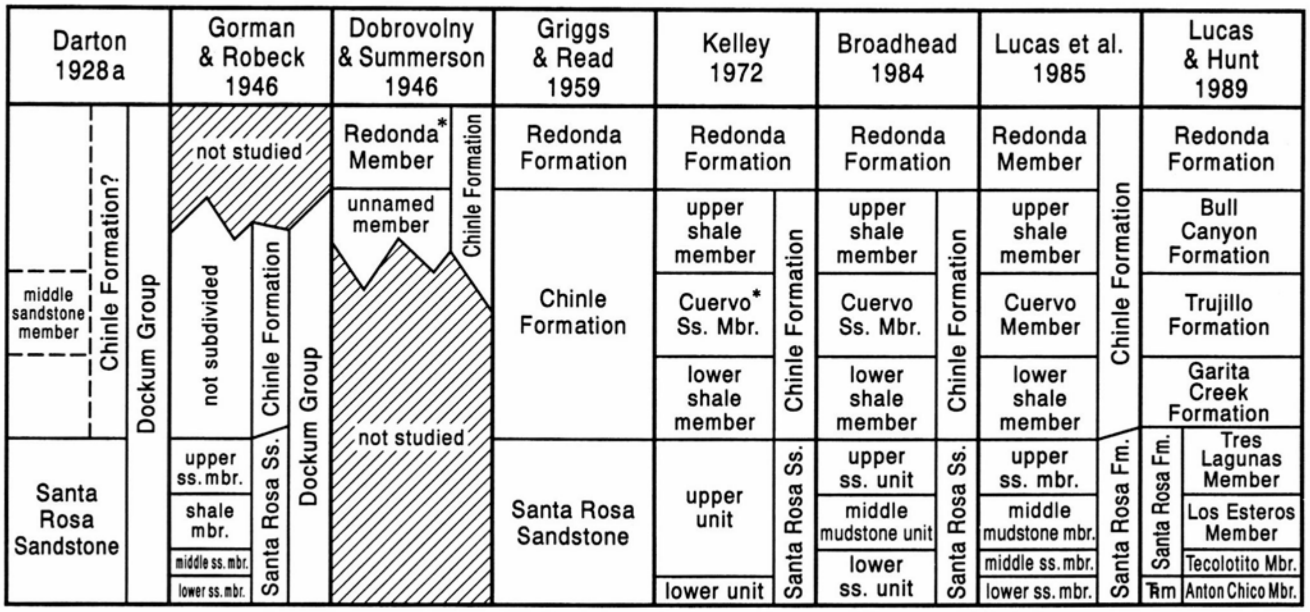


FIGURE 10—Development of Upper Triassic stratigraphic nomenclature in east-central New Mexico (after Lucas et al., 1985). TRm = Moenkopi Formation.

his figure 2 showing the San Pedro Arroyo Formation as equivalent to the Garita Creek-Redonda interval. In fact, Lucas (1991b, fig. 7) indicated correlation of the San Pedro Arroyo Formation with the Los Esteros-Bull Canyon interval, but a more likely correlation of the San Pedro Arroyo Formation with the Los Esteros-Tres Lagunas interval was presented by Lucas and Anderson (1992, 1993c). The correlation Lehman attributes to us was never published by us.

Database and stratigraphy—Lehman's critique of our work is essentially data-free. He presents very little stratigraphic information to support his point of view. His cross section of Upper Triassic strata under the High Plains of east-central New Mexico and the northern Texas Panhandle (Lehman, this volume, fig. 1) is his only data other than mapping and is, as explained above, partly incorrect. His article presents three maps: (1) his figure 1, at a scale of about 1 inch = 60 miles, is little more than a compilation of mapping of the Triassic outcrop belt as done by Dane and Bachman (1965) and Barnes (1992) with the addition of an erroneous distribution of the Dockum members in Howard and Mitchell Counties, Texas; (2) his figure 3, a map of the "type area" of the Dockum, is a useful contribution that documents the distribution of the Dockum members over about a 1700 km^2 area; and (3) his figure 5, a map of the Lubbock-Big Spring-Sweetwater area of west Texas at the scale of about 15 miles to an inch; this map is in many features much less detailed than the 1:250,000 maps of the *Geologic Atlas of Texas* that cover the same area (Lubbock and Big Spring Sheets).

Both figures 1 and 4 of Lehman indicate a large outcrop area of the uppermost Dockum (his Cooper Canyon Formation) south of the Colorado River. This runs contrary to all previous work in the area (e.g. Drake, 1892; Adams, 1929; Shamburger, 1967; Grover, 1984), which never identified any significant outcrops of post-Trujillo Dockum strata. Indeed, in this area pre-Lower Cretaceous and Cenozoic erosion has greatly truncated Dockum outcrops so that only the lower to middle Dockum is exposed in Howard and Mitchell Counties, Texas (e.g. Van Siclen, 1957; Shamburger, 1967; Gustafson, 1984). If Lehman's mapping is correct (especially his figure 4), then much of the understanding of Cretaceous and Cenozoic erosion and deposition in west Texas developed by a number of workers must be incorrect. Our observations, however, are in accord with those of earlier workers and suggest that there are few outcrops of post-Trujillo Dockum strata south of the Colorado River in west Texas. Furthermore, Lehman's mapping of Santa Rosa in his figure 4 differs from Shamburger's (1967) use of the term Santa Rosa in the same area (although Lehman states otherwise). His indication (figure 4) that the Trujillo Member rests directly on the Permian east of Post also is a new relationship inconsistent with all previous work. Finally, for reasons stated above and well understood by Adams (1929) and subsequent workers, Lehman's figure 4 mapping of the Tecovas and Trujillo Members along the Colorado River is incorrect. There is no lithologically identifiable Trujillo in this area, and available biostratigraphic data indicate that the section is not any younger than the lower strata of the type Tecovas.

Lehman's mapping is clearly wrong in several ways (his figure 3 is an exception), the geological cross section in his figure 1 is partly incorrect, and his text contains no descriptions of rock units or measured sections. The only article he has published previously on Dockum stratigraphy contains a single measured section (Lehman et al., 1992). Clearly, Lehman believes that major revisions in stratigraphic nomenclature do not merit careful analysis and presentation of a stratigraphic database. We have taken a different approach to revising the Chinle Group stratigraphic nomenclature, developing an extensive database, much of which has been published.

Regard for previous and other workers—Lehman (this volume) states that our work on the Triassic stratigraphy on the southern High Plains reflects "a lack of regard or respect for earlier generations of geologists, and for the traditional courtesy accorded to other workers." However, as the above summary and our earlier articles indicate, we have gone to great lengths to understand the work of earlier generations of geologists. We have communicated our data and conclusions to a variety of colleagues at GSA, AAPG, SVP, and NMGS meetings in Midland, Fort Worth, Albuquerque, Socorro, Flagstaff, Salt Lake City, Denver and other venues. It would appear that the real "lack of regard or respect" or "lack of traditional cour-

