1978 Int'l. Symp ... Oct ... 1978
Grande Rift
Santa Fe, N. Mex
Los Alamos Sci. Lab.

(ESL)

AREA
TX
RGRift
Magma

A magmatic evolution is observed following this tectonic evolutive process: magmas have a typical alkalic nature in the East African continental rift and become progressively less alkalic approaching Afar where transitional basalts dominate. A further evolution from transitional basalts, or tholeiites with moderate to low K content, toward abyssal MOR type tholeiites is observed passing from the protooceanic structure of Afar to the typically oceanic rift branch of Gulf of Aden. These compositional differences are often emphasized by the occurrence of volcanic rock sequences produced by fractional crystallization of basaltic magmas, that are characteristically erupted at central volcanoes located at the crossing of different tectonic trends and/or on low spreading rate zones.

A tectonic control on the origin of magmas is also suggested by the compositional differences shown by basalts erupted along leaky fractures transverse to the main tectonic trend of Afar. These transversal basalts have in fact a marked alkalic nature, contrasting with the tholeiitic affinity of coheval basalts erupted from the axial structure of Afar rift.

Available data therefore suggest that a relation exists between the magma composition and the degree of advancement of the rifting process through progressive lithosphere attenuation up to continental break-up. The magmagenetic process is however not simple and probably implies a vertically zoned mantle source, as suggested by Sr isotopic evidence.

CENOZOIC MAGMATISM IN THE TRANS-PECOS PROVINCE: RELATION TO THE RIO GRANDE RIFT

BARKER, Daniel S., Dept. of Geological Sciences, The University of Texas at Austin, Austin, Texas 78712

In style and chronology of faulting, the Trans-Pecos magmatic province of Texas closely resembles the Rio Grande Rift and merges with it, but the two provinces are strongly dissimilar in the compo sition and timing of magmatism.

Trans-Pecos Cenozoic igneous rocks form two coeval series; silic undersaturated hawaiite, mugearite, trachyte and phonolite, a quartz-normative trachybasalt, trachyandesite, quartz trachyte, rhy lite and comendite, all with hypabyssal equivalents. True alkali basa are exceedingly rare, and qrtz-normative basalts and calcalka andesites are absent. Lava fws and pyroclastic rocks were deri from shield volcanoes surmoted by small calderas (generally than 10 km in diameter). Sr, nine calderas have been identif and at least as many probal remain unrecognized. In those a where most volcanic rocks ve been eroded, clusters of sha intrusive bodies, dominantly one rock type, define roughly circ domains averaging 50 km iameter, suggesting subjacent plu similar to those in the Oslo oen.

Igneous rock compositiorade westward from peralkaline ph lite and comendite to less aic quartz trachyte and rhyolite cl to the Rio Grande (the arbitrary western limit of the Trans-Pecos province). The gradation apparently continues farther westward to the calcalkalic suite of the Sierra Madre Occidental. In the Trans-Pecos, the largest caldera complexes (and the only ones showing resurgence and repeated collapse) are the less alkalic ones nearest the Rio Grande.

Trans-Pecos magmatism began about 46 m.y. ago, culminated in voluminous eruption and intrusion at 35 to 30 m.y., and extended to at least 16 m.y. before present. The younger limit is not well established in time or space, because erosion has removed most of the younger lavas and tuffs. Initiation and cessation of magmatism in the Trans-Pecos province were both earlier than those in the Rio Grande Rift. Major normal faulting in the Trans-Pecos began after 31.5 m.y. ago and continues, and thus is broadly contemporaneous with faulting in the Rio Grande Rift. Trans-Pecos faults do not define a continuous graben system, but strike north and north-northwest, following older trends.

The Trans-Pecos province may be a southeastern extension of the Rio Grande Rift in terms of structure, but not of magmatism.

SEISMIC AND GRAVITY MODELS OF THE SNAKE RIVER PLAIN

BRAILE, Lawrence W., Dept. of Geosciences, Purdue University, West Lafayette, Indiana 47907; and KELLER, G.R., Dept. of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968

Seismic refraction profiles from quarry blasts in southeastern Idaho and from the Bingham, Utah copper mine along with existing refraction lines from Boise, Idaho to Mountain City, Nevada have been interpreted to determine the crustal and upper mantle structure of the Snake River Plain (SRP). The refraction data and surface wave dispersion interpretation confirm that the western SRP has an approximately 42 km crust having an anomalously thick lower crustal layer. The Pn velocity in the western SRP is 7.9 km/sec. Pn velocity and crustal thickness decrease in the eastern SRP toward Yellowstone. The crust is ~28 km thick and the Pn velocity 7.6 km/sec near Big Southern Butte on the eastern SRP. Although no seismic data are available, gravity models and correlation with published topography, heat flow and crustal age data suggest that the crust thins further toward the Yellowstone region. Gravity models consistent with the seismic data have been developed. These models show progressive crustal thinning along the SRP from west to east with this density effect offset by mantle density variations resulting in a combined -100 mgal anomaly at Yellowstone from the western SRP.

The surface volcanics appear to be thin ($\lesssim$ 2km) in the eastern SRP and both the gravity and seismic data indicate that a 'Basin and Range' type crust underlies the volcanics in the eastern SRP.

NEW MEXICO SOLAR ENERGY INSTITUTE

Job No. 2183-020

RIO GRANDE GEOTHERMAL RESOURCES:

A REGIONAL PERSPECTIVE

March 1977

Turner Collie & Braden Inc.
W. Tom Kleeman, Consultant

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March 23, 1977

Dr. Frank Brown
Bureau of Economic Geology
University of Texas at Austin
Austin, Texas 78712

Mr. Joe Ventura
Governor's Energy Advisory Council
Post Office Box 15286
Austin, Texas 78761

Dr. Robert L. San Martin
Energy Research Institute
New Mexico State University
Las Cruces, New Mexico 88003

Re: Rio Grande Geothermal Resources: A Regional Perspective

Gentlemen:

In compliance with the terms of our agreement and your letters of authorization, we are transmitting herewith our formal report, entitled "Rio Grande Geothermal Resources: A Regional Perspective."

The report describes the conduct and results of the workshop, or seminar, on geothermal resources held in El Paso, Texas, in December 1976, which was the culmination of several months' preparation, organization, and preliminary arrangements by our firm. The report contains certain available data and relevant information concerning potential geothermal energy in the Rio Grande region, and it includes a brief discussion of the papers presented at the seminar by the participants.

We would like to express our appreciation to Dr. C. G. Groat of the University of Texas at El Paso for his cooperation and assistance in preparing for the seminar. We also wish to acknowledge the contribution made

Turner Collie & Braden Inc.

March 23, 1977

Page Two

by Mr. Tom Kleeman, our special consultant who was retained to manage the project. And finally, we wish to recognize the participation by the Energy Research and Development Administration through the federal grant made by that office.

It has been an interesting and challenging assignment to serve the agencies responsible for authorizing this evaluation of a possible alternate source of energy. We would appreciate the opportunity to be of further service should these investigations continue. We would welcome a request for a proposal to perform such professional and technical services as might be desired for the succeeding phases of this project.

Very truly yours,

Wm. R. Ratliff, P. E.
Vice President

TABLE OF CONTENTS

PREFACE

The economy of the area surrounding the Rio Grande Valley in New Mexico and Texas is dependent on water and energy, two interrelated resources that are becoming increasingly scarce and more expensive. As this region and the rest of the United States seek solutions to pressing resource availability problems, it becomes imperative that potential energy sources of all types be carefully assessed. This is particularly true for the Rio Grande area where the availability of sufficient water, so critical in this arid area, is totally dependent on the availability of reasonably priced energy.

The Rio Grande Valley has many features that suggest the presence of thermal waters of possible economic importance. Studies in New Mexico, and more limited experience in the Texas portion of the Valley, have provided data that lay the groundwork for further and more detailed analysis of the geothermal setting. The great demands for energy in the region dictate that this energy source and every other possibility be thoroughly evaluated.

The workshop reported on in this volume was held to bring together individuals with expertise and interest in the assessment and utilization of geothermal energy in the Rio Grande Valley plus those who could speak to the present and future demand for energy there. The themes of the workshop were 1) What do we know now about the potential for geothermal energy?

2) What needs to be done to thoroughly assess the potential? and 3) Does the region's demand for energy resources provide sufficient incentive for proceeding with resource assessment and consideration of uses for the resource? As expected, more questions were posed than answered, but one conclusion can safely be stated: the region needs energy and the geothermal potential is significant enough to warrant further study.

The workshop was ably organized, coordinated, and operated by Tom Kleeman, Consultant to Turner Collie & Braden Inc. of Houston, Texas who authored this report. Funding was provided by the U.S. Energy Research and Development Administration through the Bureau of Economic Geology at the University of Texas at Austin, by the New Mexico Energy Resources Board through the New Mexico Energy Institute at New Mexico State University, and by the Texas Governor's Energy Advisory Council. The University of Texas at El Paso hosted the workshop, providing facilities and staff support. An informal steering committee consisting of Dr. Frank Kottlowski, Director of the New Mexico Bureau of Mines and Mineral Resources; Dr. Robert San Martin, Director of the New Mexico Energy Institute at New Mexico State University; Mr. Joe Ventura, Executive Director of the Texas Governor's Energy Advisory Council, and Charles G. Groat, Chairman, offered suggestions and guidance. Many individuals contributed time and effort to the workshop; special appreciation goes to Susan Conway of the Texas Governor's Energy Advisory Council and Dr. William Cornell and James Parker of the University of Texas at El Paso.

We would like to express our appreciation to the following persons for their presentations to the informal workshop sessions on resource exploration and assessment. Dr. Carlos Aiken, Department of Geology, Texas Christian University; Robert Curtis, Department of Geological Sciences, University of Texas at El Paso; Chris Henry, Bureau of Economic Geology, University of Texas at Austin, Dr. Eugene Herrin, Department of Geophysics, Southern Methodist University; Dr. G. R. Keller, Department of Geological Sciences, University of Texas at El Paso; and Rick Kopp, Department of Geological Sciences, University of Texas at El Paso.

Charles G. Groat, Chairman
Workshop Steering Committee

This report is the product of many months' work related to the geothermal energy potential of the Rio Grande Region of New Mexico and West Texas. The report contains information brought to light at a recent geothermal resource workshop held in El Paso, Texas on the 15th and 16th of December 1976. The workshop data are augmented with information from other sources as well.

The report is, as the workshop was, ambitious in its scope. It covers a wide range of subjects relating to geothermal resources. For the first time, the total framework of the region's geothermal resources is examined: resource exploration and assessment, demand and utilization of resources, environmental impacts of resource-related activity, institutional problems that arise with geothermal resource development, and recommendaion of a regional geothermal research and development program.

Trying to examine the resource system as a whole, rather than specific elements, yielded a generalized report. This may be timely. All of the previous work has dealt with singular aspects of geothermal resource potential: heat flow measurements, geochemistry studies, etc.

This treatment is concerned with the whole resource system within a regional framework. The contributors to the El Paso meetings came from a broad range of professions. There were geologists, economists, geophysicists, political scientists, and engineers, and they came from government, academia, and the private sector. This is another reason for more generalized characteristics of this report than are found in standard energy resource assessments.

The subject of geothermal resource potential in the Rio Grande Region has been covered only partially by this work. In the near future further efforts will help us to understand better what role geothermal energy might play in the energy future of this region.

The author believes that this broader perspective translates into a report that is readable by persons of varied backgrounds. The jargon is always rougher on the other side of the fence. Therefore, efforts were taken to describe this complex subject in simple and straight forward language.

The workshop sessions were held on the campus of the University of Texas at El Paso. The two days of meetings took place on the 15th and 16th of December 1976. On the first day, invited speakers presented prepared papers to the conference-at-large and answered questions. On the second day, the participants met in two smaller workshop sessions: one dealing with demand for and utilization of geothermal resources, the other for resource exploration and assessment.

The smaller workshop sessions were designed to allow the interaction of participants after they had heard the presentations covering a broad range of topics. The group discussions benefitted from the diverse professions of the participants (representing the academic research community, private industry, and government). The group members could comment on the subjects introduced on the previous day as well as other aspects of geothermal development.

First day's speakers were as follows:

V. H. Savage; Southwest Texas State University - "Regional Economics and the Demand for Electricity"

W. N. McAnulty; University of Texas at El Paso - "Geothermal Energy and Minerals Development"

Jerry Hoffer; University of Texas at El Paso - "Geothermal (Geochemical) Indicators in West Texas"

Jim Combs; University of Texas at Dallas - "Geophysical Indicators of Geothermal Resources in West Texas"

Chandler Swanberg; New Mexico State University - "Regional Geothermal Indicators"

Joel Gevirtz; Resources Systems Research - "Synthesis of Geothermal Data"

Eugene Herrin; Southern Methodist University - "Regional Geothermal Indicators"

Frank Kottlowski; New Mexico Bureau of Mines - "New Mexico Geothermal Heat Flow Research"

Marlan Blissett; University of Texas at Austin - "Institutional Factors that Affect Resource Development"

R. D. Sadow; Turner Collie & Braden Inc. - "Environmental Impacts of Resource Development"

This report represents the first attempt to gather, collate, and publish the relevant information concerning geothermal resources in the Rio Grande Region. As a result of the workshop, new information concerning the region's resources is now available. For the first time, Rio Grande geothermal resource development is treated in the conceptual framework of a regional entity. This report addresses the linkage that exists between resource use and resource development, between activities in one part of the region and activities in another part.

All of the relevant information about the region has been used in the formulation of a preliminary plan for research into the development of the region's geothermal resources. This early planning effort is general enough that it is applicable to the broader questions of energy use in the region.

Eventually, solar energy could be very important in this portion of the "sun-belt" and many of the same types of questions will need to be addressed.

Introduction to the Region of Interest

The Rio Grande has long been important in the history of American civilization. An international boundary, a source of water in an arid environment (hence the Spanish name "Great River" for a relatively small one), an important geographic reference point for the Indians, explorers, and 19th century pioneers, this river, like certain larger ones in wetter climates, has played a dominant role in the development of the region it transverses.

The headwaters of the Rio Grande are in the mountains of southern Colorado (see map, Fig. 1). Flowing southward, the river nearly bisects the State of New Mexico into eastern and western halves. The river enters Texas at its western-most point, north of the City of El Paso, separating it on the American side from the City of Juarez on the Mexican side. The Rio Grande continues in a southeasterly direction until it reaches Brewster County, Texas. Here it loops north (thus, the name "Big Bend" National Park) and then curves back into its southeastward course, flowing on to the Gulf of Mexico some 1,800 miles from its origin.

The region of interest is arid to semi-arid. The driest part include the Big Bend area and western Trans-Pecos, Texas, which are in the north-eastern quadrant of the Chihuahuan Desert. The rest of the region, parts of West Texas, the Texas Panhandle, and the State of New Mexico are semiarid.

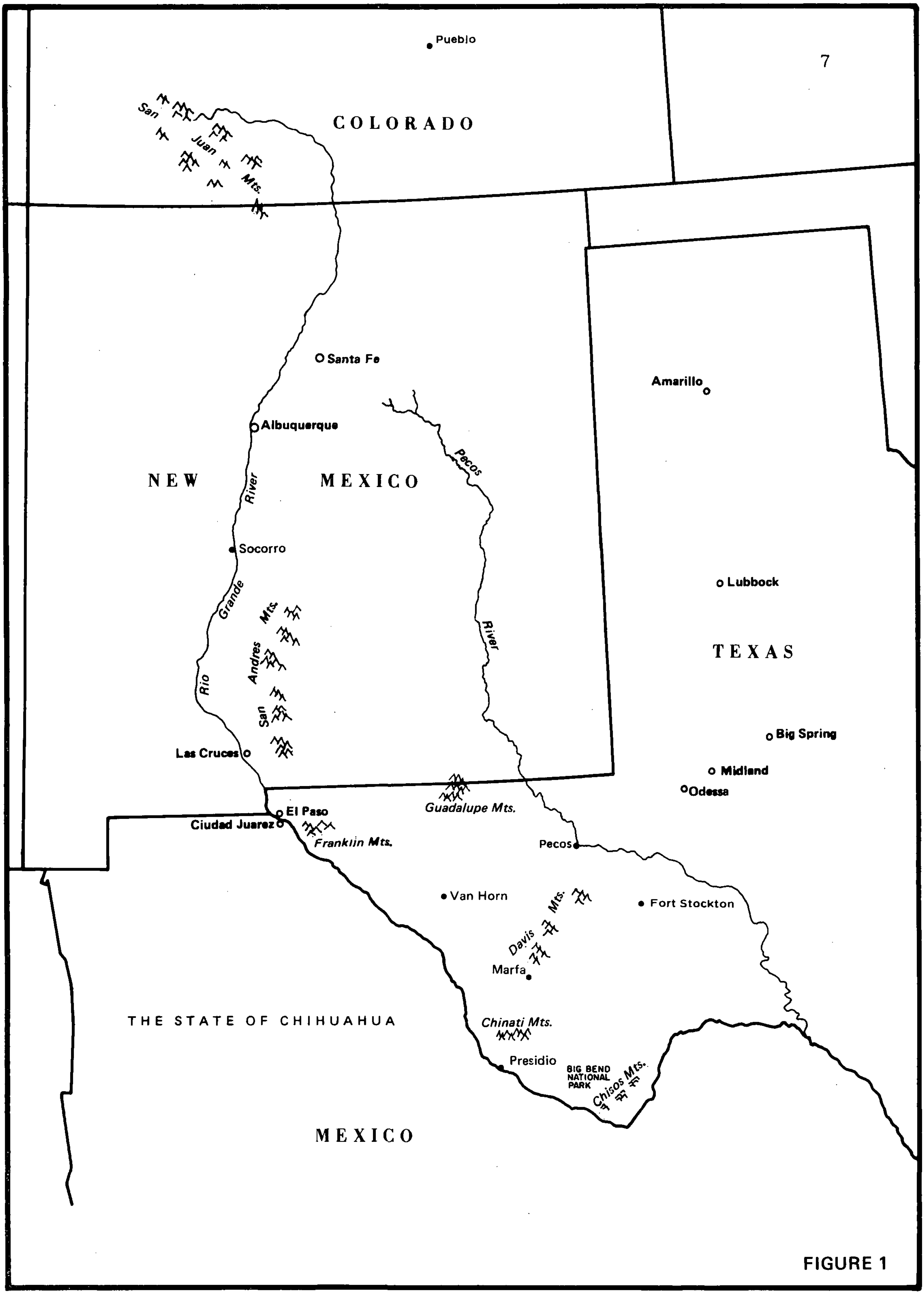

Pueblo
COLORADO
San Juan Mts.
NEW MEXICO
Santa Fe
Albuquerque
Pecos
Rio Grande River
Socorro
San Andres Mts.
Pecos River
Las Cruces
Amarillo
Lubbock
TEXAS
Big Spring
Midland
Odessa
El Paso
Ciudad Juarez
Guadalupe Mts.
Franklin Mts.
Pecos
Van Horn
Fort Stockton
Davis Mts.
Marfa
THE STATE OF CHIHUAHUA
Chinati Mts.
Presidio
BIG BEND NATIONAL PARK
Chisos Mts.
MEXICO

FIGURE 1

Dry-land farming is possible in some areas, but irrigation makes possible very high yields.