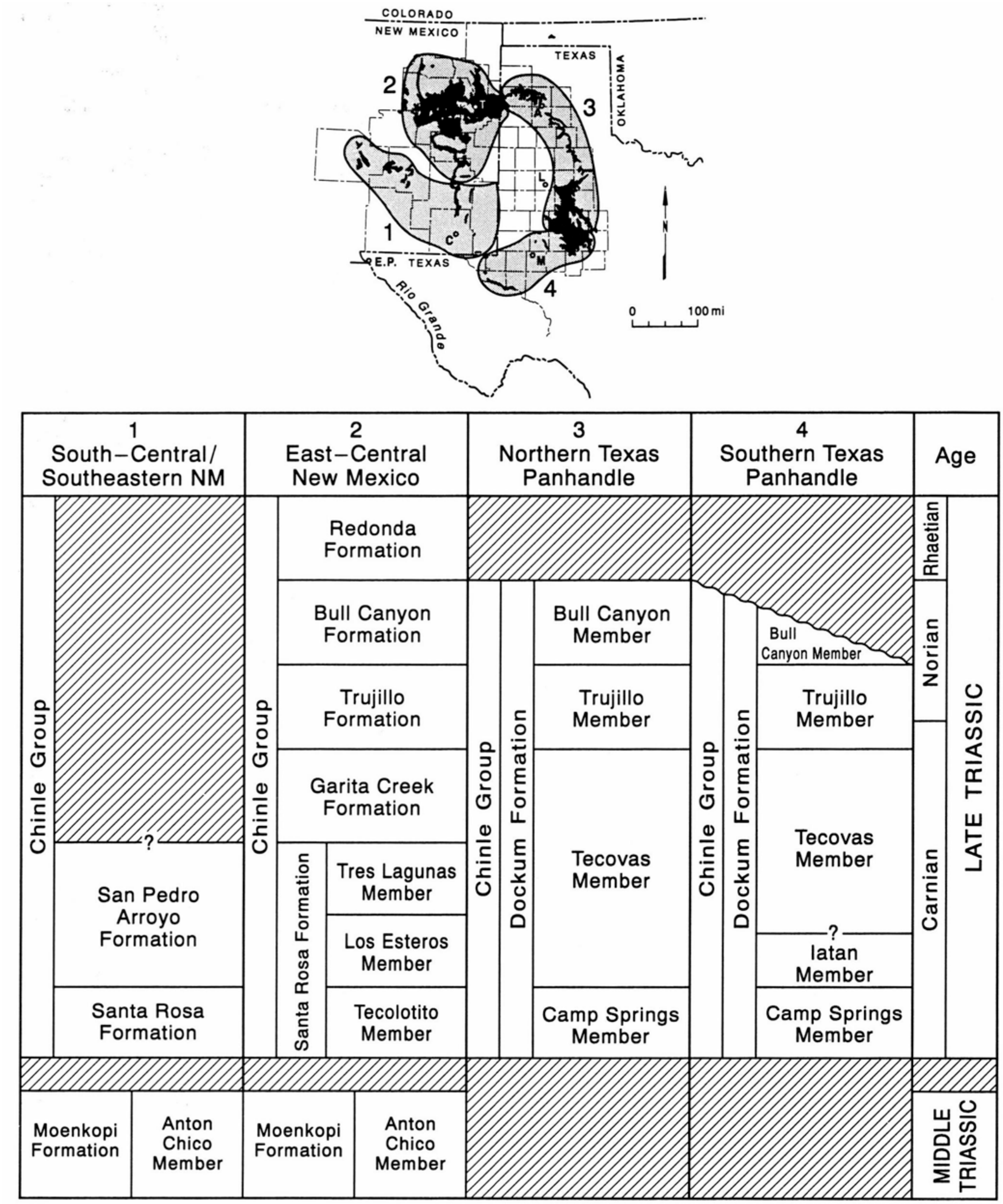


FIGURE 11—Correlation of Triassic stratigraphic units in eastern New Mexico and west Texas.

tesy" in High Plains Triassic stratigraphy is embodied in the vitriolic tone and ad hominem commentary that characterizes Lehman's article.

Conclusion

Since 1983, we have undertaken extensive stratigraphic studies of the Upper Triassic strata in eastern New Mexico and west Texas. One result of these studies has been new nomenclature, modifications of existing nomenclature and maintenance of some old nomenclature for these rocks. All of these changes have followed the rules set forth in the NASC (North American stratigraphic code) and are in accord with well-accepted stratigraphic practice. The result has been a precise lithostratigraphic nomenclature that well reflects the lithologic content and variation of Triassic strata in eastern New Mexico and west Texas (Fig. 11). More precise correlations and a much more detailed understanding of Triassic depositional history have been other products of our research. Most important though is the fact that our nomenclatural, biochronological and sedimentological conclusions have been based on an extensive database, much of it presented by us in a series of articles. These data have been gathered and marshalled by us to arrive at the first comprehensive synthesis of Triassic stratigraphy, biostratigraphy and sedimentation in eastern New Mexico-west Texas. This synthesis has incorporated previous work dating back to the 1850s, requiring painstaking and careful evaluation of that work so as to eliminate earlier errors and include the accurate observations and ideas of earlier workers.

Our work presents a striking contrast to that of Lehman (this volume). His conclusions are supported by no database (at least none is presented) other than two geologic maps, one of which is demonstrably incorrect. Instead of a careful reconsideration of previous work, Lehman's historical review is largely a misrepresentation intended to mislead the reader into supporting his conclusions. Lehman's text makes it clear that he does not understand accepted stratigraphic practice nor can he correctly apply the NASC to the naming and revising of names of stratigraphic units. Instead, Lehman applies a double standard to stratigraphic names, using the NASC *as he understands it* to support rejection of some "incorrectly proposed" names but not of other names incorrectly proposed. Finally, the tone and wording of Lehman's text is one of sarcasm and invective, which is uncalled for and has nothing to do with furthering the science of stratigraphy.

Lehman, early in his article, claims that the revisions of Triassic nomenclature we have proposed "1) are unnecessary and confusing, 2) violate the letter and spirit of the code of stratigraphic nomenclature by ignoring priority of established names, 3) are not supported by mapping, and 4) should be rejected by stratigraphers involved with mapping of Triassic strata in Texas and New Mexico." In fact, it is the changes in Triassic nomenclature that Lehman proposes that are unnecessary and confusing , contrary to the NASC and accepted stratigraphic practice, not supported by mapping and should be rejected.

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Abstracts of Talks

ADAMS, DONALD C., and KELLER, G. R., Department of Geological Sciences, The University of Texas at El Paso, El Paso, TX

Middle Proterozoic Tectonic Activity in West Texas and Eastern New Mexico from Analysis of Gravity and Magnetic Anomalies

The Precambrian history of west Texas and eastern New Mexico is complex, consisting of four events, namely Early Proterozoic orogenic activity (1630-1800 Ma), formation of the western granite—rhyolite province (WGRP) (1340-1410 Ma), Grenville age tectonics (1116-1232 Ma), and Middle Proterozoic extension possibly related to Midcontinent rifting (1086-1109 Ma). Pre-Grenville tectonics, Grenville tectonics, and Midcontinent rifting are represented in this area by the Abilene gravity minimum (AGM) and bimodal igneous rocks which are probably younger. We have used gravity modeling and the comparison of gravity and magnetic anomalies with rock types reported from wells penetrating Precambrian basement to study the AGM and Middle Proterozoic extension in this area.

The AGM is an ENE trending, 600 km long, gravity low, which extends from the Texas—Oklahoma border through the central basin platform (CBP) to the Delaware basin. This feature appears to predate formation of the mafic body in the CBP (1163 Ma) and is most likely related to Pre-Grenville tectonics, possibly representing a continental margin arc batholith.

Evidence of Middle Proterozoic extension is found in the form of igneous bodies in the CBP, the Van Horn uplift, the Franklin Mountains, and the Sacramento Mountains. Analysis of gravity and magnetic anomalies shows that paired gravity and magnetic highs are related to mafic intrusions in the upper crust. Mapping of Middle Proterozoic igneous rocks and the paired anomalies outline a 530 km diameter area of distributed E—W oriented extension. The Debaca—Swisher terrain of shallow marine and clastic sedimentary rocks is age correlative with Middle Proterozoic extension. These rocks may represent the lithology of possible Proterozoic exploration targets. Proterozoic structures were reactivated during the Paleozoic affecting both the structure and deposition in the Permian basin.

BORREGO, P. M., MORENO, F., KELLER, G. R., MARSAGLIA, K. M., and PINGITORE, N. E., Department of Geological Sciences, The University of Texas at El Paso, El Paso, TX

Investigations of a Deep Drill Hole in the Ouachita Trend, West Texas

The Exxon #1 Gatlin well was recently drilled to a depth of over 25,000 ft in Terrell County, Texas, just north of the international boundary with Mexico. It is the deepest penetration of the interior zone of the Ouachita system to date. This well is near the apex of the interior zone gravity high which elsewhere has been shown to approximately mark the Paleozoic continental margin. Gravity models constructed in this region, including one which was tied to this well, confirm that this well is in fact proximal to the Paleozoic margin.

The well was spudded in Lower Cretaceous rocks and drilled through a 23,000 ft section of low-grade metamorphic rocks. Cuttings of this metamorphic section are composed predominantly of phyllite, fine-grained schist, metaquartzite, and impure marble. Based on their mineralogy and texture, the likely precursor for these rocks was a sedimentary sequence of marls and mudstones. However, no relict sedimentary structures or fauna were observed. Phyllite and schist fragments are graphitic and locally crenulated, and large fragments exhibit multiple phases of deformation. Minor coarse carbonate and quartz may represent vein fills. Downhole textural trends include a gradual change from phyllite to schist at approximately 7500 ft, and a gradual increase in schist fragments to 19,600 ft. X-ray diffraction of bulk samples indicates a downhole decrease in total carbonate content. This metamorphic sequence appears similar to Ouachita interior zone rocks encountered in wells in central Texas and in outcrops in Oklahoma and Arkansas. However, the large thickness encountered in the well, and the even larger thickness suggested by the gravity modeling, is indicative of proximity to the continental margin and is likely the result of thrust faulting.

BOWSHER, A. L., Independent Geologist, Roswell, NM

A Look at Carbonate Rocks

Important ore deposits are found in carbonate rocks and large volumes of oil and gas are produced from carbonate rocks on a worldwide basis. Reservoir types and productive capability are most often related to rock type and the facies to which the rock belongs. Broad new understanding of carbonate rocks came with the publication in 1962 of *Classification of Carbonate Rocks* by the American Association of Petroleum Geologists.

The principal parameters of carbonate rocks are: (a) chemical composition, (b) grade size, (c) sorting and packing, (d) identification of grains in the rock, (e) cement, (f) color, (g) alteration or recrystallization, and (h) porosity. Original porosity in carbonate rocks relates to kind and packing of original particles. Secondary porosity is reduced by infilling that usually relates to some particles, or is enhanced because some types of grains are dissolved. Carbonate sediments are organic detritus. The range of solubility of organic detritus is very large. Fossils present in the carbonates are clues to the source of the detritus in the rock. Additional research is needed in faunal relations of facies and of rock types.

Ore recovery, well completion and FOR are more successful when parameters of the carbonate rocks are extensively studied. A simplified approach to carbonate description is discussed.

BRANDVOLD, LYNN A., New Mexico Bureau of Mines & Mineral Resources, Socorro, NM

Cimarron Mill, Carrizozo, New Mexico: A Typical Superfund Site?

The Cimarron Mill in Carrizozo, New Mexico, was operated by Southwest Minerals Company under the name of Cimarron Mining Company (CMC) as a cyanide mill for gold recovery from 1979 until 1982. In 1980, the

New Mexico Environmental Improvement Division (NMEID) received a report of improper use and dumping of cyanide at the site. A certified notice of violations was sent to CMC in 1982 by NMEID for discharging into a non-permitted discharge pit. CMC filed for bankruptcy in 1983 and so no action was taken on violations. A Site Inspection Follow-Up Report was done by NMEID in 1984, and in 1988 the mill site was listed as a Superfund site by the United States Environmental Agency (USEPA). A feasibility study to determine the method of remediation was completed by EPA contractors in June 1990 and a remediation method was chosen in September 1990. Clean-up was expected to begin in spring of 1991 and to be completed in 1992. However, clean-up did not begin until spring of 1992, is not yet complete, and probably never will be.

BROADHEAD, RONALD F., New Mexico Bureau of Mines & Mineral Resources, Socorro, NM

Petroleum Geology of the Estancia Basin, New Mexico— An Exploration Frontier

The Estancia basin of central New Mexico is an asymmetric, north-south trending structural depression that originated during the Pennsylvanian. The present-day basin covers 1600 me. It is bounded on the east by the late Paleozoic Pedernal uplift, on the west by the Tertiary-age Manzano and Los Pinos Mountains, on the north by the Espanola basin, and on the south by Chupadera Mesa. Depth to Precambrian ranges from 9000 ft in the eastern part of the basin to less than 1500 ft in the western part. Basin fill consists primarily of Pennsylvanian and Wolfcampian (Permian) clastics. The Pennsylvanian section contains significant shelf limestones in the western part of the basin.

Forty-three exploratory wells have been drilled in the basin; only 17 have been drilled to Precambrian. Numerous shows of oil and gas have been reported. From the 1930s until the 1960s, CO, was produced from Lower Pennsylvanian sandstones in two small fields on the western flank of the basin.

Dark-gray to black Pennsylvanian shales are probable source rocks. They are mature to marginally mature; TAI values range from less than 2.0 to 3.2. TOC is greater than 0.5% in many of these shales. Kerogen types are mixed amorphous, algal, herbaceous, and woody, indicating that gas, or both gas and oil, may have been generated.

Pennsylvanian sandstones are good reservoirs. They are fine- to coarse-grained subarkosic arenites and quartz arenites. Porosity ranges from 10 to 20% in the more porous, coarser-grained sandstones.

BUTLER, W. REX, Schlumberger, Midland, TX, and GERARD, MATTHEW G., and STEVENS, JIM, Phillips Petroleum, Odessa, TX

The Use of Monitor Logging to Evaluate CO_2 Foam Flooding in the East Vacuum Grayburg San Andres Unit

As CO, floods mature, the use of foam surfactants to improve sweep efficiency and inhibit cycling or channeling will increase. This paper proposes a method of monitoring saturation changes in various zones as CO, alternating surfactant is injected.

The East Vacuum Grayburg San Andres Unit (EVGSAU) has been under water alternating gas (WAG) since 1985. The EVGSAU CO, Foam Mobility Control Project was started as a cooperative effort of the working interest owners, the Department of Energy and the Petroleum Recovery Research Center of the New Mexico Institute of Mining & Technology to evaluate the effectiveness of surfactant.

Using log data obtained from an observation well, models were developed to analyze subsequent monitor runs. The results of this analysis were then used to determine if the surfactant was changing either the path of flooding, or the response times of different layers in the well. The methodology and results of the logging program will be presented, as well as other supporting data from the pattern.

CALHOUN, GERALD G., Independent, Midland, TX

Oil to Soil Fluorescence—A Vital Link

The aromatic component in oils may prove to be the key to defining oil traps in mature basins as well as pioneer areas. This is a direct indication of vertical oil migration and can precisely duplicate the oil signature in soil samples.

This study traces the changes that occur in San Andres oils over the Permian basin. The sequence of sync-scans along the Central Basin Platform pictures the gradual changes in the mix of lighter aromatics in the north toward predominately heavier aromatics in the south. This change parallels decreasing depth, freshening of formation waters and decreased gravity of the oil.

A comparison of oils and their source rocks is presented for the Woodford, Pennsylvanian and Wolfcamp generation-migration systems. The sieving effect of the source-shales is evident in the higher concentrations of complex molecules retained in the source rock as compared to the resultant oils trapped in conventional reservoir rocks. Movable oil retained in the source rock is also evident using synchronous scans. Productive areas are reflected at the surface with oil to soil correlation coefficients up to 90%. Barren areas are often evident in soil samples by their close resemblance to the source-rock signature. The contrast between productive and barren areas is also evident in a 100+% increase in the concentration of the various families of compounds—benzenes, naphthalenes, phenanthrenes-anthracene and compounds containing five or more aromatic rings.

Any surface geochemical evaluation should include no less than three techniques and one of these should be soil fluorescence. No other geochem technique can identify the source of microseeping oil. So only fluorescence can say not only "yes" or "no" but also name the objective horizon.

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Relationship of Laramide and Basin and Range Structures in the Pedregosa Basin, Southwestern New Mexico

The Pedregosa basin of southwestern New Mexico has long been recognized as a frontier hydrocarbon exploration target. The Paleozoic sedimentary rocks contain petroleum source and reservoir units that correlate with important producing zones in the Permian basin of west Texas and southeastern New Mexico. Factors that are commonly considered to limit the petroleum potential of the region include multiple episodes of deformation, heating due to local igneous intrusion and volcanism, and fresh-water flushing. Laramide (Late Cretaceous-Early Tertiary) fold and thrust traps are structural targets. Subsequent fracturing by Basin and Range (Late Tertiary) normal faulting may have partially destroyed the Laramide traps.

Seismic reflection and gravity data from the Playas and Hachita Valleys in southwestern New Mexico constrain the structural styles of Laramide shortening and later Basin and Range extensional deformation. These data show that Precambrian basement was involved in Laramide thrusting. This observation refutes the interpretation of some previous workers who have interpreted the Precambrian basement surface as a regional décollement for Laramide thrusting.

An east-west seismic profile that crosses the southeast end of the Little Hatchet Mountains images a range-bounding listric normal fault and associated antithetic faults beneath the Hatchita Valley fill. Near the range, "antithetic" faults show a normal sense of motion, but farther east faults are reverse. The latter may be high-angle Laramide structures or unusual features of Basin and Range deformation. The major range-bounding fault is steeply dipping near the surface, but becomes a low-angle listric fault at a depth of about 10 km.

COLLINS, E. W., and RANEY, J. A., Bureau of Economic Geology, The University of Texas at Austin, Austin, TX

Impact of Late Cenozoic Extension on Laramide Overthrust Belt and Diablo Platform Margins, Northwestern Trans-Pecos Texas

Late Cenozoic basins and normal faults were superimposed upon pre-existing Tertiary, Mesozoic, and older structures of northwestern Trans-Pecos Texas. We analyzed the structural and stratigraphic framework of the region using borehole, seismic, outcrop, and aerial-photograph interpretations; regional cross-sections were prepared to record Mesozoic and Cenozoic structural attributes. Laramide thrusting displaced Cretaceous rocks northeastward and produced northwest-trending thrust faults and related normal faults, folds, and monodines. Cenozoic extension that began 24 to 30 mya caused normal faulting that produced northwest- and north-northwest-trending, 3 to 30 mile wide fault-bounded basins and adjacent mountain ranges. Tectonism continues to the present. The pre-late Cenozoic structural grain has at least partly controlled geometries of the late Cenozoic basins and associated faults.