Today, the provinces around the river are of interest for a new type of resource development. The new developers are interested in energy resources. There are indications that within the region there are potential exploitable geothermal resources.

Natural gas has been the most important energy source in this region--as in many others. It has been used as a boiler fuel for generating electricity, heating homes and offices, and as the primary energy source for running the pumps employed in irrigated agriculture. Geothermal resources, of the type thought to be in this region, are present only in the western half of the United States. However, from a national perspective, these resources are extremely important. While geothermal resources can be utilized only at a specific site, their development means that precious supplies of oil and gas are freed for use in other areas. The lack of a coherent national energy policy has deterred the development of alternative energy resources that benefit specific, localized regions directly and the nation indirectly.

Until now, efforts to explore for and assess the potential of geothermal resources in this region have been carried out in a rather segmented fashion without much regard for considerations larger than those of the individuals involved in each specific task. The State of New Mexico has been exemplary in funding geophysical and geochemical research aimed at geothermal resource exploitation in various locations. The State of Texas has funded a geochemistry study for the Trans-Pecos area and the Federal Government has sponsored limited projects in both states. Private sector investigations have been carried out on a rather limited basis, as regards the whole region, and nearly all of these have taken place in New Mexico. In order to assure efficient development, future resource assessment should be coordinated in a regionwide framework.

The remainder of this chapter is a summary of how they can be found, how the regional geothermal resources can be used, how they might interact with the environment, and how their development relates to the institutions of the region. A detailed treatment of the information contained in this summary is presented in Chapters IV, V, VI, and VII. The information contained in these chapters was helpful in developing the suggested program of research outlined in Chapter VIII.

DEMAND AND UTILIZATION

The Regional Economy and Electricity

The supply of electricity is vital to the economic health of the region. In the regional economy as a whole, 2.71 kilowatt hours (KWH) of electricity are required to generate $1 of income. In projecting economic growth to the year 2020, it is estimated that some 51 billion KWH of electricity will be required for a total income level of 29 billion dollars.

Population growth is expected to be stable and rather low at two percent for the entire period. With a projected total income increase of 263 percent, per capita income is expected to increase dramatically. The per capita income in 1974 was only $3,500. In 2020, it is projected to reach $13,000. This statistic has important implications for a region which has traditionally lagged behind the national per capita income average.

Since natural gas, which is in short supply, is the predominate boiler fuel, the development of geothermal resources may be necessary to guarantee the projected economic growth.

Utilization of Geothermal Resources for Irrigated Agriculture

Agriculture is of economic importance to both the United States and the Rio Grande Region. The State of Texas is the third largest producer of food and fiber in the United States and the second leading exporter. One-third of the land used for farming in Texas is irrigated and accounts for 70 percent of the total output of the Texas harvest. In 1976, the Texas High Plains and Trans Pecos, which are in the Rio Grande Region described in this report, accounted for 60 percent of the food and fiber output of Texas. Over one-half of the state's irrigated farming operations are in the region.

The irrigation pumps in the region are powered mainly by natural gas or by electricity generated by natural gas-fired power plants. Natural gas costs have risen dramatically in the past two years, with increases as high as 200 percent to 500 percent in some areas. In addition to the cost increases, the supply shortage is another critical problem. In some areas supply may be terminated with as little as 10 to 30 days' notice without the supplier showing cause.

Last year, due to enormous increases in production costs, irrigated wheat farmers suffered substantial losses. With regard to natural gas, the supply situation has become so undependable and the prices so high that the effects in two West Texas counties, Reeves and Pecos, have been extreme. Between 1975 and 1976, the number of acres used for irrigated agriculture was reduced from 150,000 acres to only 15,000 acres. If an energy alternative to natural gas is not found, the situation will worsen.

Geothermal Resource Potential and Mining

The United States is faced with a well-known energy shortage and a not-so-well-known shortage of hardrock mineral resources. Minerals extraction and processing requires large amounts of energy, particularly as more marginal deposits are worked. The development of geothermal energy resources could prove to be quite beneficial to the exploitation of minerals in the Trans-Pecos area.

Known deposits of the following metals exist: berrullium, titanium, iron, gold, copper, mercury, silver, manganese, molybdenum, zinc, tin, and tungsten. Industrial rock and mineral resources known in the area include: gypsum, limestone, dolomite, sand and gravel, granite, rhyolite, basalt, marble, barite, volcanic ash, tale, asbestos, bentonite, fluorite, halite, sulfur, and uranium.

In the resurgent cauldron and/or volcanic centers of the Quitman, Eagle, Chinati, Solitario, Christmas, Chisos, and Pico Etereo mountains, there are indications of deposits of various metallic minerals. The development of thermal waters in this area could provide the stimulous to develop these mineral resources.

RESOURCE EXPLORATION AND ASSESSMENT

Introduction

At the conclusion of the first day of the workshop, C. G. Groat restated concisely the prospects for geothermal resource potential when he said, "Today we have heard the word 'indicators' used many times. There are many indicators that geothermal resources may be present in this region. We do not know their extent." At the same time, there is no reason to doubt that the resource could exist in this region.

In New Mexico high heat flow recordings, the presence of young volcanism and geochemical work all seem to indicate that geothermal resources might be present. Volcanic activity is recorded in historic time and there is a high heat region in western New Mexico (see map, Fig. 9).

Moving south, numerous hot springs are known to occur on both the Texas and Mexican sides of the Rio Grande. The preliminary geochemical studies and geophysical work indicate the possibility of geothermal anomalies. The Trans-Pecos is for the geothermal resource explorer an area that is both fascinating and frustrating. Because of its remoteness and the scarcity of data, recent considerations of the resource potential must of necessity combine both art and science. The local "old timers" will relate to the visitor tales of oil drilling crews that hit a steam pocket, "That 'durn' near blew the top off the rig and roared for two days." There are numerous stories of ranchers who drill water wells for cattle and hit hot water which was of no use to them. Whether such recountings are actual or apocryphal is impossible to know at present and cannot be proved until more data are gathered. We need more hard data. In an energy-short society, such stories remain tantalizing.

The above-mentioned accounts, the existence of the warm springs, the preliminary research results, and the existence of areas that only recently have been considered interesting with regard to geothermal resource potential, have all resulted in the development of numerous ideas for resource exploration and assessment.

Geological and Geophysical Setting

As shown in the section addressing demand for and utilization of geothermal resources, there is a need for the resource throughout the region. This section, however, will focus mainly on the geothermal indicators that exist in the Trans-Pecos area because of the newness of this information and because much of the recent meaningful New Mexico data have been collected in private sector assessment and is therefore proprietary.

The western portions of the Trans-Pecos area are located in the southeastern part of the Basin and Range physiographic province, which includes southern Arizona and New Mexico.

The Rio Grande Rift system, which is associated with high heat flow valves in New Mexico (as defined in this paper), continues from south-central New Mexico into Texas, trending south of El Paso on into Mexico somewhere west of Big Bend National Park (see map, Fig. 1).

This rift has been compared with such known geothermal resource areas as the East African Rift System and the Salton Trough of Southern California and Mexico. (This last area contains the operating Mexican geothermal power plant at Cerro Prieto as well as the promising geothermal area in the Imperial Valley.)

Quarternary basalt flows are present in New Mexico. The youngest igneous rock in West Texas is thought to be late tertiary, although dating has not been accomplished and flows may be younger than tertiary. Faulting is extensive in this area, consistent with recent tectonism. Fault zones provide avenues for circulating geothermal waters and are likely sites for drilling operations. There are numerous warm springs between El Paso and Big Bend National Park. There are also many wells of warm water. The map in Figure 14 shows the locations of the five warmest springs and three of the warmest wells in the rift zone.

Earthquakes and Micro-earthquakes

A major earthquake occurred near Valentine, Texas, northwest of Marfa, in August 1931. The epicenter of this earthquake (magnitude 6.4) as well as 24 smaller earthquakes is plotted on the map in Fig. 15. Several studies have indicated that micro-earthquakes occur continuously in much of western and southern Texas-Pecos. Micro-earthquakes correspond highly with those areas which have known geothermal resources. Micro-earthquakes have been recorded along the Rio Grande Rift system between Las Cruces, New Mexico and Albuquerque, New Mexico.

Water Chemistry Studies

Water chemistry studies can be a valuable tool for providing regional geothermal information for a relatively low cost. Geologic terrain factors must be considered further in evaluating the silica and sodium-potassium-calcium geothermometers that have been applied in the region; however, existing data provide useful indicators.

Hoffer conducted extensive samplings of area waters, and his findings indicate that the most promising areas are: (1) two hot springs in Presidio County, (2) one location south of Marfa, and (3) one location east of El Paso. Swanberg's work indicated an additional well west of Marfa, Texas as being anomalous (see map, Fig. 14).

Heat Flow Data

Heat flow determinations for the lower rift zone are shown in Fig. 17. "These heat flow valves indicate that portions of the region are characterized by abnormally high subsurfaced temperatures and potential geothermal systems," states Combs.

The anomalously low heat flow valves (shown in Fig. 17) north of Presido, Texas, as well as the 1.6 and 1.4 Heat Flow Units (H.F.U.) localities are inconsistent with the expected higher measurements associated with the Basin and Range Province. Combs argues that this is due to connective heat transfer phenomena. Obviously, more heat flow information about the region is needed, especially in the Trans-Pecos area which has received very little scrutiny.

Data Synthesis

Due to some of the inherent problems involved with the standard silica and sodium-potassium-calcium geothermometers, more sophisticated techniques are needed. Gevirtz discussed the use of data synthesis techniques that could (1) better assess the information gathered in geochemical surveys, and (2) relate the geochemical findings to automous geophysical data.

Synthesizing processes described by Gevirtz permit more comprehensive assessment of the geothermal resource potential of an area.

This chapter deals with the various economic ramifications of geothermal energy potential. The material contained in this portion of the report came from papers presented at the conference as well as outside sources. V. H. Savage of Southwest Texas State University presented a paper on the regional economy and the demand for electricity. John Kelly, consultant to the Texas Department of Agriculture, discussed the energy needs of irrigated agriculture. W. N. McAnulty introduced the possible role of geothermal energy for minerals development in the Trans-Pecos area. There is additional outside material contained in this section; therefore, all statements and all conclusions should be considered the responsibility of this author unless others are quoted directly.

THE REGIONAL ECONOMICS AND DEMAND FOR ELECTRICITY

V. H. Savage begins his introduction to the regional economy with the reminder that, "The production of electricity, economic growth and population growth are interdependent. Electricity is used in the various economic endeavors which in turn provide a substantial part of the income base for an area." Likewise, increased economic growth and population will affect the demand for electricity.

During the past few years, and especially during the harsh conditions of this winter, we have witnessed a shortage of natural gas, which is used as a boiler fuel in electricity generation. Producer claims concerning the lack of profitability in natural gas production under present regulated conditions indicate that further shortages will continue.

In those areas where natural gas sales were not limited by inter-state regulation, major price increases have occurred. The increased price of natural gas will be translated into higher costs for electricity.

In trying to assess the situation with regard to the demand for electricity in the regional economy, Savage had to rely on data that reflected short-term price changes and consumption patterns. Obviously there are inherent problems in trying to formulate economic forecasts incorporating such short-term data. Savage points out the following:

> Over the longer period, changes in life styles, technology, capital structure, and the production mix tend to increase their own price elasticity of demand for any one source of energy. However, the 'energy crisis' has not been acknowledged for a sufficient time period to all for the institutional and technological forces to exert themselves.

Despite these difficulties, if we are to avoid some of our past mistakes and begin to plan for our energy future, energy-related economic forecasts are very much needed. It should be mentioned that Savage's effort was a noble attempt under severe time limitations resulting from an unfulfilled previous commitment. In addition to the constraints of time and data, there was an unfortunate lack of funds. Although a very useful product resulted, future efforts should not be so restricted.

The Region

The reader should keep in mind that the question, "What is a region?" is very complex. Definitions can be elusive. Economists and geographers engaged in regional studies continuously argue this question. [Perhaps tiring of the "angels-on-the-head-of-a-pin" aspect of the argument led one scholar to declare that a region is any arbitrary area for which one can obtain funds to study. Such forthrightness, if not inspiring, seems at times to be accurate.]

Several factors determined the boundaries of the region. Since the Rio Grande approximated the heart of the area believed to have geothermal resource potential, it was decided that the boundaries should be within 500 miles of the river. This arbitrarily assigned distance is well within the range in which the transmission of electricity is economically feasible. Existing political boundaries of states and counties were taken into consideration. Finally, since the study had to rely on existing economic data, the most reliable figures known were to be found in the OBERS 1/ projections

1/The OBERS Projections represent the output of a joint effort in a program of economic measurement, analysis and projection by The Bureau of Economic Analysis which was formerly The Office of Business Economics (OBE), U. S. Dept. of Commerce and The Economic Research Service (ERS), U. S. Dept. of Agriculture. In Jan. of 1972 The OBE was renamed The Bureau of Economic Analysis. Prior to that time the report of OBE and ERS had acquired the acronym OBERS. In the ever changing, i.e., reorganizing, world of bureaucracies this report title offers a symbol of permanence.

of the Bureau of Economic Analysis (BEA). (See map on the following page.) The region includes BEA economic areas 122, 123, 145, 146, and San Juan County, New Mexico. These areas include the Texas and Oklahoma Panhandles, that part of West Texas west of a line originating at the southeast corner of the Texas Panhandle and extending approximately 20 degrees south by southwest to the southeast corner of Terrell County, Texas. The area designated also includes all of the State of New Mexico. Within the region are vast sparsely populated areas as well as the major metropolitan centers of the Texas Panhandle, West Texas (except San Angelo and Abilene), and New Mexico.

Regional Economic Activity, Income, and the Demand for Electricity

The range of economic activity in the regional economy spans most standard economic categories (manufacturing, trade and commerce, government and services, etc.). Table 1 displays the income derived in the region by economic category. The income data are for the year 1974 due to the need to relate this information to the data on demand for electricity. This was the latest year for which electricity-use data were available.

The economic activities create direct demand for electricity, as production inputs, and the derived income produces additional indirect demand through the household sector. Future demand for electricity will be determined by the growth of existing economic sectors and the development of new

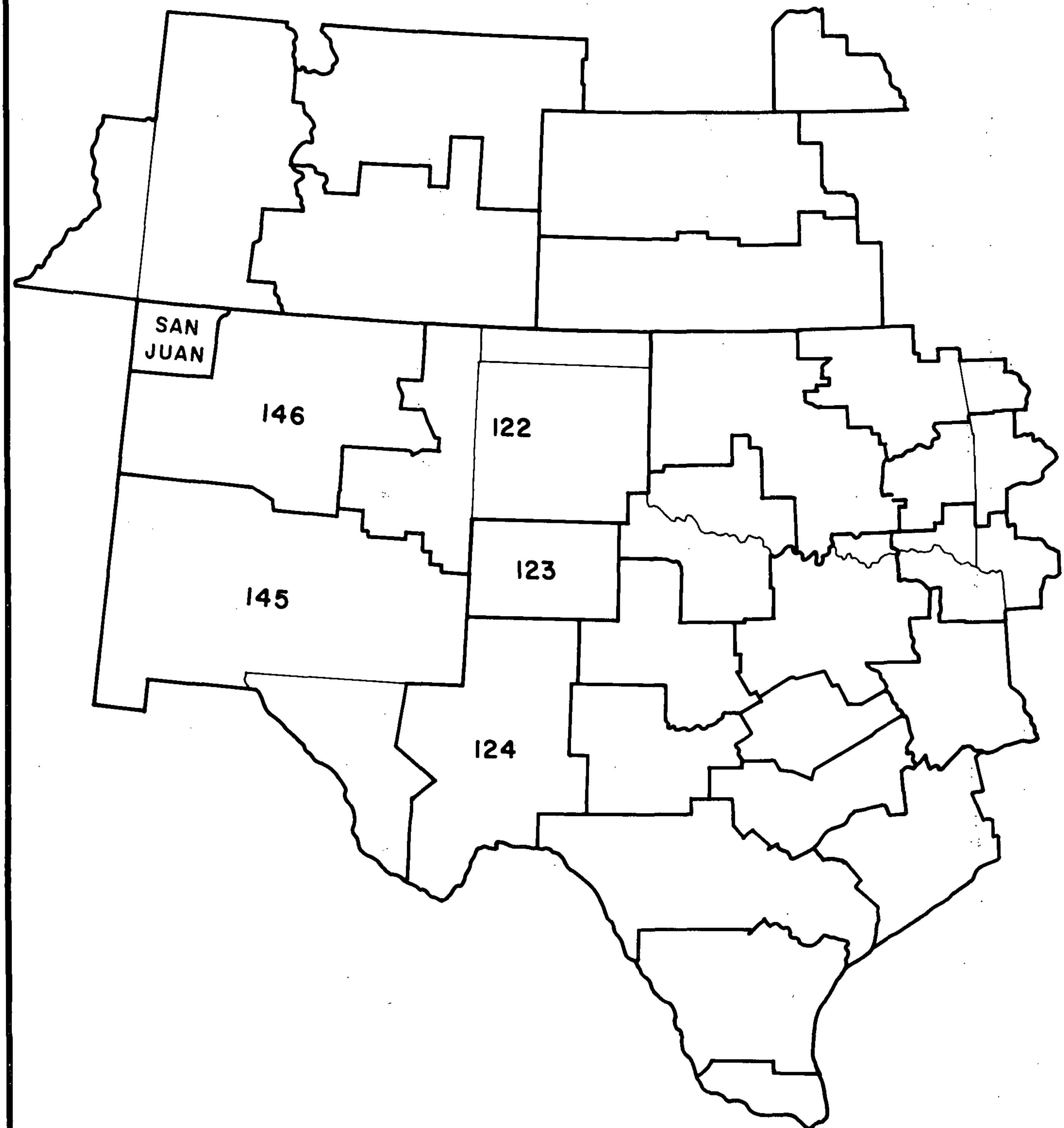


FIGURE 2

TABLE 1

Total Income and Income Derived
from Each Broad Economic Category
West Texas, New Mexico Region, Year 1974
(Thousands of 1967 Dollars)

Economic Activity, Earnings and Income	West Texas, New Mexico (Total)
Total Personal Income	8,018,055
Total Earnings	6,151,509
Agriculture	785,728
Mining	372,524
Contract Construction	343,152
Manufacturing	602,775
Transportation, Commercial & Public Utilities	459,097
Trade	1,000,752
Fire	248,644
Services	851,217
Government	1,487,620
	6,151,509

Source: Computed from 1972 OBERS Projections: V2 BEA Areas
U. S. Water Resources Council, Washington, D.C., 1974.

activities in the regional economy. It should be remembered that the interdependent nature of an economy is such that future economic activity will also depend on the supply of electricity for growth to take place.

The 1974 data for electricity use in the region were available only in categories broader than those in Table 1. These categories were industrial, commercial, other (agriculture, government employment, and all remaining undesignated activities), residential (households), and other income (not to be confused with the category "other"). This group includes rents, interest, government transfers, etc. This last category does not require direct inputs of electricity, but demand will be affected through the residential sector which derives increased purchasing power from this sector. The electricity use data are presented in Table 2 by broad economic category in 1000 KWH. This table also contains the data in Table 1 after it has been combined in compatible economic categories.

Households, as seen in Table 2, account for only 20 percent of the regional demand for electricity. This is an important point and Savage notes the following:

> This fact renders the analysis of electricity demand based simply on population growth (a common practice of less rigorous analysts) very suspect. Regional population declines could be accompanied by increased production in the various electricity-using industries dictating an increasing demand.

TABLE 2

Income and Electricity Demand by Broad Category
of Economic Activity and Household Electricity Demand,
West Texas, New Mexico Region
(Thousands of 1967 Dollars, Thousands of KWH)

	Income	KWH
Industrial	$1,777,548	7,324,719
Commercial	2,100,613	5,333,000
Other	2,273,348	3,339,001
Residential	NA	4,343,145
Other Income	1,866,546	NA
Total	$8,018,055	20,339,865

NA: Category does not apply.

Source: Table 1, U. S. Dept. of Agriculture, *1974 Annual Statistical Report Rural Electric Borrowers, Federal Power Commission Statistics of Publicly Owned Electric Utilities in the United States 1974 and Federal Power Commission Statistics of Privately Owned Electric Utilities in the United States 1974,* Govt. Printing Office, Washington, D. C. 1976.

From the information contained in Table 2, it is possible to compute the number of KWH required to derive a dollar of income from each sector. This relationship is shown in Table 3. The industrial sector had the highest requirement, 4.14, and other (government agencies, etc.) the lowest, with 1.47. The average for the whole economy was 2.71.

If one employs certain basic assumptions (less valid over longer time frames) of no real change in life styles, technology and capital structure, then it is possible to make some predictions of future electricity demand, based on the growth rates of the various economic sectors. The ratio of KWH to income means that demand for electricity can be computed on the basis of total economic activity and not on the more limited basis of population growth. In the past, the "double-ten" estimate was considered a reliable guide in forecasting future electricity demand. 2/ With the recent energy situation, it seems reasonable to presume, a priori, that more sophisticated techniques are necessary.

The OBERS projections indicate a continuous rate of economic growth to the year 2000, with a relatively stable two percent population growth. Interestingly, the absolute size of the work force is projected to increase by

2/ The "Double-Ten" assumption was employed for years by those making forecasts of future levels of electricity demand. The assumption, substantiated by post W. W. II history, was that demand for electricity would double every ten years.

TABLE 3

KWH Required to Produce
One Dollar in Income by Broad
Limited Economic Sector

	$	KWH
Industrial	1.00	4.12
Commercial	1.00	2.54
Other	1.00	1.47
Average for Region		2.71

Source: Table 2.

14 percent over the same time period. Savage notes: "This, of course, implies a changing age distribution and possibly an increase in the incidence of working wives. One implication is a reduction in the size of households, which by itself on a ceterus paribus basis, implies an increased electricity use per capita."

Savage has predicted growth rates for electricity demand, by broad category, based on the projected increases in economic activity. Figure 3 shows these projections for the broad categories of earned income.

The projected rate of growth of predicted total income is shown on the graph in Figure 4. From these growth rates, we may derive the projected growth rates in the demand for electricity. On the basis of increased total income, demand for electricity should increase from 16 billion KWH in 1974 to about 51 billion KWH in 2020. The rates of growth of income and electricity use correspond closely (under the above-mentioned assumptions). In noting this phenomenon, Savage states: "For although the commerce sector and 'other' sector have growth rates in excess of the industrial sector, the relative amounts of electricity used produce an increase in the demand for electricity which is almost identical to the overall income growth rate."

PROJECTED INPUT ELECTRICITY DEMAND BY BROAD CATEGORY (IN MILLION KWH) 1974-2020 & PROJECTED INCOME GROWTH BY BROAD CATEGORY (IN $1 MILLION—1967) 1974-2020

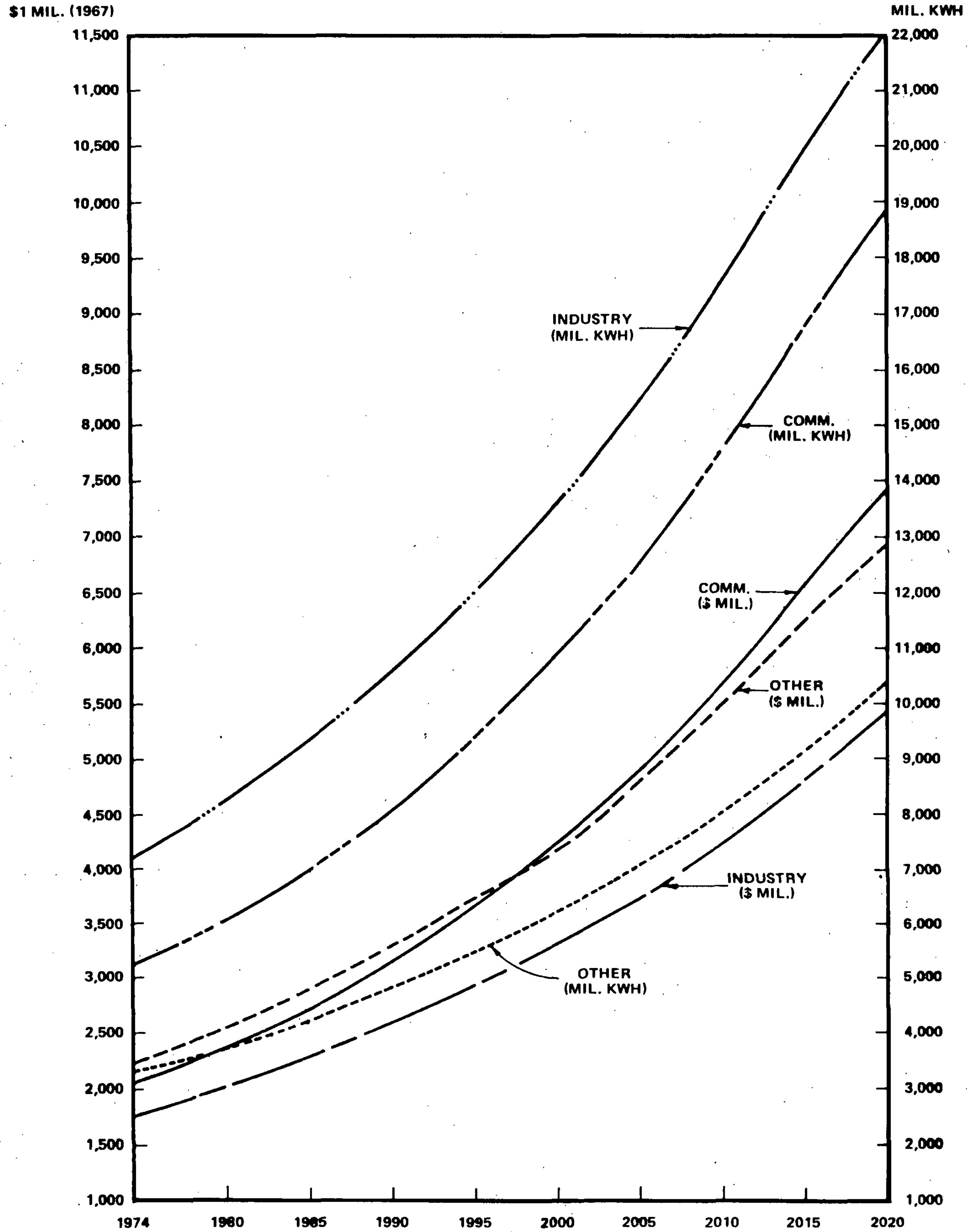


FIGURE 3

PROJECTED INPUT ELECTRICITY DEMAND (TOTAL FOR REGION) 1974-2020 &
PROJECTED INCOME GROWTH (TOTAL FOR REGION) (IN $1 MILLION—1967) 1974-2020

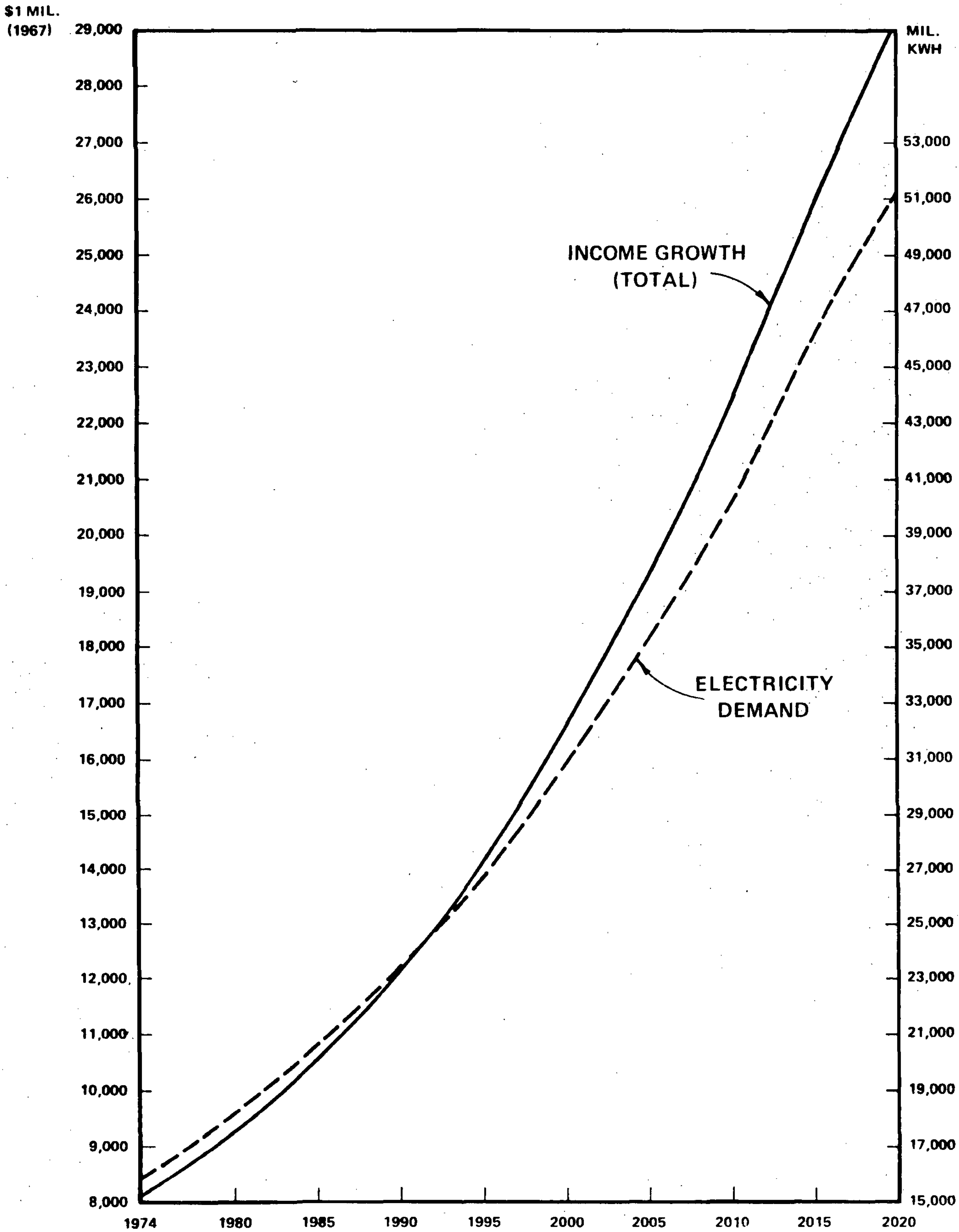


FIGURE 4

The Residential Sector

Little has been said about the demand for electricity generated by the residential sector. Households accounted for 21 percent of the demand in 1974. Over the time period considered, the behavior of this sector becomes harder to predict. For instance, if the residential sector accounts for the same share of the electricity market in 2020 as it did in 1974, then approximately 14 billion KWH will be consumed by households. However, it has been projected that population size will increase very little by the year 2020.

It is important to note that income for the region is predicted to increase at a considerably greater rate (263 percent) than population (two percent) according to OBERS statistics. Thus, regional per capita income will undergo significant increases, $3,500 in 1974 to about $13,000 in 2020--measured in constant 1967 dollars. This represents an increase of 242 percent.

Given the population projections, it is likely that household demand will decline relative to other sectors. Savage, however, has observed:

> ...other forces will tend to increase the per capita demand for electricity. Fewer residents per household as the population ages will tend to produce diseconomies of scale. The smaller households will use marginally less electricity due to reduced size. They will not, however, use proportionately less. The other force tending to increase per capita household demand is increased affluence. While the currently affluent may have satisfied their tastes and preference for electrical appliances and gadgets, the less affluent still have a pent up demand for these conveniences which will manifest itself when circumstances permit.

Responses of Electricity Demand to Price Changes

The price of electricity has been relatively stable until recently. Prices began to move up slowly during the early 1970's and have skyrocketed since the fuel price increases following the 1973 boycott. The United States' experience with sharp increases in the price of electricity has been short termed.

The work on the price elasticity (change in the demand for electricity resulting from a change in the price of electricity) has been based on historical data. Obviously, there are serious problems associated with relying on pre-1973 studies. Because of the scarcity of reliable data, the subject of price elasticity has not been addressed in this report.

Regarding the effects of price elasticities, Savage's comment does seem to the point, "The extent that the rate of growth of demand for electricity is modified or reversed depends on whether or not alternative sources of energy are found, the extent to which they are substitutable, etc." Given the interdependent relationships which exist among the various economic sectors, failure to develop alternatives to natural gas will preclude the realization of the economic growth that has been projected. Without a dependable and relatively inexpensive source of electricity, the per capita income levels will not increase as projected and may very well stagnate in this area which is already below the national average.

UTILIZATION OF GEOTHERMAL RESOURCES FOR IRRIGATED AGRICULTURE

Agriculture is an important component of both the United States' economy and the economy of the region under consideration. The United States exported from 25 to 30 percent of all food imported by developing countries in 1975.

The State of Texas is the third largest producer of food and fiber in the United States and the second leading exporter. A breakdown of the Texas agricultural output for selected crops and years is given in Table 4.

The 1975 harvest in Texas represented 25 million acres of farming activity. Approximately one-third, 8.6 million acres, of the farm land was classified as irrigated agriculture. This one-third of the total acres used for farming accounted for 70 percent of the total output of the Texas harvest. A comparison of the crop statistics in Table 4 reveals the significantly increased yields resulting from irrigation. In some areas such as the Trans-Pecos, the differential between irrigated and nonirrigated is even greater than the state averages.

The high level of farm output in Texas requires large amounts of energy inputs. Table 5 shows the amount of energy used in agriculturally related activities for the period 1 July 1973 to 30 June 1974. Natural gas

TABLE 4

Texas: Harvested Acres, Yield, by Crop and Year

Year		Harvested Acres	Yield/ Harvested Acre	Total Yield
1973	Corn	640,000	95 bu	60,800,000 bu
1973	Irrigated Cotton	1,915,000	533 lbs	1,020,695 tons
1973	Non-irrigated Cotton	3,285,000	372 lbs	1,222,020 tons
1973	Irrigated Sorghum	2,245,000	92.4 bu	2,093,725 bu
1973	Non-irrigated Sorghum	4,705,000	44.5 bu	2,093,725 bu
1976	Irrigated Wheat	1,000,000	35.4 bu	35,400,000 bu
1976	Non-irrigated Wheat	2,300,000	17.4 bu	40,020,000 bu
1973	Hay	2,400,000	2.42 tons	580,800,000 tons
1973	Vegetables	224,000	NA	NA

Turner Collie & Braden Inc.

TABLE 5

Texas: Energy Purchases and Uses on Farms, 1 July '73 – 30 June '74

Item	Type of Fuel					
	Diesel 1,000 Gal.	Gasoline 1,000 Gal.	L. P. Gas 1,000 Gal.	Fuel Oil 1,000 Gal.	Natural Gas 1,000 Cu. Ft.	Electricity 1,000 Kwh
1. Total purchases 1 July '74–30 June '73	270,000	380,000	289,000	4,500	140,000	3,329,000
2. Of total purchases Amounts Used for:						
a) Crop production	205,000	160,000	119,000	4,000	130,000	1,250,000
b) Live stock production	35,000	101,000	35,000	200	–	300,000
c) Poultry production	4,000	10,000	30,000	–	1,000	49,000
d) Custom services for others	22,000	23,000	2,000	–	1,000	3,000
e) Home heating, cooking and other non-farm activities	4,000	86,000	103,000	300	8,000	1,727,000
3. Item 2 as a percent of Item 1: *(approximate)*						
a) Crop production	75.9%	42.1%	41.2%	88.9%	92.9%	37.5%
b) Live stock production	12.9%	26.6%	12.1%	8.9%	–	9.0%
c) Poultry production	1.5%	26.3%	10.4%	–	.1%	1.5%
d) Custom services	8.1%	22.6%	35.6%	–	.1%	.1%
e) Heating, cooking and other non-farm activities	1.5%	22.6%	35.6%	6.6%	5.7%	51.9%

Source: Texas Department of Agriculture.

accounted for approximately 93 percent of the energy used in farm production.

Figure 5 is a map of the three Texas Department of Agriculture (TDA) districts that make up the Texas High Plains and Trans-Pecos area. These three districts correspond closely with the geographic boundaries of the EDA economic regions used in the OBERS projections discussed in the preceding section. The High Plains and Trans-Pecos region account for 60 percent of the food and fiber produced in the state.

The information in Table 6 is pertinent to the subject of irrigated agriculture in this area. This table shows the number of farms, land comprising farms, and irrigation pumps by fuel type for 1976. The three districts have over 23,000 farming operations covering 41.25 million acres of land. This represents 11 percent of the farms in the state and 29 percent of all Texas land used for farming. The 12,000 irrigated farming operations in this area account for 52 percent of the state's irrigated farming operations. The 6.4 million acres of irrigated farm land in this area represents over 70 percent of all irrigated farm land in the state.