The deepest Cenozoic basin of this area, the 105 mile long Hueco Bolson, developed along the leading edge of the Laramide thrust belt and the southwest margin of the Diablo Plateau, and has as much as 9800 ft of Cenozoic basin fill. The most active Quaternary faults vertically displace middle Pleistocene deposits by about 33 to 105 ft. The 56 mile long Red Light Bolson, containing more than 2000 ft of Cenozoic deposits, also formed near the leading edge of the older thrust belt. A northwest-striking Quaternary fault zone bounds this basin on its east margin. A fault in southeast Red Light Bolson vertically displaces middle Pleistocene deposits by about 30 ft.

Two series of Cenozoic basins also have formed northeast of the overthrust belt. The 50 mile long Eagle Flat-Green River basin system consists of three basins that contain 900 to more than 2000 ft of basin fill. Late Tertiary-Quaternary tectonism has not been as active there as in the other large basins. The 124 mile long Salt Basin graben system comprises five basins and marks the east edge of Quaternary faulting in this region. Cenozoic fill is more than 2000 ft thick, and the most active Quaternary faults vertically displace middle Pleistocene deposits by at least 13 to 36 ft.

GOODBAR, JAMES, R., Bureau of Land Management, Carlsbad Resource Area, Carlsbad, NM

Oil and Gas Drilling and Operations in Cave and Karst Areas: Background and Development of a BLM Approach

Karst lands pose a unique set of problems for the oil and gas industry, as well as for the cave and karst environments. Since 1987, the Bureau of Land Management (BLM) has been working with the oil and gas industry to develop acceptable practices for drilling and operation in karst lands. The mutual goal of industry and of the BLM is to minimize the potential of encountering those problems and reduce the extent of the problems, if they are encountered. The BLM's approach is described in their *Draft Guide for Oil and Gas Drilling and Operations in Cave and Karst Areas.* This paper discusses the background and development of this guide with an emphasis on the conflict resolution approach of the BLM.

HANSON, BERNOLD M., Independent Geologist, Midland, TX

A Great Opportunity for Geoscientists

If basic mineralogy had been used to define asbestos, billions of dollars could have been saved on the cleanup because 95% of the asbestos is harmless to mankind. Only 5% causes pulmonary problems.

Scientific research has revealed that the ozone "layer" is a naturally occurring event. The chlorine released from chlorofluorocarbons (CFC's) is insignificant when compared to oceans and volcanoes.

Carbon dioxide has been named as the major cause of global warming. Scientific data show that all of the air pollution materials produced by man since the beginning of the Industrial Revolution do not begin to equal the quantities of materials spewed into the atmosphere by just three volcanoes, Krakatoa in 1883, Mt. Katmai in 1912, and Hekla in 1947. Carbon dioxide is essential for plant growth.

It cost 600 million dollars for the 10-year study by the National Acid Precipitation Assessment Program. The study concluded: "There is no evidence of widespread forest damage from current levels of acidic rains in the U.S." The acidity of the soil, not precipitation, determines the acidity in watershed.

We cannot reach zero pollution. A baseline must be established by calculating the amount from naturally occurring pollution and adding what mankind is contributing so reasonable scientific limits can be achieved for mankind's survival. We must also have economic impact statements along with environmental impact statements. This rational approach is the only realistic way to address the problem.

The notion of climate disasters has been widely propagated by those who want to impose controls—"to be effective these wildly expensive constraints must apply globally, condemning most of the world's population to a life of continued poverty."

Let us study scientific data and move prudently so we do not destroy the industries on which we so much depend. Nature is tough, humans are ingenious, and both are resilient.

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The Role of Diagenetic Studies in Flow-Unit Modeling: San Andres Formation, Yoakum County, Texas

The Permian San Andres Formation represents one of the most prolific hydrocarbon-producing intervals of the Permian basin. Dolostone lithofacies intercalated with thin evaporites accommodate highly compartmentalized reservoirs resulting from complex depositional and diagenetic histories. This compartmentalization often facilitates the use of these reservoirs in flow-unit studies. Perhaps more important than the relationship of productive intervals to depositional facies is the degree to which diagenetic processes have influenced reservoir properties.

Detailed petrographic evaluation of the reservoir in question, though often overlooked, should be an integral part of flow unit studies. Once a diagenetic sequence is established, the information may be incorporated into the facies model in order to better understand how to subdivide the reservoir. Such an investigation has been conducted on the San Andres Formation in Reeves Field of southeastern Yoakum County, Texas. Here, multistage diagenetic overprints are superimposed on depositional facies that vary in degree of lateral extent, thereby complicating the geometries of individual productive zones within the reservoir.

Analysis of the reservoir reveals that Reeves San Andres sediments were subjected to dominant diagenetic processes including dolomitization and sulfate implacement, both of which are major factors in porosity preservation, and a variety of minor processes that have had little effect on reservoir quality. The recognition of diagenetic facies, an understanding of the processes that have created them, and identification of the implications of these processes on reservoir properties are vital parts of any flow-unit study.

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Effects of Depositional Facies and Diagenesis on Calculating Petrophysical Properties from Wireline Logs in Permian Carbonate Reservoirs of West Texas

The complex interplay between depositional facies and diagenesis in carbonate rocks presents numerous problems for calculating petrophysical properties from wire-line logs. If carbonate reservoirs are divided into flow units of similar depositional and diagenetic textures, empirical equations that apply specifically to that geologically identified flow unit can be developed to accurately measure porosity and water saturation.

In Guadalupian and Leonardian reservoirs, carbonate mudstones deposited in subtidal marine settings are predominantly dolomite, although they commonly contain some shale. The presence of shale in these rocks can be detected with gamma-ray logs, and empirical equations for calculation of porosity from logs must include a gamma-ray component to compensate for the presence of shale. Because porosity in these rocks is dominantly intercrystalline, capillary-pressure characteristics are predictable and saturations can be calculated with the Archie equation.

Subtidal carbonate packstones and grainstones are composed of dolomite, anhydrite, and gypsum. The matrix acoustic transit times of these three minerals are similar, and acoustic logs are the best tool for measuring porosity. Neutron logs are the least accurate porosity tools if gypsum is present. Photo-electric density logs can distinguish gypsum from anhydrite. Because porosity in these rocks is dominantly interparticle and/or moldic, dual porosity cementation exponent corrections are needed to calculate saturations with the Archie equation, and capillary-pressure saturation relationships are variable.

Carbonates deposited in tidal-flat environments are generally composed of dolomite, sulfate minerals, and quartz silt. This more complex mineralogy requires a full suite of open-hole logs to make reliable porosity measurements. Porosity is commonly vuggy, and vugs are poorly connected. Thus the Archie equation may not accurately calculate saturations, and capillary-pressure characteristics are unpredictable.

Diagenesis influences reservoir mineralogy and pore types. A common style of burial diagenesis in Guadalupian and Leonardian reservoirs is hydration of anhydrite to gypsum and leaching of sulfate cement and dolomite matrix. This results in a significant amount of moldic (vuggy) porosity, although commonly these moldic pores are sufficiently well connected that saturations can be reliably calculated with the Archie equation and capillary-pressure characteristics are predictable.

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Late Triassic Tetrapod Biostratigraphy and Biochronology in West Texas and Eastern New Mexico

Upper Triassic strata in west Texas and eastern New Mexico belong to the Chinle Group of late CarnianRhaetian age. In west Texas, four members of the Dockum Formation of the Chinle Group contain biochronologically significant tetrapod assemblages (oldest to youngest): (1) Camp Springs Member assemblage with the primitive metoposaurid amphibian *Metoposaurus* and the most primitive phytosaur *Paleorhinus,* both index fossils of the late Carnian (Tuvalian); (2) Iatan Member assemblage from Howard County characterized by *Paleorhinus, Angistorhinus, Buettneria, Longosuchus, Trilophosaurus,* and the rare rhynchosaur *Otischalkia;* (3) Tecovas Member assemblage characterized by *Rutiodon, Buettneria, Desmatosuchus,* **and** *Stagonolepis;* (4) lowermost Bull Canyon Member assemblage characterized by *Pseudopalatus, Apachesaurus* and *Typothorax.* With reference to the land-vertebrate faunachrons established for Chinle Group tetrapods, the Camp Springs-Iatan assemblages are of Otischalkian age, the Tecovas assemblage is of Adamanian age, and the Bull Canyon assemblage is of Revueltian age.