There are 95,000 irrigation wells in the State of Texas and 85,000 are in the High Plains and Trans-Pecos region. Of these 85,000 irrigation wells, 50,000 are driven by natural gas-powered pumps. The second largest group are powered by electricity. It is important to remember that

1976 FARM IRRIGATION ENERGY SURVEY AREA

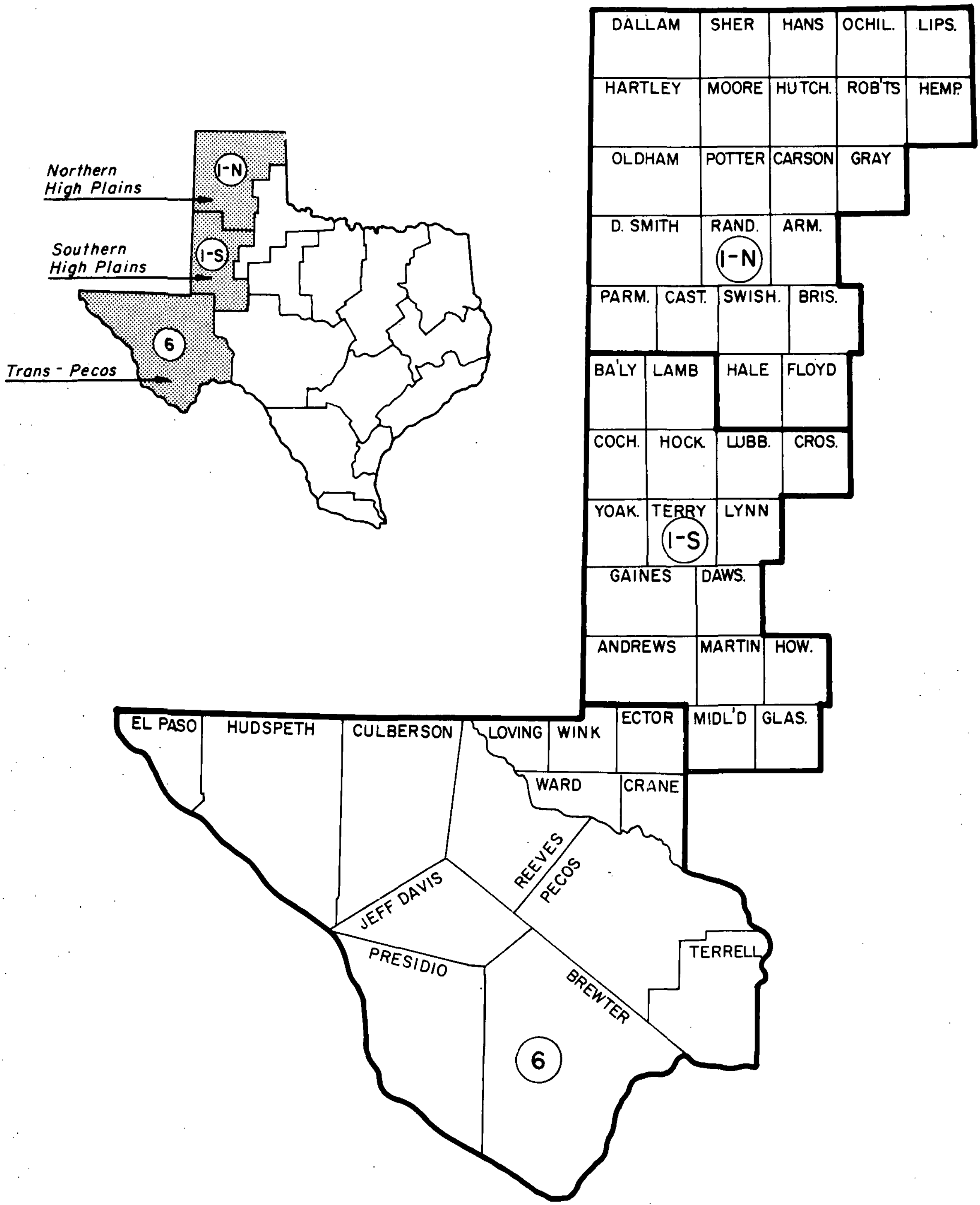


FIGURE 5

TABLE 6

Number of Farms, Land in Farms and Irrigation Pumps by Fuel Type, 1976

Farms, Land and Irrigation Pumps	Northern High Plains	Southern High Plains	Trans-Pecos	Three District Total
1. Number of farms	10,900	10,500	1,900	23,300
All land in farms (acres)	14,350,000	9,200,000	17,700,000	41,250,000
2. Number of farms with irrigation	6,000	5,600	400	12,000
Land irrigated during '76 (acres)	3,900,000	2,250,000	250,000	6,400,000
3. Number of irrigation pump motors	43,000	40,300	1,700	85,000
4. Number of irrigation pump motors fueled by:				
a) Natural gas	31,450	17,490	1,060	50,000
b) Electricity	10,240	21,790	470	32,500
c) L.P. gas (butane/propane)	1,240	1,000	160	2,400
d) Diesel and other	70	20	10	100

Source: Texas Department of Agriculture.

nearly all of the electricity in the region is generated by natural gas-fired power plants. Therefore, nearly all of the irrigation farming in this region depends on natural gas. Table 7 breaks down the relative importance of energy types on the basis of Btu consumption for each of the three districts and for the region as a whole.

Table 8 displays the amount of energy used, the amount of water pumped, and the cost of fuel according to fuel type. This data, as well as that shown in the above tables, helps to provide an understanding of the relationship between energy use and irrigated farming in the region. There are certain deficiencies in the presently assembled data; this subject will be covered later in the report.

With regard to natural gas, two primary problems face the region's farmers. One is cost and the other is dependability of supply. Most of the farmers operate under contracts which are written on a January-to-January basis. From the farmer's point of view, these contracts are becoming more onerous each year. Some contracts have even stipulated retroactive price increases. Price increases have been as high as 200 percent to 500 percent in some areas. The price of gas sold to farmers has gone up from 38 cents mcf (38 cents per 1000 cubic feet) to $1.85/mcf in two High Plains counties. It should be noted that the average prices of natural gas, as seen in Table 8, range from a low of $1.35/mcf to a high of $1.65/mcf. These farmers could

TABLE 7

Relative Importance of Energy Types Used in Pump Irrigation in the High Plains and Trans-Pecos Areas

District	Energy Type and Unit	Energy Used in Pump Irrigating in 1976 Season	BTU Per Unit	BTU Total	% of Total
1-N	Natural gas – cu. ft.	78,625,000,000	1,062	$83{,}500 \times 10^9$	97.8
	Electricity – Kwh	378,880,000	3,412	$1{,}293 \times 10^9$	1.5
	L.P. gas – gallons	6,076,000	96,000	583×10^9	.7
	Diesel – gallons	574,000	140,000	80×10^9	–
	All types	xxxx	xxxx	$85{,}456 \times 10^9$	100.0
1-S	Natural gas – cu. ft.	22,737,000,000	1,062	$24{,}100 \times 10^9$	93.3
	Electricity – Kwh	403,115,000	3,412	$1{,}380 \times 10^9$	5.4
	L.P. gas – gallons	3,500,000	96,000	336×10^9	1.3
	Diesel – gallons	60,000	140,000	8×10^9	–
	All types	xxxx	xxxx	$25{,}824 \times 10^9$	100.0
6	Natural gas – cu. ft.	3,286,000,000	1,062	$3{,}490 \times 10^9$	97.5
	Electricity – Kwh	10,810,000	3,412	37×10^9	1.0
	L.P. gas – gallons	544,000	96,000	52×10^9	1.5
	Diesel – gallons	33,000	140,000	5×10^9	–
	All types	xxxx	xxxx	$3{,}584 \times 10^9$	100.0
Three Districts	Natural gas – cu. ft.	104,648,000,000	1,062	$111{,}100 \times 10^9$	96.7
	Electricity – Kwh	792,805,000	3,412	$2{,}705 \times 10^9$	2.4
	L.P. gas – gallons	10,120,000	96,000	972×10^9	.9
	Diesel – gallons	667,000	140,000	90×10^9	–
	All types	xxxx	xxxx	$114{,}867 \times 10^9$	100.0

Source: Texas Department of Agriculture.

TABLE 8

Energy Used, Water Pumped and Cost of Fuel by Fuel Type, 1976 Season

Energy Used, Water Pumped and Cost of Fuel	1-N	1-S	6	Three Districts
1. Natural Gas:				
a) Energy used – MCF (000 cu. ft.)	78,625,000	22,737,000	3,286,000	104,648,000
b) Acre feet of water pumped	13,492,000	2,309,000	286,000	16,087,000
c) Acre feet per MCF (b ÷ a)	.171	.102	.087	.154
d) Cost of fuel per MCF (Dollars)	1.25	1.55	1.65	1.35
e) Cost per acre foot (d ÷ c) (Dollars)	7.31	15.20	18.97	8.77
2. Electricity:				
a) Energy used – Kwh	378,880,000	403,115,000	10,810,000	702,805,000
b) Acre feet of water pumped	788,000	1,264,000	24,000	2,076,000
c) Acre feet per Kwh (b ÷ a)	.00208	.00314	.00222	.00262
d) Cost of fuel per Kwh (Cents)	2.6	3.1	2.6	2.9
e) Cost per acre foot (d ÷ c) (Dollars)	12.50	9.87	11.71	11.07
3. L.P. Gas – Butane/Propane:				
a) Energy used – Gallons	6,076,000	3,500,000	544,000	10,120,000
b) Acre feet of water pumped	186,000	46,000	7,000	239,000
c) Acre feet per gallon of fuel (b ÷ a)	.0306	.0131	.0128	.0236
d) Cost of fuel per gallon (Cents)	30	30	30	30
e) Cost per acre foot (d ÷ c) (Dollars)	9.80	22.90	23.40	12.70
4. Diesel:				
a) Energy used – Gallons	574,000	60,000	33,000	667,000
b) Acre feet of water pumped	21,000	2,000	1,000	24,000
c) Acre feet per gallon of fuel (b ÷ a)	.0365	.0333	.0303	.0360
d) Cost of fuel per gallon (Cents)	35	35	35	35
e) Cost per acre foot (d ÷ c) (Dollars)	9.59	10.51	11.55	9.72

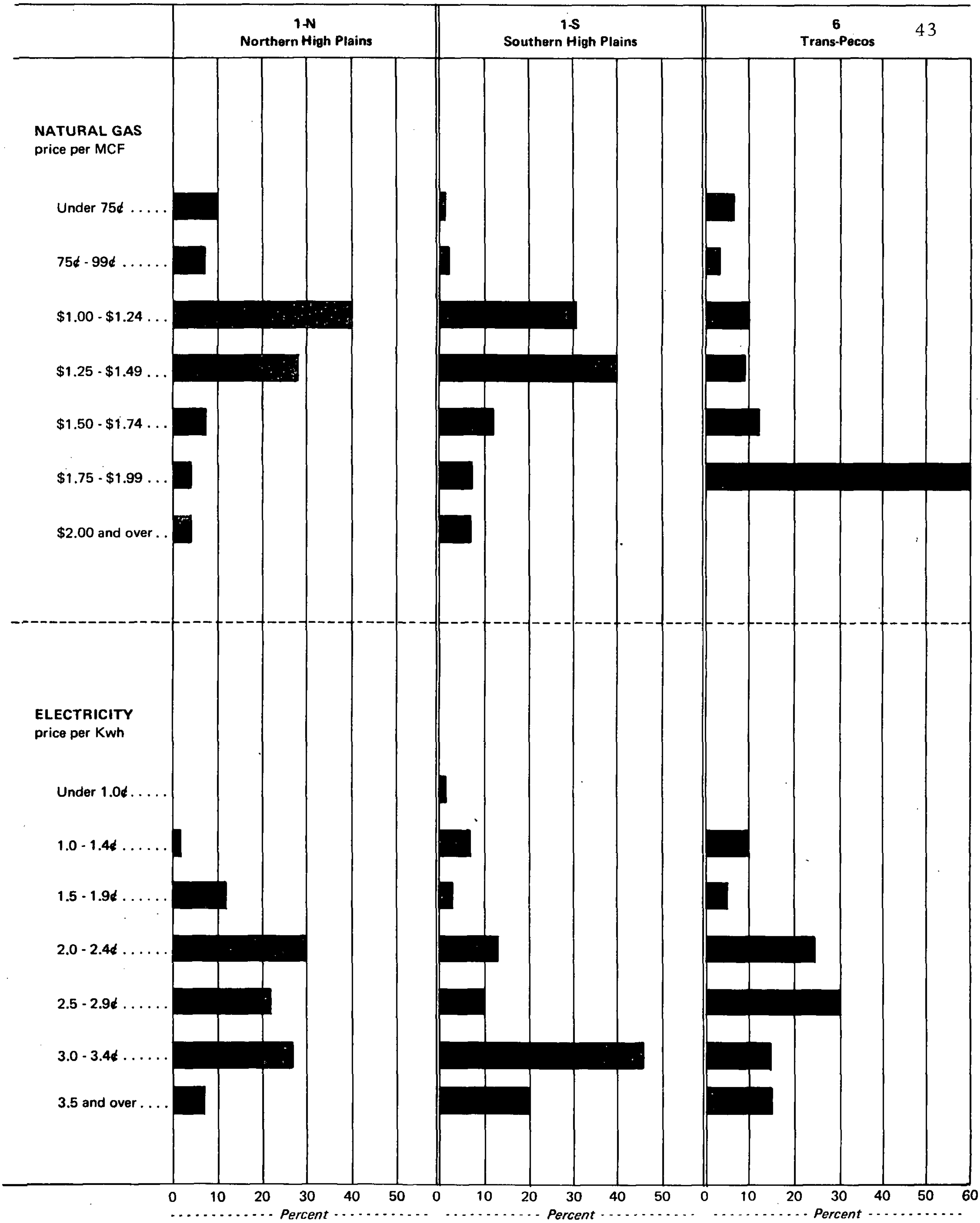
actually purchase the gas at a lower cost if it were delivered in an interstate pipeline. Figure 6 is a bar graph that shows the distribution of energy costs to farmers in the three regions.

Such fuel cost rises act to increase the prices consumers pay for farm products. The wheat crop of 1975 brought the farmers \$3.38 per bushel; the average price in 1976 was \$3.15 per bushel. The 1976 cost of production according to the Texas Agricultural Extension Service, was \$5.25 per bushel. The effect in the long run will be to drive up consumer prices and make farming less profitable. Figure 7 shows a series of graphs which represent how the inexorable market forces would drive up consumer prices.

Also of concern to the farmer is the dependability of the natural gas supply. If the prices go up, the farmer may be able to pass these costs on to the consumer. If the supply fails, the farmer is faced with a decreased or non-existent harvest. Many of the gas contracts stipulate that service may be terminated at the option of the pipeline companies with only 10 to 30 days' notice and with or without cause.

With regard to natural gas supply, the situation has become so undependable and the prices so high that the effects in two West Texas counties, Reeves and Pecos, have been extreme. Between 1975 and 1976, the number of acres used for irrigated agriculture was reduced from 150,000 acres to only 15,000 acres. Operations in these two counties might be

Price paid for energy used in pump irrigation by price ranges – Percent of producers by fuel type



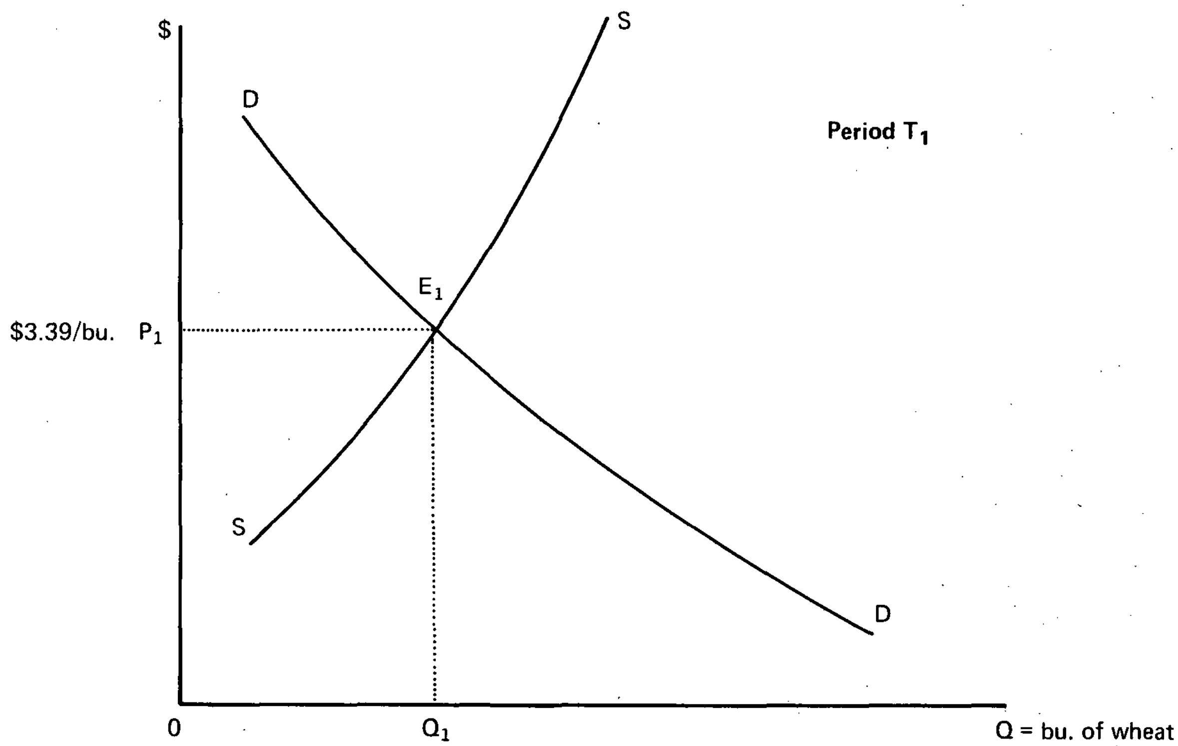
Source – Texas Dept. of Agriculture

FIGURE 6

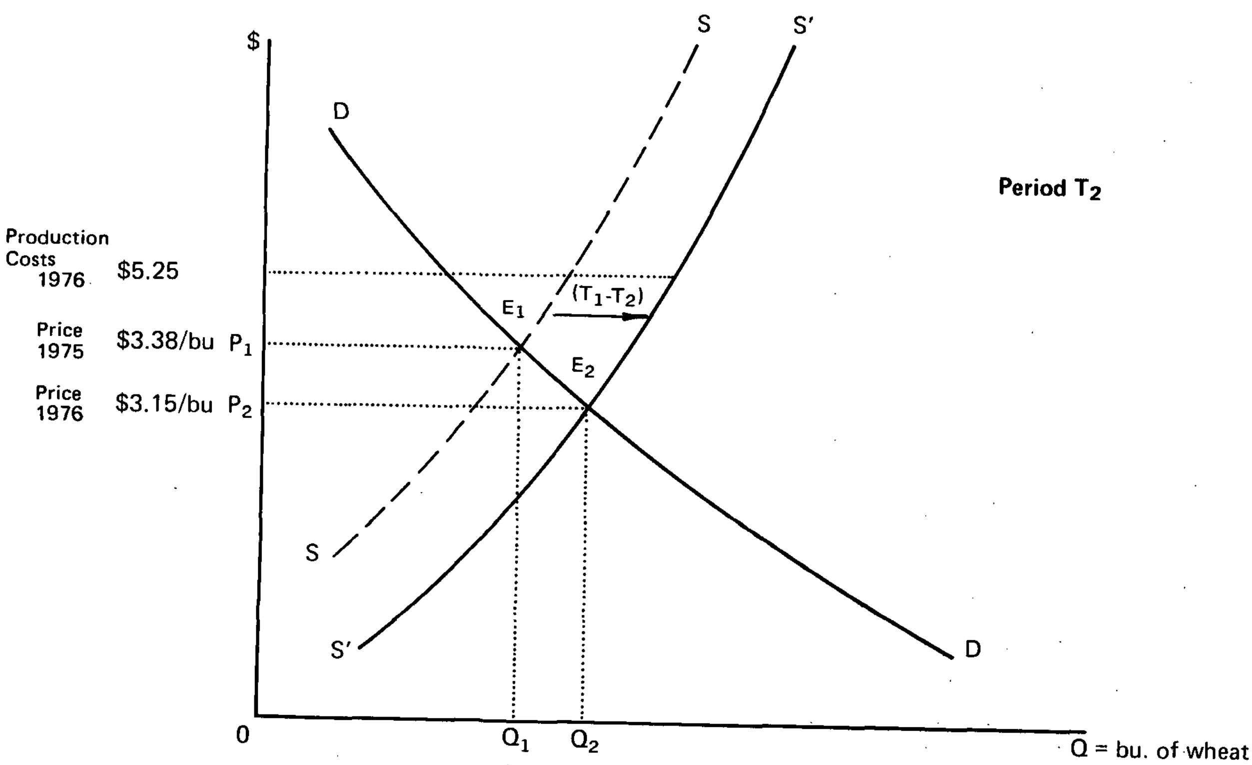
FIGURE 7

Consumer Prices and Fuel Costs

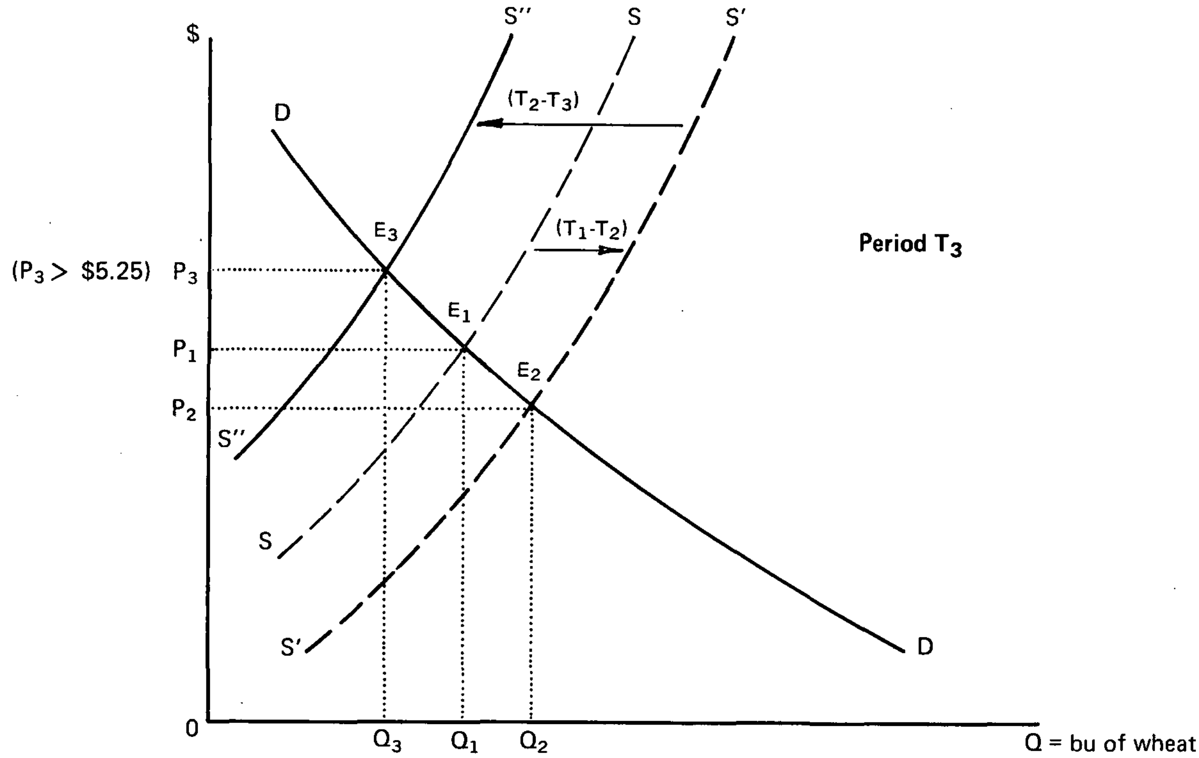
The following series of graphs are an abstract representation of the interaction of the market forces with regard to the supply and demand for wheat. (This does not purport to show the actual case since such factors as price and cross elasticities are not known.)



In time period T_1 (1975) market equilibrium (E_1) exists where wheat is selling at the price of \$3.38/bu. Farmers are willing to supply quantity Q_1. Buyers demand quantity Q_1 at that same price.



In period T_2 supply has increased and wheat is selling on the average for $3.15 per bushel. Assuming no changes in demand (reflected in the stationary demand curve), the new market equilibrium can be seen at point E_2. This is the point at which the new supply curve S′ intersects the demand curve. However, in 1976 the costs of production have risen to $5.25 per bushel. With a selling price of $3.15 per bushel, farmers will take a substantial lost. The likely response of farmers will be a cutback in wheat production as seen in the graph for T_3.



Obviously the actions of the individual farmer have no effect on the market price of wheat. However, if it is assumed that most farmers responding to the 1976 loss will reduce their wheat production, there will be a decreased supply available. In T_3 it is assumed that demand has remained the same while supply has decreased – manifested by a shift in the supply curve from S′–S″. The new market equilibrium point is E_3. This point is assumed to be at a price greater than $5.25 per bushel.

marginal with regard to other areas in the region; however, once the supply situation becomes serious enough in the rest of the region, similar reductions will occur.

Recent heat flow measurements taken in New Mexico (Reiter, et al, 1975) indicate a north-south pattern of temperature differentials as shown on the map (Figure 9). The north-south line divides the normal heat flow region which extends throughout most of the central and eastern United States, from the high heat flow region found in the western one-half of the country, particularly the Basin and Range Province of western New Mexico and southern Arizona.

The New Mexico heat flow work has indicated that the highest heat flow lies in general along the Rio Grande Rift. (This might mean that potential geothermal resources will be found only in the western one-half of the state.) This may indicate an unwarping of the mantle above even that of the regions of high heat flow elsewhere, with a crustal thickness of only 15-20 km beneath the rift zone. Alternatively, the rift could have a normal Basin and Range crustal thickness, but with extensive intrusive activity in the crust. Either of these two possibilities would lead to extremely high regional heat flow values, and to an even greater possibility for the occurrence of geothermal areas beneath this very anomalous province than beneath the general heat flow regions of the western United States.

This area in the high heat flow region is currently regarded as having high potential for the production of geothermal power. Currently in New

Mexico, there are several ongoing geothermal resource assessments, some of which are commercial, albeit on a limited basis.

The disposition of the high/normal heat flow division, once it crosses the Texas border, is unknown. There are good measurements of surface heat flow in the Pecos River valley of Texas and along an east-west line just north of the Texas-New Mexico border. The published heat flow measurements (Herrin & Clark, 1956) were obtained from studies of temperature measurements in oil wells in or near the Pecos River valley. These results indicate that the area east of a line between Carlsbad, New Mexico, and Fort Stockton, Texas, has a normal thermal gradient for the continental interior (about 1.1 cal/cm2 sec.). Thus, the dotted line on the map (Fig. 9) indicates the easternmost border of the potential high heat flow region. Of interest is whether or not the area to the west of the Pecos River valley--the Trans-Pecos (indicated on the map by the diagonal lines)--is in the high heat flow region. There are many reasons to seek additional information about the little known Trans-Pecos area.

Most of the geothermal exploration and assessment efforts have taken place in New Mexico. A few of the reasons for this are (1) the presence of readily observable, very young volcanic formations, (2) early and generous funding on the part of the State of New Mexico (the foresight and interest of

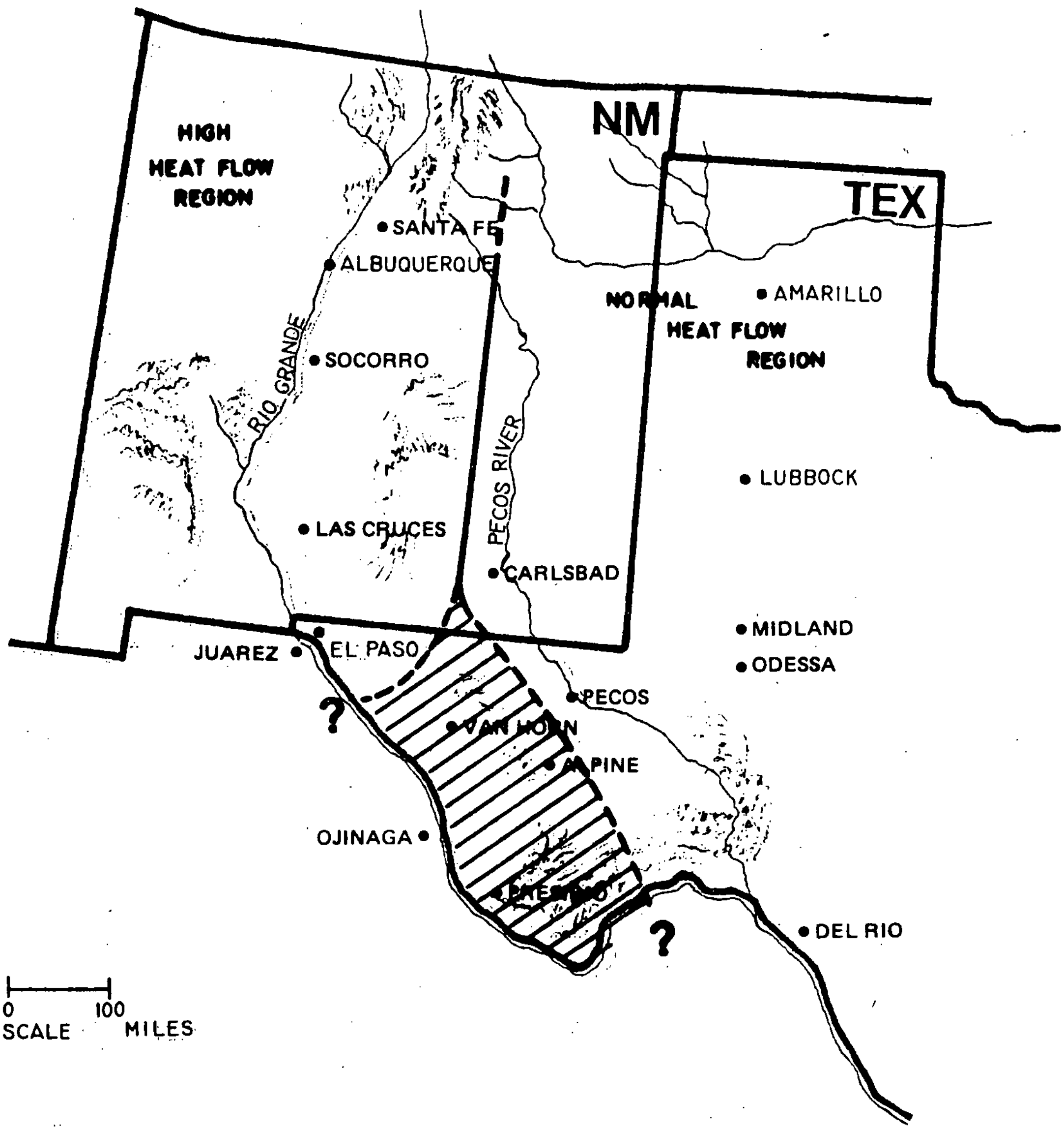

NM
TEX
HIGH
HEAT FLOW
REGION
SANTA FE
ALBUQUERQUE
SOCORRO
RIO GRANDE
LAS CRUCES
PECOS RIVER
CARLSBAD
NORMAL
HEAT FLOW
REGION
AMARILLO
LUBBOCK
MIDLAND
ODESSA
JUAREZ
EL PASO
PECOS
VAN HORN
ALPINE
OJINAGA
?
?
DEL RIO
0
100
SCALE
MILES

FIGURE 9

this state in alternative energy resources has been exceptional), (3) with better accessibility, this state was covered in earlier USGS geothermal resource surveys which did not include the Trans-Pecos for the most part. The need for geothermal resources exists throughout the Rio Grande Region as was seen in Savage's paper. However, this chapter will focus mainly on the geothermal indicators that exist in the Trans-Pecos. This limitation is partly because the information is relatively new and partly because much of the new data in New Mexico are proprietary.

Much of the information in this chapter came from papers presented at the El Paso meetings by the following persons: Jim Combs, University of Texas at Dallas; Joe Gevirtz, Resource Systems Research; Eugene Herrin, Southern Methodist University; Jerry Hoffer, University of Texas at El Paso; Frank Kottlowski, New Mexico Institute of Mining and Technology; Chandler Swanberg, New Mexico State University.

This chapter contains additional information gathered by the author from previous research efforts (his own and others) as well as an unpublished, recently written (subsequent to the conference) manuscript made available by Jim Combs.

Geological and Geophysical Setting

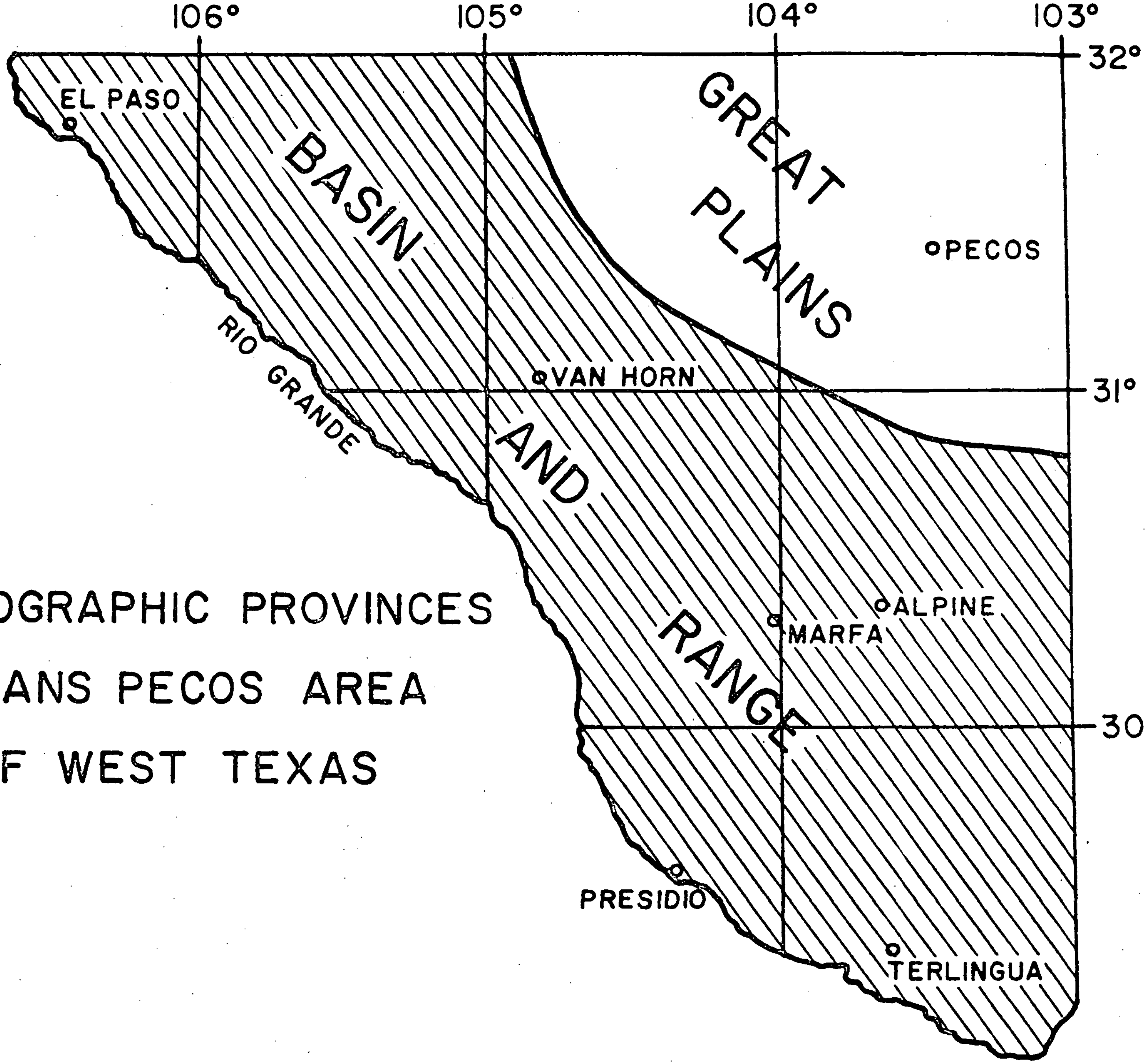
In an unpublished manuscript, Jim Combs describes the following geological setting:

> The State of Texas is centered on a Precambrian shield, the Texas Craton. Thrust against its southeast margin, during Paleozoic tectonic activity, is the Ouachita Folded Belt. Draped over the Ouachita Folded Belt is a Cambrian to Recent sequence of gently warped sedimentary rocks. To the north and west, a large basin area formed, primarily during the Permian. Erosion is now cutting through these Paleozoic sequences to form Tertiary and Quaternary sedimentary basins. To the south and east, deposition has been and is still building out toward the Gulf of Mexico. Fault systems (e.g., the Balcones-Luling-Mexia zone) tend to parallel the Gulf Coast in several belts from the Central Texas mineral region toward the coast. These fault systems have formed discontinuously from the Cretaceous to the Miocene. Intermittent tectonic activity is continuing to the present.

The "semi-stable" portions of West Texas, which are part of the Great Plains physiographic province described above, are significantly broken in the Trans-Pecos Area of West Texas by the tectonically active portions which are located in the southeastern part of the Basin and Range physiographic Province (Fig. 10). This highly faulted region, with its Basin and Range structural style, has been metamorphosed and subjected to several types of volcanic activity. The Trans-Pecos Area of West Texas appears to be situated in the southern extension of the Rio Grande Rift System.