In eastern New Mexico, the Los Esteros Member of the Santa Rosa Formation and the Garita Creek Formation contain Adamanian-age tetrapods, the Bull Canyon Formation contains Revueltian-age tetrapods, and the Redonda Formation contains Apachean-age tetrapods. Tetrapod biostratigraphy/biochronology thus supports lithostratigraphic correlation between west Texas and eastern New Mexico to indicate the following equivalences: Camp Springs-Iatan = basal Santa Rosa, Tecovas = Los Esteros-Garita Creek and Bull Canyon = Bull Canyon. Recent claims by T. Lehman that in west Texas Camp Springs = Trujillo and Iatan = Bull Canyon are refuted not only by careful lithostratigraphy but also by tetrapod biostratigraphy.

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Geophysical Studies at Proposed Low-Level Radioactive Waste Disposal Sites in West Texas

Although the disposal of high-level nuclear waste is officially a national problem, the federal government has charged each state with the responsibility of disposing of its own low-level nuclear waste. The State of Texas has considered many possible areas for its disposal facility, but has studied two sites in Hudspeth County extensively. Geophysical methods have been used to study the subsurface structure of these sites, evaluate the earthquake hazards, and set up monitoring of possible leakage from the sites. The structural studies employed the same techniques as used in petroleum exploration, but with a more balanced reliance between seismic and potential field methods. Since the scale of these investigations was relatively small (a few miles in extent), high-resolution methodology was employed. This aspect of the project mainly impacted the seismic-reflection work. The depth to bedrock was a major concern because the near-surface alluvium is generally a good natural barrier to any potential leakage. The location of any faults near the sites was also a major concern, because faults were both an indicator of potential earthquake hazards and a possible pathway for rapid movement of any material which might leak from the site. Analysis of the tectonic stability of the site involved regional geophysical data on a crustal scale and an evaluation of the historical earthquake record. A network of seismograph stations was established in the region in order to monitor contemporary seismicity. Compared to typical petroleum applications of geophysical data, these studies involved a wide variety of data and an analysis that required the methodical integration of these data.

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The Saga of the Dockum Group and the Case of the Texas/New Mexico Boundary Fault

The Upper Triassic Dockum Group consists of continental red beds exposed around the Southern High Plains of western Texas and eastern New Mexico. Although these strata are contiguous between the two states, different stratigraphic nomenclature is used in Texas and New Mexico. New mapping of the type area in Texas and physical tracing into New Mexico allows recognition of five units in the Dockum Group. A distinctive quartzose conglomeratic sandstone, the Santa Rosa Sandstone, is recognized as the base of the Dockum Group in New Mexico. The informal name "Camp Spring Conglomerate should not be used for this same unit in Texas. The Santa Rosa Sandstone is overlain by multicolored shale of the Tecovas Formation in Texas. The name "Garita Creek Formation" should not be used for these same strata in New Mexico. The Tecovas Formation is overlain by cliff-forming lithic sandstone of the Trujillo Sandstone. The same unit was later named the "Cuervo Sandstone" in New Mexico. Overlying the Trujillo Sandstone is a thick sequence of red shale called the Cooper Canyon Formation in Texas. These same strata were given the name "Bull Canyon Formation" in New Mexico. The Redonda Formation comprises the uppermost unit in the Dockum Group, and it is only present in New Mexico. Use of the name "Chinle Formation" or "Chinle Group" for part or all of these strata in eastern New Mexico is not appropriate, and ignores the fact that formal names had previously been given to these strata in Texas.

"Stratigraphy can be defined as the complete triumph of terminology over facts and common sense"—attributed to P. D. Krynine by J. Ferm (in Burton et al., 1987).

LE MONE, DAVID V., Department of Geological Sciences, The University of Texas at El Paso, El Paso, TX **The Role of Tubiphytes in Bioherms**

Tubiphytes was first described by Maslov in 1956. It is typically found associated with biohermal developments. Fagerstrom (1987) interprets the form as belonging to the binder guild. It is primarily restricted to shallow-water environments. It ranges in age from the Mississippian (Osagean) (Rigby, 1958) to the Middle Cretaceous (Albian) (Crescenti, 1969).

Tubiphytes, in association with calcareous inozoan and sphinctozoan sponges, becomes an important biohermal consortium in the Early Permian (Leonardian) to Late Permian (Ochoan). In the Leonardian (*Parafusulina* Zone) of the Finlay Mountains of west Texas, for example, binding and stabilizing tubiphytes coexists with baffling calcareous sponges and crinoidal thickets. This consortium displaces the older dominant phylloid algal mounds which enjoy their best development between the Middle Pennsylvanian (Desmoinesian) and the Lower Permian (Wolfcampian). The uppermost Dorashamian Permian reefs (Skiathos Series) on Skyros Island, Greece, and the Changhsiang Formation in Sichuan, China, are considered to be among the youngest Paleozoic occurrences of the consortium. No biohermal occurrences of any type are recorded in Lower Triassic sediments. Tubiphytes, scleractinid corals, and calcareous inozoan and sphinctozoan sponges are major contributors to Middle Triassic to Late Jurassic bioherms.

Tubiphytes, as an organism, has been assigned to such divergent taxa as the Porifera, Foraminifera, algal-foraminiferal consortium, Hydrozoa, Cyanobacteria, Microproblematicum, Rhodophycophyta, and Cyanobacterium-Chlorophycophyta consortium. Most workers today would align tubiphytes with either the sponges or the algae.

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Cretaceous Stratigraphy and Biostratigraphy, Sierra Blanca Basin, Southeastern New Mexico

The Sierra Blanca basin of Otero and Lincoln Counties, New Mexico, contains a Lower (upper Albian)—Upper (Santonian) Cretaceous section of marine and non-marine strata as much as 700 m thick. These strata represent the upper part of a regressive cycle followed by two transgressive—regressive cycles of deposition. The lower 55 m of Cretaceous section are the same tripartite Dakota Group units recognized to the north in Guadalupe and San Miguel Counties: basal Mesa Rica Sandstone (late Albian), medial Pajarito Formation (late Albian) and upper Romeroville Sandstone (earliest Cenomanian). The Mesa Rica and Pajarito represent a regression and are overlain disconformably by the transgressive Romeroville Sandstone. Overlying transgressive marine clastics and minor carbonates of the Mancos Shale are as much as 73 m thick and include the early Turonian Greenhorn Limestone. The overlying Tres Hermanos Formation (up to 91 m thick) consists of the (ascending) Atarque Sandstone and the Carthage and Fite Ranch Sandstone Members. These strata represent a mid-Turonian regression in response to regional tectonism (Atarque Sandstone and Carthage Members), followed by a transgression (Fite Ranch Sandstone Member) that culminated in the deposition of the D-Cross Tongue of the Mancos Shale and Fort Hays Member of the Niobrara Formation (combined maximum thickness = 152 m) during the late Turonian. The subsequent regression began with the Coniacian Gallup Sandstone (55 m) followed by coal-bearing Crevasse Canyon Formation (up to 244 m thick). The Coniacian—Santonian Crevasse Canyon Formation is the youngest Cretaceous unit in the basin; it is disconformably overlain by middle Eocene conglomerates and red-bed siliciclastics of the Cub Mountain Formation.

Dakota Group age determinations in the Sierra Blanca basin are those of well-dated sections to the north, but ammonites and inoceramid bivalves from the Sierra Blanca basin provide precise age control for Cenomanian—Santonian marine and marginal—marine strata. Palynology and plant megafossils provide the age control of non-marine strata of Coniacian—Santonian age in the Sierra Blanca basin.

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Ochoan (Upper Permian) Stratigraphy and Age Determinations, Southeastern New Mexico and West Texas

Upper Permian strata, which are the stratotype of the Ochoan Stage (Series), have an extensive subsurface distribution and limited outcrop area in southeastern New Mexico and west Texas. The oldest strata are alternating laminae of anhydrite and calcite of the Castile Formation and are as much as 600 m thick. The closely related and overlying Salado Formation is as much as 600 m thick and is mostly halite and argillaceous halite with minor anhydrite. The overlying Rustler Formation is as much as 150 m thick and consists of anhydrite, red silty shale and magnesian limestone. Overlying red beds are the Quartermaster Formation (Dewey Lake Formation is a synonym, as is the term Pierce Canyon Red-beds), which is as much as 106 m thick and consists of fine sandstones, siltstones and minor gypsum.

The Castile rests disconformably on the Capitanian (Middle Permian) Lamar Limestone Member of the Bell Canyon Formation and its equivalent, the Tansill Formation of the Artesia Group. Counting of Castile—Salado laminae and their posited relationship to astronomical cycles suggest that Castile—Salado deposition took only 200-300,000 years. Limited assemblages of brachiopods and conodonts from the Rustler Formation indicate a Late Permian age, but are no more precise age indicators. A small assemblage of bivalves, K—Ar ages and magnetostratigraphy indicate a Late Permian age for the Quartermaster Formation. There is no evidence to support a Triassic age assignment for the Quartermaster; it is disconformably overlain by the Upper Triassic (Carnian) Chinle Group. Most workers use the Ochoan as a Late Permian Stage—Age, although its typical strata generally lack good age indicators and may represent relatively short and sporadic intervals of Late Permian time. We prefer recognition of the Ochoan as a lithostratigraphic unit (group) without regional or global geochronological significance.