Rio Grande Rift System

As mentioned above, the Rio Grande Rift System currently provides the most promise for potential geothermal resource development in New



PHYSIOGRAPHIC PROVINCES
TRANS PECOS AREA
OF WEST TEXAS

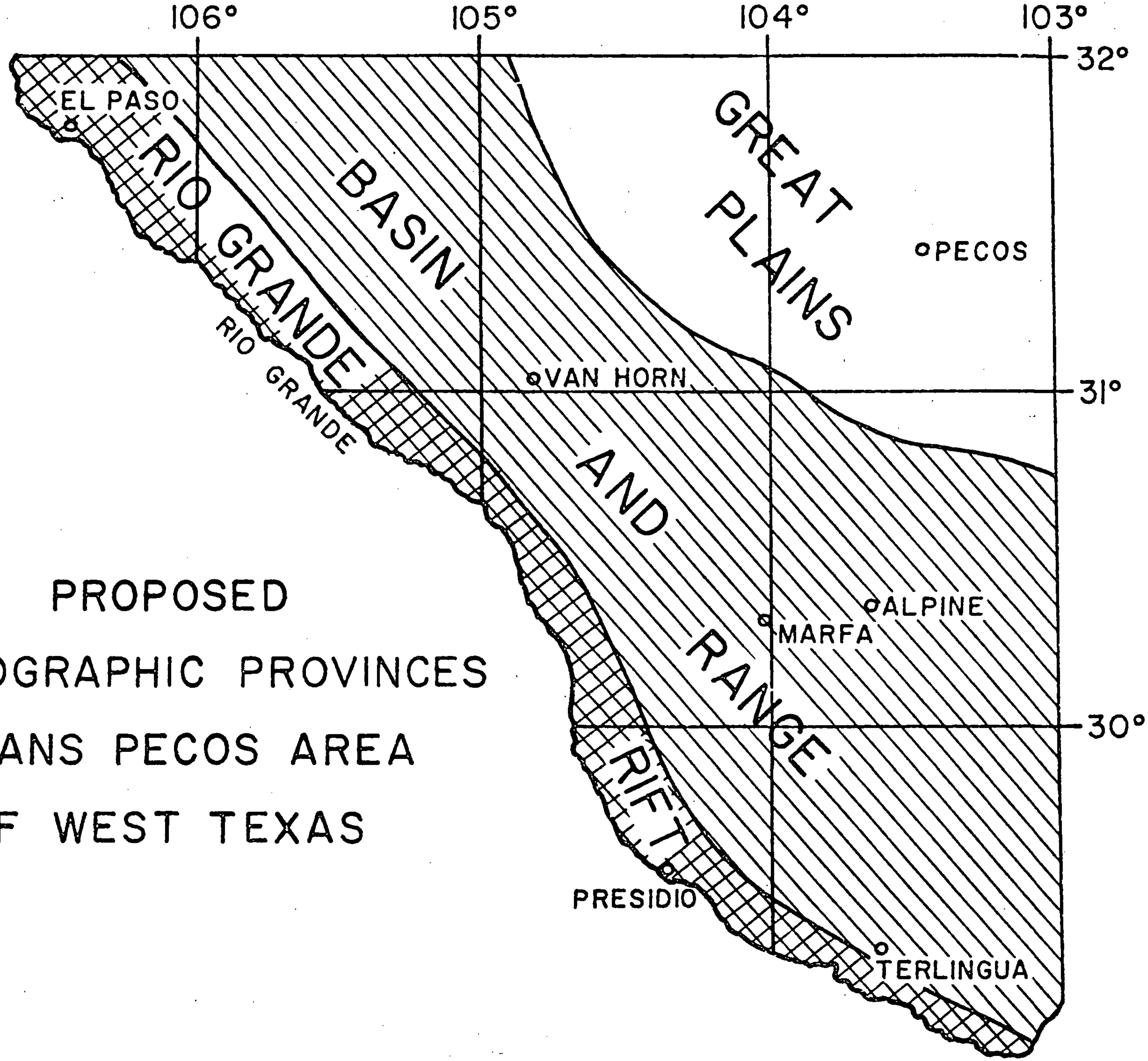
FIGURE 10

Mexico. There are many geological and geophysical similarities between the Rio Grande Rift System and such known geothermal resource areas as the East African Rift System and Salton Trough of Southern California and Mexico. The ongoing geothermal resource development projects, as well as the Mexican geothermal power plant at Cerro Prieto, are located along the Salton Trough.

Some geologists (McAnulty, 1975) claim that the Rift does not extend beyond the El Paso-Las Cruces area. However, this argument is countered with the presence of the warm springs in western Trans-Pecos, the earthquake epicenter in Presidio County, Texas, the available geomagnetic variometry data, the available heat flow data, and tectonism.

The potential for geothermal resources in New Mexico does not mean a priori that the same potential will exist in Trans-Pecos. On the other hand, there is no evidence to conclude that this potential may not continue into Texas. The map in Figure 11 shows the Trans-Pecos divided into three separate physiographic regions. In the discussion that follows, information will come to light that is purported to support the claim of a southward trending rift.

The map in Fig. 11 will become important later with discussions of the various distinctions between the Rio Grande Rift Zone and the rest of the Basin and Range Province in Trans-Pecos.



PROPOSED
PHYSIOGRAPHIC PROVINCES
TRANS PECOS AREA
OF WEST TEXAS

FIGURE 11

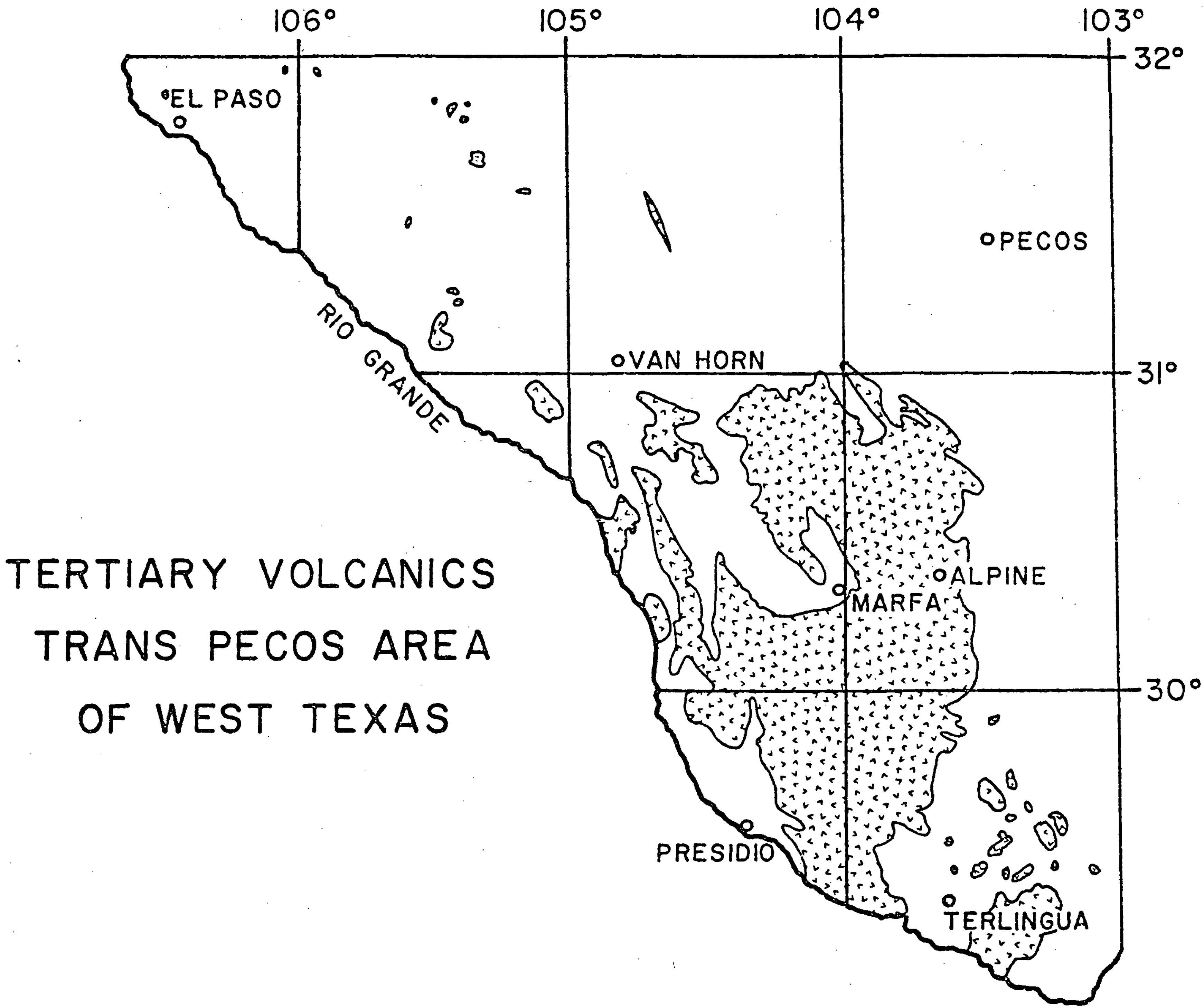
Tertiary and Recent Igneous Rocks

Again from the unpublished report, Combs has written:

In West Texas, there is a great variety of Tertiary Igneous rocks. The intrusive rocks range in composition from dioritic to granitic, and the extrusive rocks and andesitic to rhyolitic (Harvill, 1961; Burt, 1970). Intrusives, flows, and tuff deposits are all common, particularly in the Trans-Pecos region (Fig. 12). There are many types of volcanic eruptions, representing different eruptive centers commonly differing from and inter-fingering with each other and associated sediments. In addition, the relative stratigraphic relationships place most of them between the Upper Cretaceous and Upper Pliocene. Although there have been very few absolute age determinations made on igneous rocks from the Trans-Pecos area of West Texas, it is possible that some of the volcanic eruptions could be younger than Tertiary, since Quaternary flows are know to be located in the Basin and Range Province of New Mexico. The Tertiary sequence of ash flow tuffs and lava beds, ranging in composition from rhyolite to basalt and distributed through a thick section of clastic sediments, accumulated on a highly irregular surface of eroded Cretaceous and Paleozoic rocks (Maxwell and Dietrich, 1970).

Faults and Faulting

Faulting is a significant factor in most areas where geothermal resource development is being carried out. There is extensive faulting in the Salton Trough area on both sides of the U.S.-Mexico border. This faulting is expected in areas of recent tectonism. Fault zones provide avenues for circulating geothermal waters. Thus, they are likely sites for drilling operations.



106°
105°
104°
103°
32°
31°
30°
EL PASO
PECOS
RIO GRANDE
VAN HORN
ALPINE
MARFA
PRESIDIO
TERLINGUA
TERTIARY VOLCANICS
TRANS PECOS AREA
OF WEST TEXAS

FIGURE 12

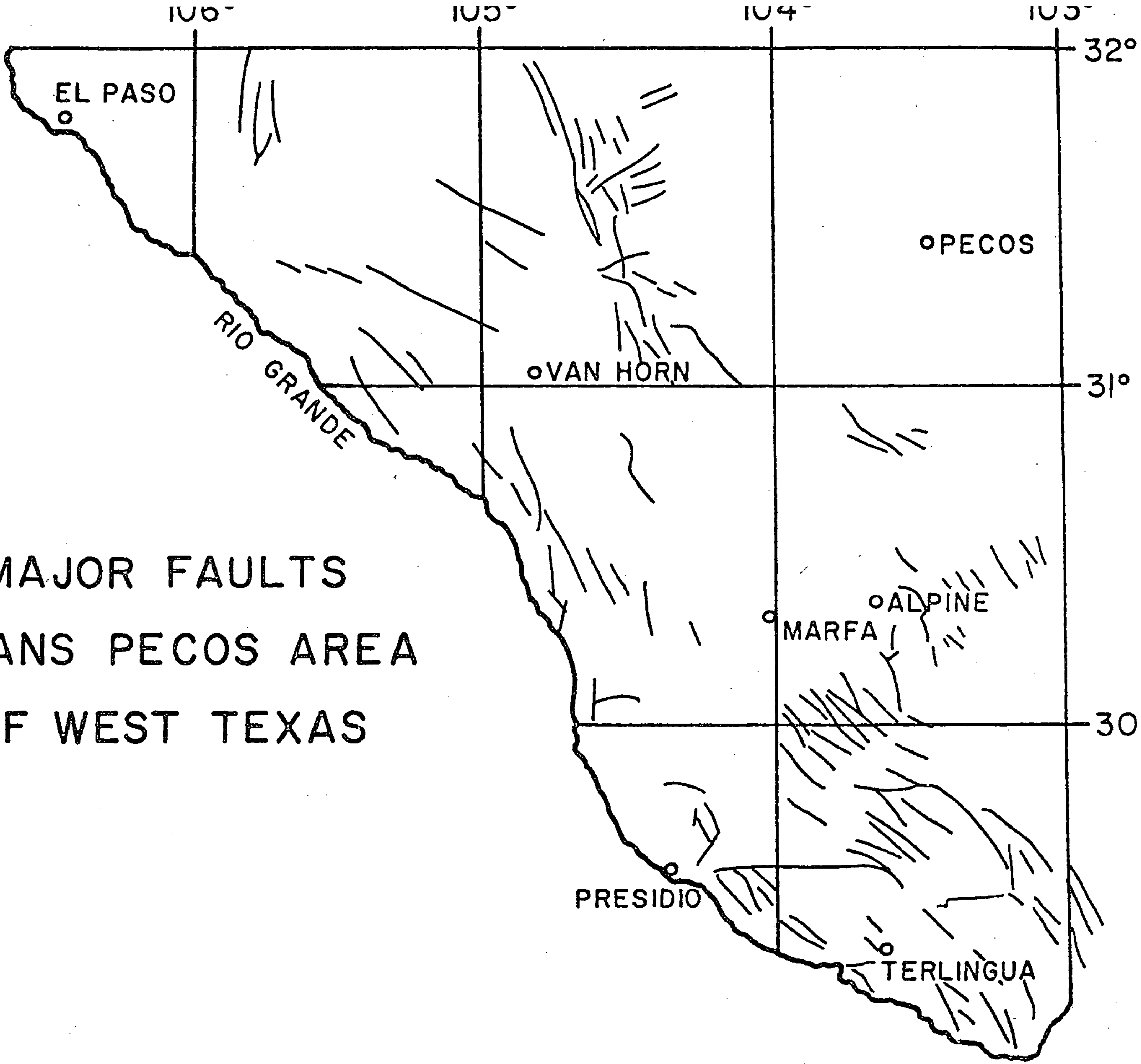
The Trans-Pecos region has numerous large faults, of the type that is important in localizing geothermal circulation (Fig. 13). This faulting is consistent with the structural style of the Basin and Range Province.

The Springs

The warm springs along the Rio Grande between El Paso and Big Bend National Park are legendary in that area. Some have been used at various times for recreational and medicinal (mineral baths) purposes. In the Trans-Pecos, these springs, "occur along the edges of the sedimentary basins (bolsons) at what appears to be the surface juncture of boundary faults," Combs wrote. He continued, "For example, Groat (1972) has noted several of these springs along the periphery of the Presidio bolson."

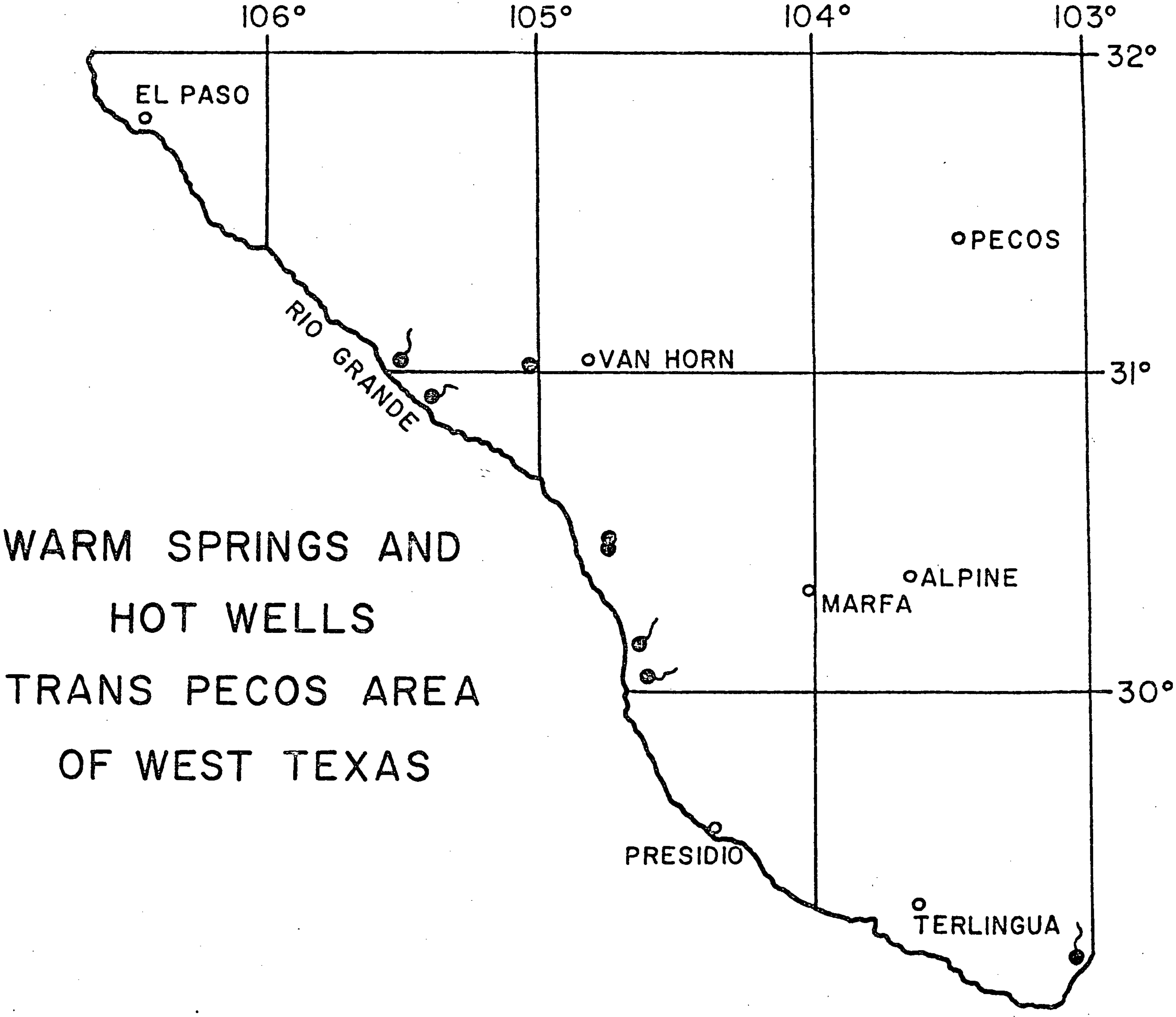
The Map in Figure 14 shows the locations of the five warmest springs and three warmest wells in the Rift Zone. The two springs west of Van Horn measured 38° C and 48° C. The two downstream springs are approximately 50° C. In Big Bend National Park there is a cluster of warm springs which have an average surface temperature of about 39° C. There are similar occurrences on the Mexican side of the border (Groat, 1972).