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Triassic Stratigraphy and Correlation, East-Central New Mexico and West Texas

Nonmarine Upper Triassic strata exposed in east-central New Mexico (principally San Miguel, Guadalupe and Quay Counties) and west Texas (from Oldham to Mitchell Counties) are readily correlated using lithostratigraphy and biostratigraphy. In east-central New Mexico, Chinle Group strata rest disconformably on Middle Triassic red beds of the Moenkopi Formation (Anton Chico Member), which are mostly grayish-red litharenites and mudstones of fluvial origin. These Moenkopi strata can be correlated lithostratigraphically across northern New Mexico to the Holbrook Member of the Moenkopi Formation in northeastern Arizona, a correlation supported biostratigraphically. However, no Moenkopi strata or correlative rocks are present in west Texas.

The lowermost portion of the Chinle Group in east-central New Mexico is the Santa Rosa Formation consisting of three members (ascending): Tecolotito (mostly quartzarenite), Los Esteros (mostly variegated bentonitic mudstone) and Tres Lagunas (mostly quartzarenite). The overlying Garita Creek Formation is red-bed mudstones, sandstones and intraformational conglomerates. Fossil plants and vertebrates indicate a late Carnian age for the Santa Rosa and Garita Creek Formations. Lithostratigraphy and biostratigraphy indicate that their west Texas correlatives are the Camp Springs, Iatan and Tecovas Members of the Dockum Formation: Camp Springs = Tecolotito, Iatan = Los Esteros and Tecovas = Los Esteros, Tres Lagunas and at least part of Garita Creek. Facies differences reflected in lithology and thickness differences allow ready distinction of the New Mexico and Texas units, thus justifying their separate lithostratigraphic names.

The younger part of the Chinle Group in east-central New Mexico begins with the sandstones and intrabasinal conglomerates of the Trujillo Formation, which disconformably overlies older Chinle Group strata. It is readily traced into west Texas as the Trujillo Member of the Dockum Formation. Fossil plants and vertebrates indicate an early Norian age for the Trujillo in east-central New Mexico and west Texas. Suggestions that it is correlative to the late Carnian Santa Rosa Formation or Camp Springs Member are refuted by lithostratigraphic correlations. The lower-middle Norian Bull Canyon Formation of east-central New Mexico conformably overlies the Trujillo, and this thick red-bed sequence of mudstones and sandstones can be traced into west Texas as the Bull Canyon Member of the Dockum (Cooper Canyon Member is an unnecessary synonym). The youngest Chinle Group strata in east-central New Mexico are the cyclically bedded siltstones and sandstones of the Rhaetian Redonda Formation. They have no correlative in west Texas.

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Can Regional Porosity Occurrence in Carbonate Slope and Basin Facies Systems be Predicted?

Subsurface carbonate depositional sequences (i.e. coeval platform-to-basin facies mosaics), which can most readily be identified by application of seismic sequence analysis, include porous units of complex geometry and occurrence. A highly sought-after occurrence of reservoir-grade porosity commonly, but not always, is associated with sequence boundaries. Therefore porosity can be predicted to possibly occur in already-lithified platform strata beneath significant unconformities of regional extent (e.g. cavernous porosity). By this method, however, the possible existence of porosity in carbonate slope and basin deposits may be overlooked because they do not lie beneath sequence-bounding unconformities insofar as they are not usually exposed subaerially during platform emergence. Yet, such facies compose locally significant hydrocarbon reservoirs in the Permian basin by virtue of high porosities and permeabilities and water-free production histories. Short of drilling or seismic wavelet analysis, can porosity in such facies by predicted a priori?

Reservoirs in carbonate slope and basin deposits in the Midland basin include both porous limestones and dolomites. Petrographic and geochemical studies indicate that syndepositional and shallow-burial diagenesis of such deposits mainly involved porosity reduction via calcite cementation, dolomitization, and compaction. Most of the porosity present in reservoirs in these facies was created by later dissolution in the deep-burial environment as a consequence of rock interaction with connate fluids enriched in carbonic and sulfuric acid and/or organic acids generated during hydrocarbon maturation. These fluids migrated up and out from deeper parts of the basin, through slope and basin deposits and into platform carbonate strata. Insofar as fluid migration pathways can be mapped or at least inferred by various means, it follows that porosity created (or destroyed) by these fluids also can be mapped predictively.

OHLMACHER, GREGORY C., Department of Geological Sciences, The University of Texas at El Paso, El Paso, TX **Fracture Networks, Fracture Connectivity, and Environmental Implications**

Detailed outcrop-scale mapping has revealed fracture networks (set of fractures) which result from combinations of tectonic stresses, stress relief, and blasting. Because of the intersecting nature of the fractures associated with these sets, they form potential pathways for fluid migration, including ground water. Other factors, however, also affect the fractures' ability to transmit fluids. These include aperture, fillings, roughness, density, and connectivity. Analysis of fracture networks for environmental purposes is primarily done using statistical methods which provide most of the data required for fracture permeability models. However, missing from this data is the actual connectivity between the fractures. This can be obtained from detailed outcrop-scale structure sections. A fracture set is composed of a number of fracture segments that may or may not link up to form conduits. This segmentation may alter the ability of what would otherwise be a connected fracture network to convey fluids. Thus, this lack of connectivity would decrease the fracture permeability, which might reduce the water supply potential, but improve the potential for waste storage. The examination of the connectivity of vein and joint networks mapped in detail reveals some networks have at least two sets of well-connected intersecting fractures forming a two-dimensional network for fluid flow, while other networks have one well-connected set and a secondary set of poorly connected fractures. This latter case would have good permeability in one direction and poor in the other.

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Permian (Leonardian) Crinoidal/Tubiphytes Bioherms of the Wilkie Ranch Formation, Finlay Mountains, West Texas

Permian (Leonardian) sponge / tubiphytes, crinoidal/ tubiphytes, and multi-taxa bioherms occur in at least three major stratigraphic zones within the Wilkie Ranch Formation of the Finlay Mountains, Hudspeth County, Texas.

The lowest zone of outcropping bioherms occurs 400-430 m above the subsurface base (Stewart, 1980) and contains excellent examples of the crinoidal/tubiphytes type of biohermal development. Exposed bioherms are approximately 3 m in thickness and 13 m in width. Bioherms may be roughly divided into four horizontal zones, which are interpreted to be (from current orientation): (a) winnowed bioclastic debris pile, (b) crinoidal thicket (approximately 70% crinoids), (c) core-complex zone consisting of tubiphytes, laminated algae and crinoids (10%), and (d) muddier flank beds consisting of allochthonous and bioclastic debris. Vertically, three different stages of development are recognized within the bioherms. The colonization (pioneer) stage of development is dominated by a crinoidal thicket growing on a topographic high on the sea floor. Climax communities (intermediate) are represented by a group of abundant brachiopods, bryozoans, and solitary rugose corals. The stabilization (mature) stage is typified by tubiphytes, algal laminae and large, rare, sparse crinoids forming a bindstone.

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Discovery and Early Development History of Bravo Dome CO, Field

American Producing Corporation drilled a small surface structure with their No. 1 Bueyeros well (Section 32, T31N, R31E, Harding County, New Mexico) in 1916. The Tubb Sandstone (Permian, Leonardian) contained CO2, but the well was never completed.

Southern Dry Ice and Kummbach Oil and Gas tested another small structure nearby in 1931. This well, the No. 1 Kerun, discovered CO, in the Triassic Santa Rosa Sandstone and was completed as the initial CO, well in northeastern New Mexico.

Bueyeros Field supplied the CO, necessary for a dry ice business during the following several decades.

Although the above facts relate to discovery of the first CO, in northeastern New Mexico, the dry ice industry, and Bueyeros Field, this history played a minor role as regards Bravo Dome CO, Field.

The economic need for CO, in the petroleum industry realized initially in the late 1960s, and Amoco's reaction to their needs in this regard, led to the discovery and development of Bravo Dome CO, Field. Using original documentation, this report traces Amoco's discovery, acreage acquisition, unitization, and early development of Bravo Dome CO, Field.

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Stratigraphy of Midland Basin in Regional and Global Context

A new correlation of 85 well logs provides the data for a continuous set of structure and isopach maps covering one square degree of longitude and latitude from 101 to 102 West and 32 to 33 North. A corresponding set of maps showing paleogeography and tectonics relates each of the above maps to its surroundings in the SW/4 of North America. A further set of maps of the globe then relates the paleogeographic settings to global plate tectonics. The logs were chosen for an even distribution throughout the study area, and they illustrate the stratigraphic development of the Midland basin from the Early Ordovician up to the middle of the Leonardian Stage, i.e. up to the union of Gondwana.

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Fracture Identification and Evaluation Using Borehole Imaging and Full Wave Form Logs in the Permian Basin

The borehole imaging and acoustic full wave form logs provide an excellent means for identifying and evaluating naturally occurring fractures. The natural fractures can provide the porosity and permeability essential for a productive reservoir. The detection of these fractures may be accomplished by two types of wireline logging tools, borehole imaging devices and acoustic full wave form tools. The borehole imaging tools produce images based upon the electromagnetic or the acoustic properties of the borehole wall. Fractures will appear as darker images that are distinct from the non-fracture formation. These images are coupled with a reference azimuth which allows for the determination of the orientation of the fracture image. The acoustic full wave form logs are used to detect fractures by analyzing various acoustic properties of the formation. The travel time, amplitude and frequency responses of fractured formations differ remarkably from the responses of non-fractured formations, because of the reduction of the acoustic energy in the fractures. The various field examples from the Queen Sandstone to the Ellenburger Formation demonstrate the advantages and disadvantages unique to the borehole imaging and the acoustic full wave form devices. Within this geologic framework, comparisons are made among the data extracted from whole cores, borehole imaging devices and the acoustic full wave form tools in establishing a systematic approach for the identification and evaluation of fractures.

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Waulsortian-Type Buildups in the Lower Carboniferous of the Bechar Basin, Northwestern Sahara of Algeria, North Africa

The Carboniferous strata in the Bechar basin can be subdivided into three major groups. The lower group is composed of bioclastic and perireefal carbonates. The middle group is exemplified by carbonate platform deposits that were eroded during episodes of emergence by channels of continental-derived sediments. The upper group is represented by terrigenous deposits composed mainly of deltaic, fluvial, and lacustrine deposits, with the sporadic presence of coal seams.

The Carboniferous Waulsortian-type buildups within the Bechar basin occur in the lower group. They are exposed above the desert floor along a south to north-northwest-trending axis, with the younger buildups located to the south and the older ones to the north. These bioherms are apparently younger than those recognized in Europe and North America. These Algerian bioherms were initiated and persisted during the time interval represented by the conodont *Gnathodus bilineatus* zone (lower Visean-upper Visean boundary). Although they are younger than their European and North American counterparts that are of Tournaisian-lower Visean age, these mounds appear to have formed in similar environmental and tectono-sedimentary conditions. Their areal extent, geometry, and facies relationships suggest that they were limited to a shelf edge. Their environments of deposition range from shallow marine to deep sea.

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Late Paleozoic Tectonic Evolution of the Eastern Margin of the Diablo Platform, West Texas

The Diablo Platform is a long-lived positive tectonic feature that forms the western and southwestern margin of the Delaware basin of west Texas and New Mexico. The platform is known to have been episodically active from at least early Paleozoic time to the Recent. Although the western margin of the platform is well exposed in fault blocks formed during Tertiary Basin-and-Range-style deformation, the eastern margin is largely concealed beneath Cretaceous to Recent sediments and Tertiary volcanics. Well control along the eastern margin of the Diablo Platform is sparse, averaging less than one sub-Permian penetration per 128 km^2 (50 mi^2).

This study is part of a larger effort to utilize newly acquired seismic data, reprocessed older seismic data, and subsurface well control to formulate a structural interpretation of the Delaware basin and its margins. Early 1970s-age Delaware basin group-shoot seismic data were reprocessed to image parts of the eastern margin of the Diablo Platform. Data were reprocessed with a high-performance interactive computer workstation and commercially available software. Improved seismic imaging is obtained by detailed velocity analysis and residual statics.

Results show that part of the eastern margin of the Diablo Platform is bounded by west-dipping reverse faults having up to 1000 m (3300 ft) of vertical displacement. These features are Pennsylvanian and Early Permian in age and are analogous to compressional features on the eastern side of the Delaware Basin bordering the Central Basin Platform. High-angle normal (oblique?) faults having as much as 2000 m (6600 ft) of vertical displacement are, in part, younger than the reverse faults, cutting beds as young as Permian (Ochoan) in age (Rustler Formation). These features are interpreted to reflect Pennsylvanian-aged NE—SW-oriented compression followed by Middle to Late Permian differential subsidence of the Delaware basin relative to the Diablo Platform. Analogy with the basin-bounding margin adjacent to the Central Basin Platform suggests that undiscovered compressional structures may exist along the eastern margin of the Diablo Platform.

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Depositional Regimes and Reservoir Characteristics of the Red Tank—East Livingston Ridge Delaware Field, Lea County, New Mexico

The Red Tank—East Livingston Ridge Delaware Field was discovered in January 1992, with the completion of the Strata Production Cercion Federal #1 for a daily pumping potential of 108 barrels of oil, 77,000 cubic feet of gas, and 84 barrels of water. Oil production in the field is from the lower Guadalupian (Permian) Brushy Canyon Formation. Cumulative production from 21 wells through March 1993 is over 500,000 barrels of oil, 365,000,000 cubic feet of gas, and 740,000 barrels of water.

The Brushy Canyon Formation in the Red Tank—East Livingston Ridge Field consists of clean (no detrital shales) subarkosic sandstones and siltstones. The grains are subangular to angular and moderately sorted. The sandstones and siltstones have mean grain sizes (M_z) of 0.10 mm and 0.06 mm, respectively. Quartz overgrowths, carbonate cement, extensive dissolution of feldspars, and emplacement of authigenic clays have altered the original depositional fabric. Authigenic clays present are fibrous illite and expandable fixed layer smectite/illite.

The Brushy Canyon reservoirs of the Red Tank—East Livingston Ridge Field are combination stratigraphic-structural traps. A generalized sand-rich submarine fan/channel complex model is used to describe these reservoirs. The Brushy Canyon in the Red Tank—East Livingston Ridge Field is subdivided into an upper and basal package based upon the different depositional regime interpreted for each package as a result of their relative positions to the shelf edge. The sandstones of the upper Brushy Canyon package resulted in the massive channel, overbank, and levee facies generally associated with the inner and middle fan. The distal fringe sands of the basal Brushy Canyon package are characteristic of the outer fan and basin plain.

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The Effects of Residual Oil Saturations on the Interpretation of Water Productive Versus Oil Productive Delaware Sandstones

Delaware sandstones in west Texas and southeast New Mexico that have excellent hydrocarbon shows and calculated water saturations of 60% or less sometimes produce only water. The problem with these silt to very fine-grained reservoirs is whether or not the hydrocarbons are movable. Using net pay cut-offs of Vcl<15%, effective porosity>15% and Archie water saturation<60%, Bell Canyon and Brushy Canyon example zones contained 18 feet and 22 feet of net pay, respectively. However, when these two zones were tested, the Bell Canyon zone produced only water and the Brushy Canyon zone produced 125 BOPD and some water.

A series of cross plots that include: (1) shallow resistivity porosity versus deep resistivity porosity, (2) Archie water saturation versus Ratio water saturation, and (3) Rxo/Rmf versus Rt/Rw (Dew Plot) were used to differentiate movable and residual oil. On all three cross plots the Bell Canyon example exhibited almost no movable oil. In contrast, the Brushy Canyon example exhibited a higher proportion of movable oil. Thus, with the use of these cross plots, the oil-productive versus water-productive Delaware oil-bearing sandstones were differentiated by determining what proportion of the oil was movable.

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Variations in Cementation Exponent (m) and Fracture Porosity, Permian Delaware Mountain Group Sandstones, Reeves and Culberson Counties, Texas

In order to calculate accurate volumetric oil reserves in the Permian Delaware Mountain Group, reliable values for cementation exponent (m) are required in addition to the other reservoir parameters. The porosity in these siltstone and very fine-grained sandstone reservoirs is intergranular and therefore cementation exponent should be approximately 2.0. However, crossplots of core-derived porosity versus formation resistivity factor (Fr) indicate an average cementation exponent (m) of 1.80. The lower cementation exponent is a result of minor amounts of fracture porosity. Comparison of the Delaware Mountain Group porosity versus Fr crossplot with the laboratory data of Rasmus (1987) reveals a similar decrease in Fr with a decrease in porosity due to the presence of 1% fracture porosity.