West of Van Horn is a well with 35° C water brought from a depth of 150 meters. The Gulf wells, two wildcat oil wells, are the hottest, with water of approximately 80° C from depths of less than a kilometer.



MAJOR FAULTS
TRANS PECOS AREA
OF WEST TEXAS

FIGURE 13


106°
105°
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EL PASO
PECOS
VAN HORN
RIO GRANDE
WARM SPRINGS AND
HOT WELLS
TRANS PECOS AREA
OF WEST TEXAS
ALPINE
MARFA
PRESIDIO
TERLINGUA

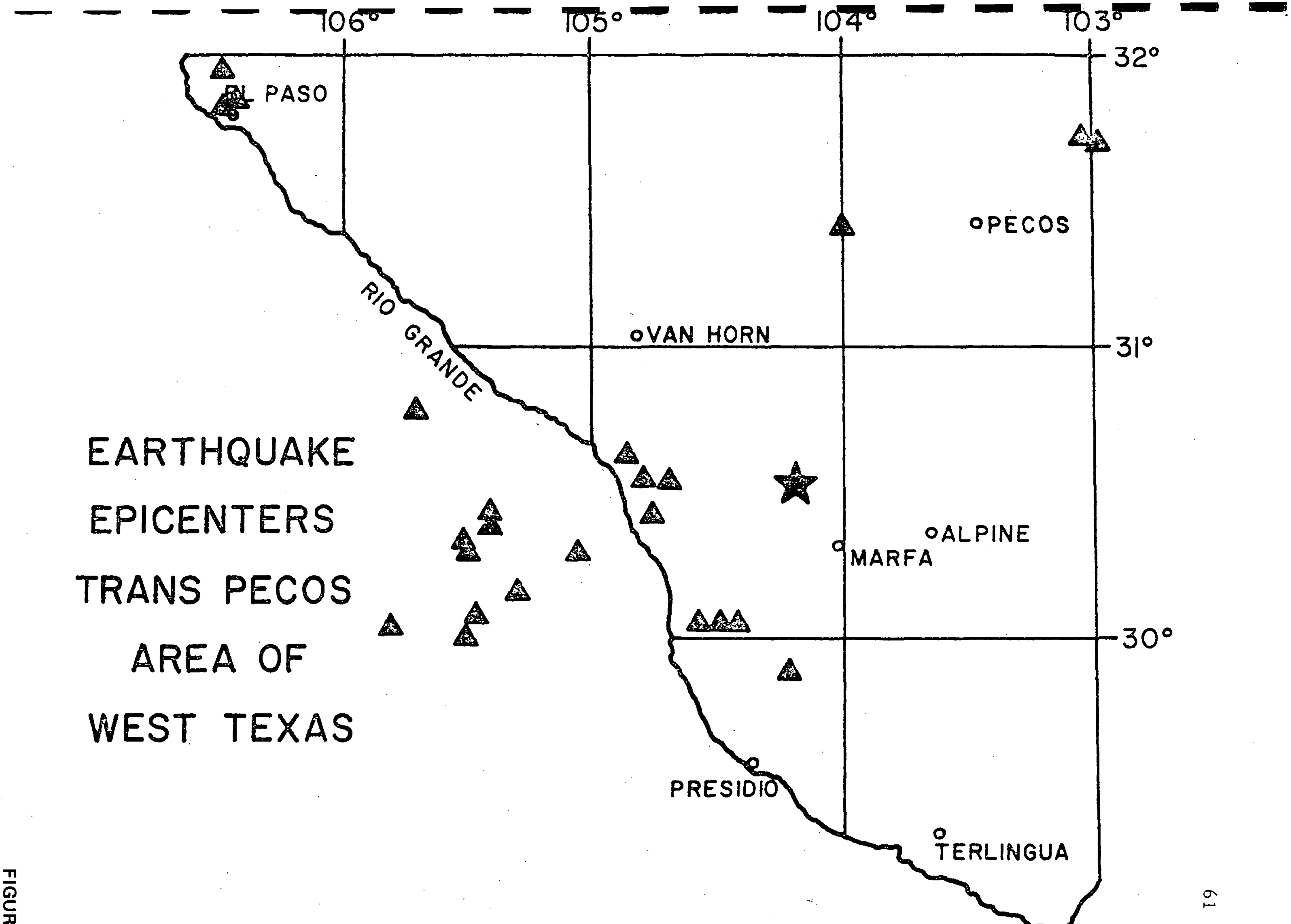
FIGURE 14

In summary, the Trans-Pecos area of West Texas is part of the Rio Grande Rift Zone. The Rio Grande Rift System, like the East African Rift System or the Salton Trough of Southern California and Mexico, seems to be associated with continental overriding of an active sea-floor spreading center. In the case of the Rio Grande Rift System, the spreading center is or was the probable extension of the East Pacific Rise and its associated convective system (Cook, 1969). It must be remembered, however, that due to the time dependence of cooling and deep temperatures, these geological features may have existed since Late Cretaceous or Early Tertiary, and evidence from surface geophysical exploration of an anomalously high state for the shallower crust is needed.

Earthquakes and Micro-Earthquakes

The Trans-Pecos is a seismically active area. A major earthquake (6.4 magnitude) occurred near Valentine, Texas, northwest of Marfa, in August 1931. The epicenter is marked with a star on the map in Fig. 15. This map also plots 24 other major quakes.

If the Big Bend Park is a potential earthquake area as indicated by the NOAA seismic risk map, then there should have been movement along the younger faults during the last 10,000 years. If this is the case, micro-earthquakes could still be occurring along the faults at this time. In the summer



EARTHQUAKE EPICENTERS TRANS PECOS AREA OF WEST TEXAS

FIGURE 15

of 1975, Eugene Herrin and John Waugh (unpublished data) established sensitive, portable seismic stations in the vicinity of Terlingua and Castolon near the western border of Big Bend National Park. Several micro-earthquakes were located as occurring to the west of the array. Herrin has subsequently measured significant micro-earthquaking from Terlingua, Texas to north of Presidio, Texas.

A team of geophysicists from the University of Texas at Galveston, working on a NASA project at the MacDonald observatory, have located continuous micro-earthquakes in the Davis Mountains.

The presence of micro-earthquakes can be a very important indicator of local geothermal anomalies (Cook, 1972). These micro-earthquakes can result from active faults where geothermal fluids may circulate. Micro-earthquakes have been recorded along fault zones in the Rio Grande Valley between Las Cruces, New Mexico and Albuquerque, New Mexico. This points out another similarity of the area along the Rio Grande in Trans-Pecos and that in New Mexico.

With modern portable seismographic equipment, it is possible to cover large areas in relatively brief time periods.

Water Chemistry Studies

Water chemistry studies are a valuable method of geothermal reconnaissance, in that such studies provide information on so many phases of geothermal development. For example, water chemistry studies have been used by a number of workers to estimate reservoir base temperatures, locate hidden geothermal systems, determine the origin and history of geothermal fluids, evaluate environmental effects associated with geothermal development and to assess the likelihood of encountering production problems such corrosion and/or scaling of geothermal hardware (Swanberg, 1974; Ellis, 1970; White, 1968, 1970; White et al., 1971; Fournier and Truesdell, 1973; Coplen, 1973; Mahon, 1966; Fournier and Rowe, 1966; Ellis and Mahon, 1964; Mathias, 1974; Yanagese et al., 1970).

While the carbonate formations are a good distance from the area of interest, migrating alluvial material from this terrain is rich in carbonate debris. Therefore, it is to be expected that groundwater derived from the alluvial basins (bolsoms) are enriched in calcium and magnesium.

Nonetheless, the geothermometers have provided us with a relatively cheaper first cut estimate of which areas might be anomalous. Indeed, the results of these findings raise more questions than they answer. However, they are the sort of questions that lead to even more reliable estimates of the geothermal resource potential in the area.

In applying both silica (SiO_2) and sodium-potassium-calcium (Na-K-Ca) geothermometers to over 600 groundwater samples in the Trans-Pecos, Swanberg and Herrin (1976) have shown considerably higher temperatures in the Basin and Range Province than in the Great Plains. Based on SiO_2 measurements, the geotemperatures in the Basin and Range Province averaged 90°C with a typical range of 75°C to 120°C. Whereas in the Great Plains, the same sorts of measurements averaged 65° with a typical range between 45° to 85°C.

Both geothermometers indicated the Gulf well south of Van Horn (see Fig. 14) as being anomalous. The predicted reservoir base temperature was approximately 180°C. The well currently discharges water at 82°C.

These findings are consistent with similar results obtained by Jerry Hoffer and his group at the University of Texas at Dallas. The Hoffer group collected 722 water samples from all of the Basin and Range Province in the Trans-Pecos area.

The Hoffer findings indicated three locations were most promising geothermal areas:

1) Two hot springs in Presidio County.
2) One location south of Marfa.
3) One location east of El Paso.

These measurements are of interest to those involved in geothermal resource research and are fine, as far as they go, However, Swanberg and Henry pointed out in the El Paso meeting that there were several difficulties that could make the geothermometers less than wholly reliable. In a volcanic terrain, it is possible for amorphous silica to be present that is not the result of geothermal heat. Also, there is the problem of dilution from migrating waters. These factors can have serious effects on the results. The Na-K-Ca geothermometer is subject to error in an area which has carbonate and/or evaporite formations in the vicinity, as is the case in Trans-Pecos.

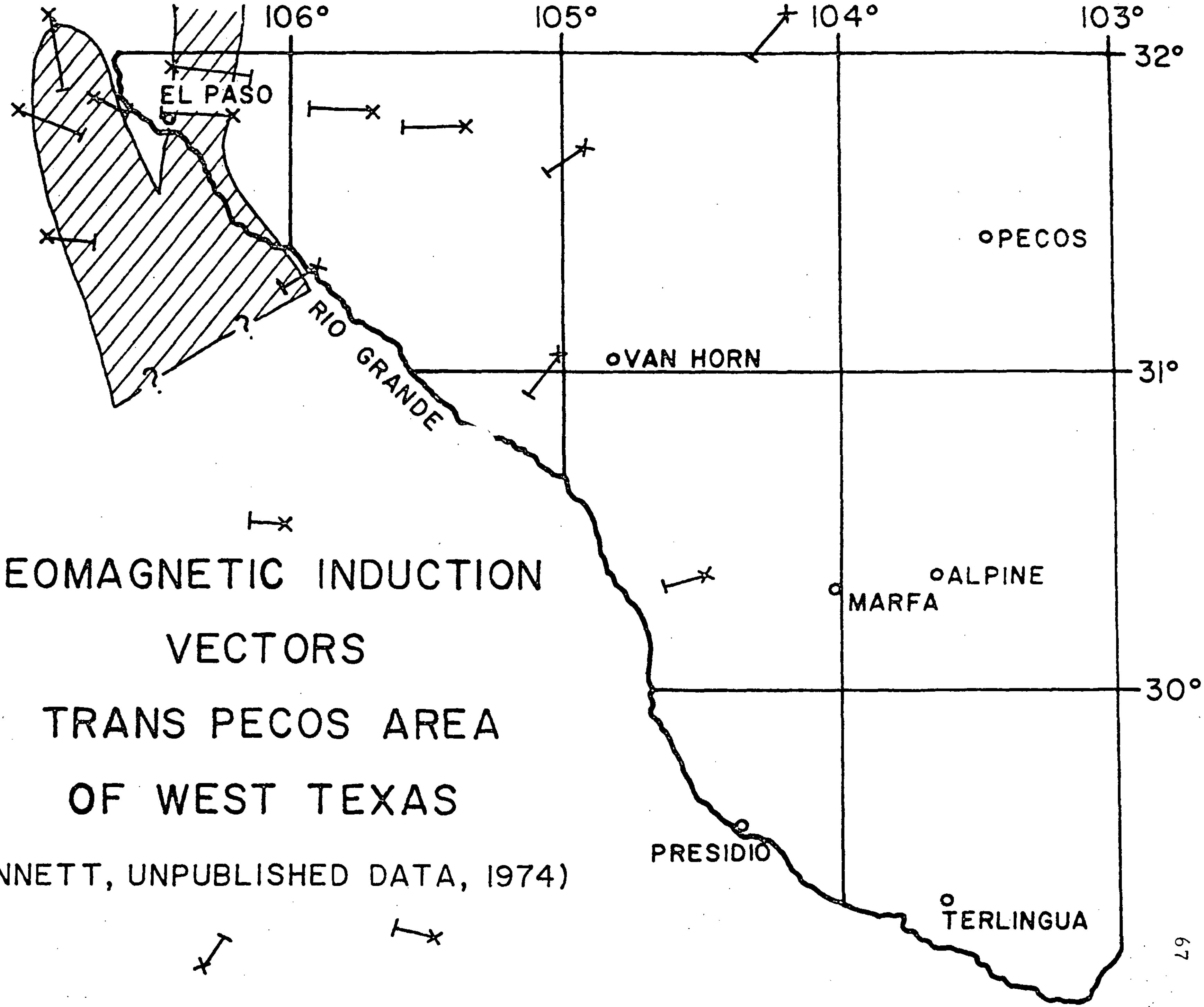
Geophysical Setting

The following description of the geophysical setting has been provided by Jim Combs.

> Several types of regional geophysical surveys confirm an anomalous mantle structure for the Basin and Range portion of the Trans-Pecos Area of West Texas. For example, anomalous short-period geomagnetic variations are expected above an elevated electrical conducting layer, usually implying a local high temperature zone in the crust and upper mantle. The Texas Anomaly (Schmucker, 1964; 1970) where a north-south step-type conductivity is suggested, has been cited as a typical example. The high electrical conductivity step at a depth of 160 km toward the west changes to a depth of 320 km on the east under Cornudas, New Mexico, with a shallower 150 km-wide highly conductive ridge between Las Cruces and Cornudas. Magnetotelluric and heat flow data substantiate this anomaly. When projected along the 32

degree north latitude, all of the data imply a thermal imbalance in the upper mantle with a 1200° C isotherm which is at a depth of 75 km on the west and 200 km toward the east (Warren et al., 1969).

Recently, an array of thirty geomagnetic variometers were deployed at thirty-three sites in the Trans-Pecos area of West Texas, in southern New Mexico, and in northern Chihuahua province, Mexico (David Bennett, unpublished data, 1974) to examine in detail the Texas Anomaly of Schmucker (1970). Several of the geomagnetic induction vectors for a period of about 30 minutes have been plotted in Fig. 16. A major electrical conductivity boundary runs southward near El Paso. Vectors west of the boundary generally point southeast and tend to increase as the boundary is approached. These observations are consistent with those of Schmucker (1970) whose broader-scale study was located just to the north of the El Paso area. Furthermore, the feature defined by Bennett (unpublished data, 1974) is probably a shallow crustal conductive volume caused by high temperature and partial melting in the intermediate-to-deep crust. Both conductive features (the Texas Anomaly of Schmucker and the El Paso Anomaly of Bennett) are probably manifestations of the same regional tectonics; i.e., upwelling of the mantle beneath the Rio Grande Rift Zone.



GEOMAGNETIC INDUCTION VECTORS
TRANS PECOS AREA
OF WEST TEXAS

(BENNETT, UNPUBLISHED DATA, 1974)

FIGURE 16

Deep crustal seismic studies east of and adjacent to the Trans-Pecos Area do not indicate any type of crustal thinning or anomalous velocities. Rather they imply a gradual change from a 60 km-thick crust in the Texas panhandle to 30 km along the Gulf Coast (Warren and Healy, 1973). However, no single, long, seismic profile is located anywhere in the region of interest. Subcrustal velocities are typically 7.9 km/sec below southern Arizona, western New Mexico, and the Basin and Range portion of Trans-Pecos Area, whereas the Great Plains province of West Texas is characterized by P_n velocities of 8.0 km/sec or greater (Herrin, 1969). Isostatic gravity models indicate compatible results (Decker and Smithson, 1975). Although few of these data have been gathered directly from the region of interest, it appears certain that anomalous upper mantle temperatures exist beneath the Trans-Pecos Area.

Heat Flow Data

The following discussion of heat flow measurements comes entirely from the unpublished report of Jim Combs:

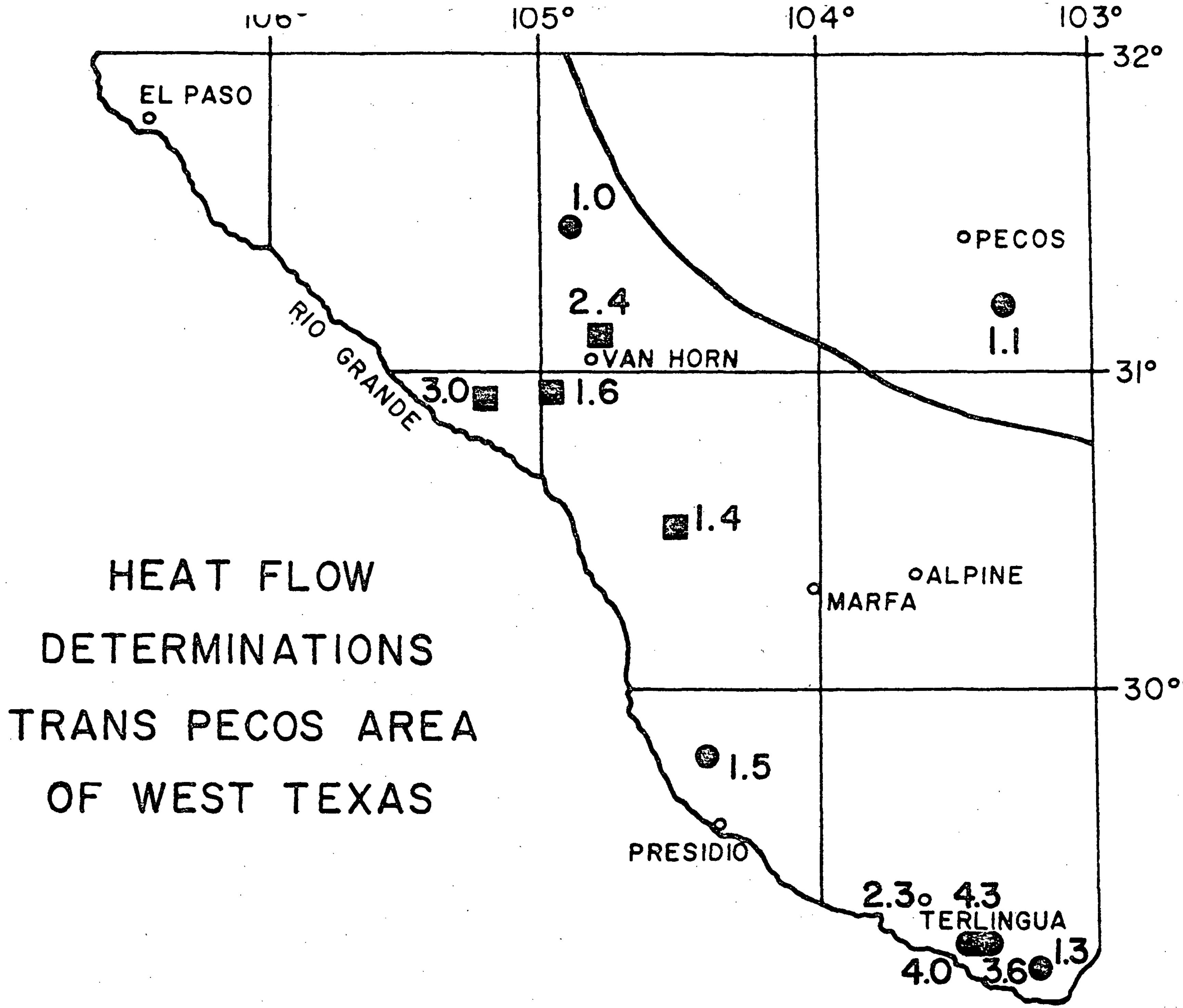
> Heat flow surveys provide valuable data on the distribution of heat within the shallow subsurface and on the rate of temperature increase with depth. In other words, thermal exploration techniques provide a

direct method for assessing the size and potential of a geothermal system (Combs and Muffler, 1973). Heat flow determinations are the most effective geophysical technique for locating subsurface geothermal anomalies. Broad regions of anomalously high heat flux can be defined by a few carefully located heat flow boreholes. If the regional heat flow so determined is significantly higher than normal, we can infer the presence of hydrothermal convective systems and/or young, hot intrusive rocks.