The lower cementation exponent (1.80) results in the calculation of substantially lower water saturations which increases the amount of volumetric oil reserves. Analysis of three zones in the Bell Canyon and Cherry Canyon Formations of the Delaware Mountain Group using standard methods of calculating water saturation resulted in volumetric oil reserves (based on 40 acre drainage) of 1.37 to 1.42 million barrels. However, using a cementation exponent of 1.80 resulted in volumetric oil reserves of 1.55 million barrels. The 9 to 13% increase in volumetric oil reserves from only three zones in the Bell Canyon and Cherry Canyon Formations illustrates the critical importance of combining core analysis with log analysis when doing volumetric reserve calculations.

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Surface Reclamation of the Big Lake Oil Field, Reagan County, Texas

Since the discovery of Santa Rita #1 in 1923, millions of barrels of salt water have been produced along with 135 million barrels of oil from the Big Lake Oil Field in Reagan County, Texas. Until the early 1960s, the accepted disposal method for the produced water was surface discharge to a large evaporation pond north of the field. Produced water was allowed to flow from wells to the pond via natural topographic drainage. This practice resulted in 2000 acres of eroded, barren landscape characterized by highly saline soils incapable of supporting vegetation.

In 1989, the University of Texas System, the U.S. Soil Conservation Service, and Marathon Oil Company, which acquired Big Lake Field in 1962, initiated an experimental project to reclaim the affected land and restore rangeland productivity. An underground drainage system, consisting of 125,000 ft of buried drainage conduit and eight collection sumps, was installed over 205 acres of the affected area. Earthen terraces were constructed to capture and hold rain water to facilitate downward percolation and leaching of salts from the soil profile. Salts leached from the soil are captured by the drainage system and pumped to injection wells for disposal.

The excellent revegetation that has occurred over the test area after three years of operations is encouraging and has shown the need for expanding and enhancing the existing system with supplemental water from fresh water wells, application of soil amending agents, additional terracing, and selective planting with salt-tolerant species.

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Petrologic Constraints on the P-T Path of the Taihu Eclogites, Eastern Dabieshan, Central China

The eclogites are found as tectonic lenses in the Archean gneisses in Taihu area, eastern Dabieshan. The block under study shows the typical section with Dabieshan-episode eclogites in the inner zone and the retrograded amphibolites in the marginal zone. According to the petrographic microstructure, reaction relationship and chemistry of minerals and zoning, the evolution history is recognized as following stages: (1) loweclogite stage indicated by the assemblage of omphacite I (jadeite 27-35%)+garnet+phengite+quartz+ rutile, (2) High-eclogite stage: Kyanite I with quartz and omphacite II (jadeite 45-52%), as porphyroblasts overprint the low-eclogite assemblage and coexist with the omphacite II (the rim of the omphacite I), (3) amphibolite I stage indicated by fine-grained amphibole plus plagioclase symplectite of garnet and omphacite, (4) glaucophanekyanite stage where the glaucophane-barroisite+epidote+kyanite II porphyroblasts overlapping the previous aggregates, (5) amphibolite II stage recorded by the occurrence of barroisite-hornblede+phengite+plagioclase+magnetite+epidote, strongly mylonitized, and (6) regional metamorphic greenschist stage.

The P-T condition of the low eclogite is estimated to be 1.2-1.6 GPa (minimum pressure) and 600-720°C based on Fe-Mg exchange between garnet and omphacite (Krogh 1988) and jadeite contents of omphacite. The high-eclogite may indicate a prograde up to the P-T condition of 1.8-2.2 GPa and 750-850°C. The fine-grained amphibole-plagioclase symplectite may record an abrupt pressure and temperature drop retrogression when glaucophane-barroisite formed at the expense of omphacite or amphibole-plagioclase symplectite. The pressure is estimated about 1.0-1.2 GPa and temperature 550600°C. Followed that is amphibolite II with P-T condition of 0.4-0.6 GPa and <550°C. The P-T path inferred from the Taihu eclogites records in detail the unique evolution history of the continent-continent collision of the Yangtze and Sino-Korean plates.

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Paleomagnetic Characterization of the Proposed Texas Low-Level Radioactive Waste Repository, Sierra Blanca, West Texas

The results of paleomagnetic studies conducted on cores collected from a proposed site for the Texas low-level radioactive waste repository are presented. The proposed site is located six kilometers east of Sierra Blanca, west Texas, and occurs within the Eagle Flat basin. A total of 648 oriented samples from nine cores and a single trench were collected for magnetostratigraphic study. The study was highly successful, producing high-fidelity records which allow correlation between cores and a determination of the age of the basin.

The longest core, YM#17/53 (672 ft), penetrated Cretaceous bedrock and preserves a magnetostratigraphic record which indicates that sedimentation was initiated in the Eagle Flat basin by approximately 12.0 my ago. Cores YM#4 (249.5 ft) and YM#6 (250.5 ft), both also to Cretaceous bedrock, preserve records of the Brunhes, Matuyama, Gauss and Gilbert Chrons, indicating that sedimentation was initiated in these shallower parts of the basin by 5.0 my ago, and perhaps as early as 5.5 my ago. Thickness variations of characteristic magnetozones preserved within the nine cores suggest that basinal sedimentation rates have varied considerably, both within and between cores. The Brunhes Chron is represented by anomalously short magnetozones at the top of each core, suggesting radical changes in depositional regime over the last 780 ka.

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Were Big Lake and Yates Really Discovered in the Hills of West Virginia?

Some find it interesting and perhaps instructive to search for and discover links, connections, and ties within the history and heritage of their profession—at least I do. I believe a beneficial sense of perspective is gained. However, the history of petroleum geology and the search for oil and natural gas, like the science of geology itself, is often clouded, imperfectly known, and incompletely chronicled by even the most learned, dedicated and unbiased authorities—and I claim none of those qualifications! Having conceded that, the purpose of my talk today is to attempt to persuade you that the early exploration for oil in the Permian basin really began in the hills of West Virginia.

Most authorities, albeit different views do exist, cite the 1859 Drake well oil discovery near Titusville, PA, as the inception of the modern oil industry. Following that, exploration for oil, and later natural gas, spread to other areas. A detailed history of the science of petroleum geology, its early practitioners, and their utilization or lack thereof, in the early oil industry is beyond the scope of my talk. Although I will touch on that history, albeit incompletely, to make my point, namely and no doubt arguably, that Big Lake and Yates Fields were actually discovered in the Appalachian basin.

My line of reasoning is as follows. As a given, I accept Wallace Pratt's often quoted dictum, "Oil is found in the minds of men" (to which I would add "and women"). A mind is trained in large part through formal education and practical experience. Now, some in this audience are aware that Ray V. Hennen played a major role in the discovery of Big Lake and Yates Fields. That story is well told in the superb oil and gas museum of Midland. However, probably fewer are aware that Hennen was a native West Virginian, a graduate of West Virginia University, and began his career in geology with the West Virginia Geological and Economic Survey under the tutelage of his uncle, the venerable I. C. White, then State Geologist of West Virginia. Though formally educated as a civil engineer, during his tenure at the Survey (1902-18) he became a very proficient field geologist, field mapper, stratigrapher, and structural geologist. He mastered both the theory and practice of those disciplines and their practical application vis-a-vis the "Anticlinal Theory" in the search for oil and gas. He brought that knowledge and those skills to his subsequent association as chief geologist with Transcontinental Oil Company (1919-29). Under his direction, Transcontinental field parties using plane tables delineated the surface structure that led to the discovery of Big Lake and Yates Fields. (As an aside, it should also be noted that Transcontinental was largely controlled by the Benedum-Trees interests—yet another West Virginia connection!)

Now the story is complete from Hennen's West Virginia roots to the discovery of Big Lake and Yates, and I rest my case. As they say in mathematics, Q.E.D., "Big Lake and Yates were really discovered in the hills of West Virginia!"

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East Shugart Delaware Field: Geology and Development

The East Shugart Delaware Field in Eddy and Lea Counties, New Mexico, produces oil from over 300 ft of upper Brushy Canyon (Delaware Formation, Permian, Guadalupian) sandstones. Sands deposited in a shelf-to-basin transition environment form multiple, stacked reservoirs with at least 14 separate oil-water contacts across the field. Each reservoir is relatively continuous over the structure, with slight variations in porosity and permeability.

Discovered in 1985, oil production peaked in late 1987 at 32,000 barrels per month from 19 wells. Currently the field is producing 12,500 barrels per month. Ultimate primary reserves are projected to exceed 5 million barrels of oil and 10 billion cubic feet of gas. A secondary-recovery feasibility study concluded an additional 5 million barrels of oil could be recovered. However, a lack of analogous fields for comparison study makes the secondary-reserve projection less certain. Pilot projects are in progress in two similar fields, Parkway and Avalon, which will provide additional information on secondary-reserve projections.

Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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