Exploration based only on geothermal gradient measurements is often considered sufficient to indicate the presence of a geothermal area since the lowest gradients measured over a geothermal anomaly are usually about 2 to 10 times higher than the average regional geothermal gradient. When the mean thermal conductivity of the subsurface is essentially constant throughout the complex in which boreholes are drilled, the thermal gradients measured are obviously proportional to the heat flow values. However, one essential advantage of heat flow measurements, as opposed to only making gradient measurements, is that heat flow is independent of the in situ thermal conductivity of each rock type. Therefore, in nonhomogenous terrains as those of the Trans-Pecos Area of West Texas, only heat flow measurements enable us to obtain accurate information on the potentially productive geothermal zones. Secondly, by obtaining heat flow determinations and not simply gradient determinations, the effects of convective heat transfer associated with geothermal systems can be readily identified.

Many heat flow investigations and measurements have shown high heat flow and high temperatures in the New Mexico portion of both the Basin and Range province and Rio Grande Rift (Warren et al., 1969; Roy et al., 1972; Reiter et al., 1975; Decker and Smithson, 1975). As has been discussed above, several surface features attest to the continuation of these anomalous conditions through the Basin and Range province of West Texas. The heat flow determinations from the Trans-Pecos Area of West Texas are presented in Figure 17. The solid circles indicate published values (Herrin and Clark, 1956; Decker and Smithson, 1975; Swanberg and Herrin, 1976) whereas the solid squares are preliminary values derived by the principal investigator using published temperature and geological data (Gates and White, 1976). These heat flow values indicate that portions of the region are characterized by abnormally high subsurface temperatures and potential geothermal systems.

The heat flow values of 1.1 HFU reported by Herrin and Clark (1956) southeast of Pecos (Fig. 17) and of 1.0 HFU reported by Decker and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RIO GRANDE
3.0
1.6
1.4
ALPINE
MARFA
1.5
PRESIDIO
2.3
4.3
TERLINGUA
1.3
4.0
3.6
HEAT FLOW
DETERMINATIONS
TRANS PECOS AREA
OF WEST TEXAS

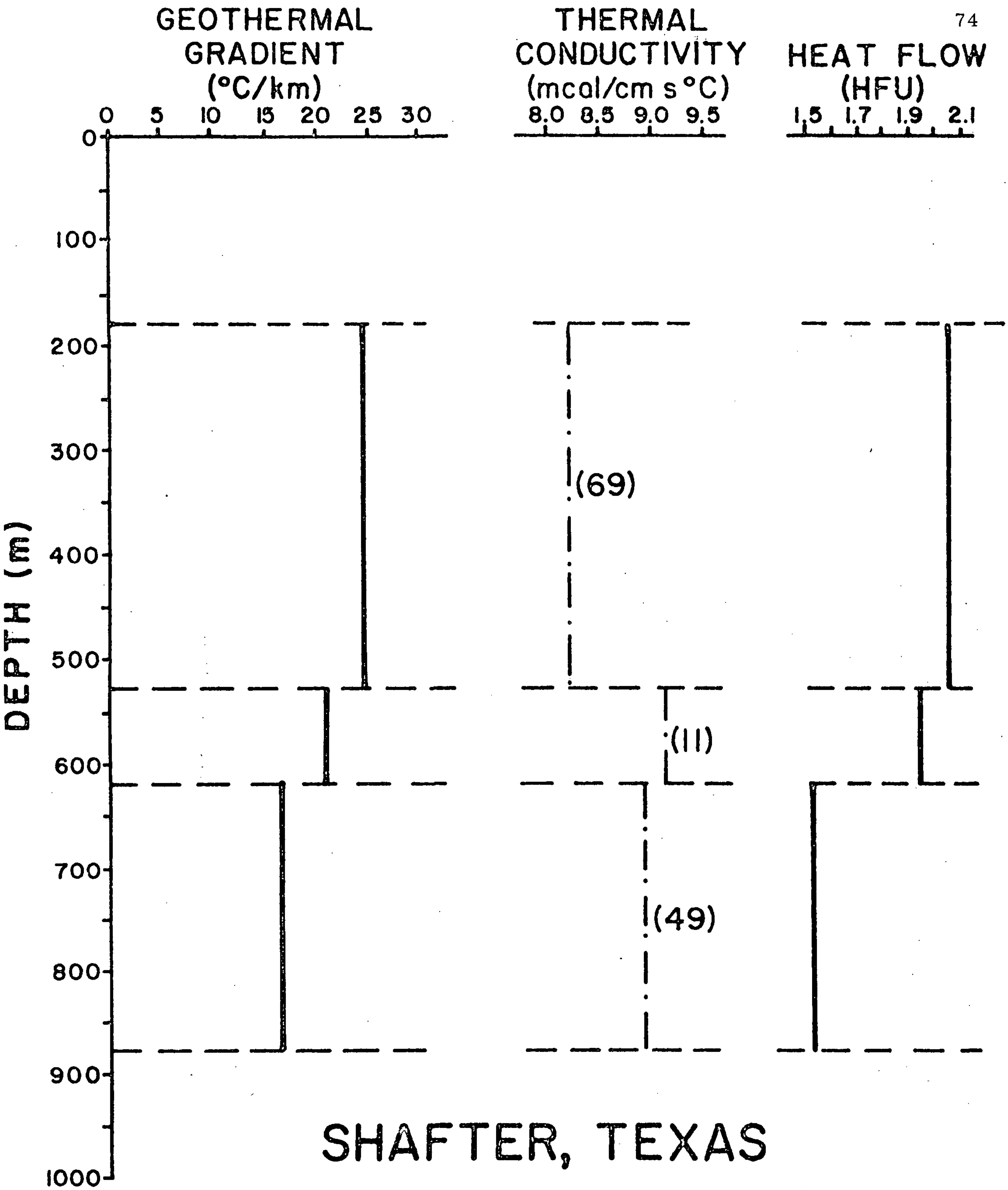
FIGURE 17

Smithson (1975) indicate that the Great Plains province of West Texas is a part of the normal heat flow province of the stable interior of the United States. Additionally, the heat flow of 1.3 HFU reported by Swanberg and Herrin (1976) from the Big Bend National Park implies that some of the Big Bend region lies within the Great Plains normal heat flows province.

The Basin and Range Physiographic province of the western United States is considered to be a high heat flow province although heat flow values vary greatly throughout the entire Basin and Range. As can be seen in Fig. 17 there is considerable variability in the West Texas portion of the Basin and Range. The heat flow value of 1.5 HFU near Schafter, north of Presidio, of Decker and Smithson (1975), as well as the 1.4 and 1.6 HFU localities, all appear to be anomalously low for the Basin and Range. Even though these boreholes penetrated both sedimentary and igneous rock types, i.e., sandstone (1.4 HFU), tuff (1.6 HFU) and monzonite porphyry (1.5 HFU), all three determinations are low because of the effects of convective heat transfer.

If heat transfer in the subsurface is due totally to a conductive transfer mechanism, the measured heat flow will be a constant throughout the entire depth of the borehole. However, if there is a significant amount of convective heat transfer the increases or decreases in the geothermal gradient as a function of depth are not offset by corresponding decreases or increases in the thermal conductivity. Numerous investigators have argued that since basement rocks and igneous bodies (plutons) have very low porosities and permeabilities, there is essentially no convective heat transfer in these types of rocks. Therefore, by drilling boreholes into these rock types, reliable conductive heat flow determinations can be obtained without the problem of groundwater circulation and the resultant convective heat transfer that is encountered in many sedimentary environments. However, as demonstrated in Figure 18 the decrease in the value of heat flow as a function of depth is obviously the effect of convective heat transfer in the monzonite porphyry pluton.

Similarly, the effects of convection are seen in the data of Swanberg and Herrin (1976) for the Big Bend region. A single deep well penetrating below the local water table yields heat flow values of 3.6 and 1.0 HFU, respectively, for sections of the well above and below the water table. In both of these cases, the local heat flow is characterized by the high values of 2.1 and 3.6 HFU rather than by the low, convectively disturbed, values of 1.0 and 1.5 HFU, respectively.



SHAFTER, TEXAS

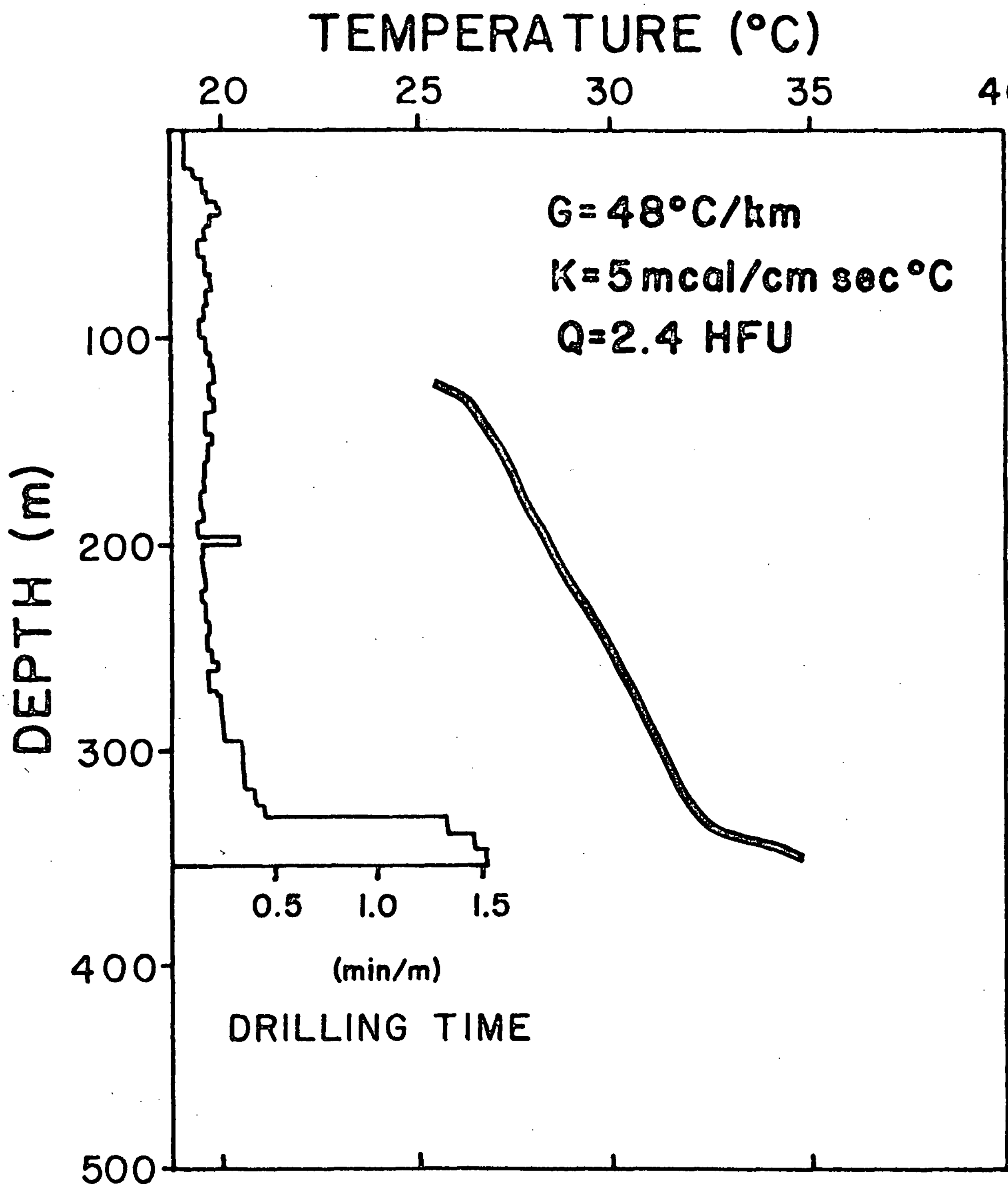
(DECKER AND SMITHSON, 1975)

FIGURE 18

The new heat flow deteminations indicated by solid squares in Figure 17 were obtained by using the temperature data, geophysical logs, and geological information published by Gates and White (1976). Since the geological information provided rock type by using the geophysical logs to provide constraints on the porosity, estimates for the thermal conductivities could be obtained. Heat flow values were derived by combining these estimated thermal conductivities with the temperature data of Gates and White (1976). An example is presented in Figure 19. Although these four preliminary heat flow values will need to be verified by more precise temperature and thermal conductivity measurements, they provide a further indication that the Basin and Range province of the Trans-Pecos is indeed a high heat flow province.

Data Synthesis

Standard geothermometers can be a valuable tool in providing low cost rough estimates of the resource potential of a region. However, as Swanberg and Henry have indicated, there are certain problems inherent in the use of this technique. The process of locating specific highly probable geothermal resource sites will require more information, in both quantity and sophistication, than is available from the SiO_2 and Na-K-Ca geothermometers. This will be particularly true with regard to test well site selection and evaluation.



GUERRA NO. 1 TEST HOLE

(GATES AND WHITE, 1976)

FIGURE 19

J. L. Gevirtz of Resource Systems Research presented the workshop with a discussion of techniques to : (1) better assess the information gathered in geochemical surveys, and (2) relate the geochemical findings to autonomous geophysical data from other sources.

After noting the inherent problems associated with employing standard geothermometry, Gevirtz states:

> Therefore, other, more subtle indices of reservoir temperatures must be sought. Information already available consists of a fairly complete suite of geochemical analyses of waters collected from springs and wells throughout West Texas, some heat flow measurements, general geology, and varieties of geographic information. At the time of this conference, the geochemical and the general geologic information is most extensive. [There exist] ... strategies by which reliable indices of reservoir temperatures may be extracted from the information already available...

In order to avoid some of the problems that result from relying solely on SiO_2 and Na-K-Ca assessments, Gevirtz recommends a broader assessment. He states:

> In situations where mineralogy of country rocks leads to ambiguous interpretation of these geothermometers, or where groundwater regimes are complex, all quantitative relationships among elements should be evaluated with respect to aquifer lithologies from which waters were obtained. No doubt some of these relationships will reflect nothing more than these lithologies, but if sufficient information concerning enough elements is available, some relationships may reflect water-rock equilibria and can serve as semi-quantitative geothermometers.

The evaluation efforts described above lead to the establishment of mappable geochemical provinces. Once the provinces are established, it becomes possible to assess the other geological and geophysical data in an organized framework. Relationships between water chemistry and geologic features such as fault trends and dated igneous rock bodies may be established. Those areas in which water chemistry is apparently unrelated to local geology are anomalous. Such chemical anomalies would be of interest.

Through a procedure known as the Unweighted Pair-Group method of cluster analysis (Sokal and Sneath, 1963; Sneath and Sokal, 1971) data from numerous water sources can be analyzed simultaneously. The procedure is capable of indicating previously unsuspected relationships that exist among elements in the groundwater of the region. Also, because data are displayed as hierarchical relationships, all possible groups can be quickly evaluated with respect to their relationship to the existence of a potential geothermal resource.

The data are arranged in an array in which each row represents a sample and each column represents an element. Based on certain assumptions about the nature of the data and their mathematical and statistical properties, the analyst will make the requisite decisions concerning scaling of data and other suitable analysis measures. (For detail, see Sokal and Sneath, 1963; Sneath and Sokal, 1971; Gevirtz, Park and Friedman, 1971; Gevirtz and Rowe, 1977.)

Gevirtz describes subsequent iterative process as follows:

> Assuming that these decisions have been made, a symmetric matrix containing pariwise similarities representing relationships between possible pairs of samples (Q mode) or all possible pairs of variables (R mode) is computed from the distributional information in the original or scaled data array. This similarity matrix is equivalent to a covariance matrix if standard variables are compared using the multidimensional extension of Pearson's product-moment correlation coefficient (r). From this similarity matrix, the sample or variable pair showing the highest similarity (lowest in-space distance) is extracted and a new sample is created by averaging the variables for the two items (samples or variables). This average sample replaces the two original samples. The matrix is reduced by one row and similarities involving the two original samples are recomputed using the new average sample.

The process described above is repeated until the original matrix has been reduced to triviality. The results of the process described above are displayed in a dendogram, such as shown in Fig. 20. A dendogram is a polynodal graph representing the structure of theoriginal similarity matrix. The graph will demonstrate the hierarchical nature of the relationships. The fartherest left boxes represent relationships between individual samples while movement to the right increases the number of samples included in the group.

The classification procedures have associated problems of partitioning "the system into discrete portions somewhat arbitrarily assigning boundaries between groups." To overcome this problem, Gevirtz describes a companion

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FIGURE 20

technique which will "enable visualization of important geochemical, geological and geophysical gradients."

To do so, he employes measures of dissimilarity. Once obtained, the results can be presented as a multidimensional scatter diagram.

Synthesizing procedures described by Gevirtz permit more comprehensive assessment of the geothermal resource potential of an area. The advantages of the analytical techniques described by Gevirtz are:

(1) No initial assumptions are required.

(2) Input of samples yields samples in the final result (not aggregates of samples).

(3) Allows easy investigative machine iteration.

(4) Results are mappable.

(5) Model will accept mixed-mode data with biasing results.

(6) Each level of the heirarchy can be evaluated by the researcher.

(7) A suite of samples is arranged in a manner that permits ready interpretation.

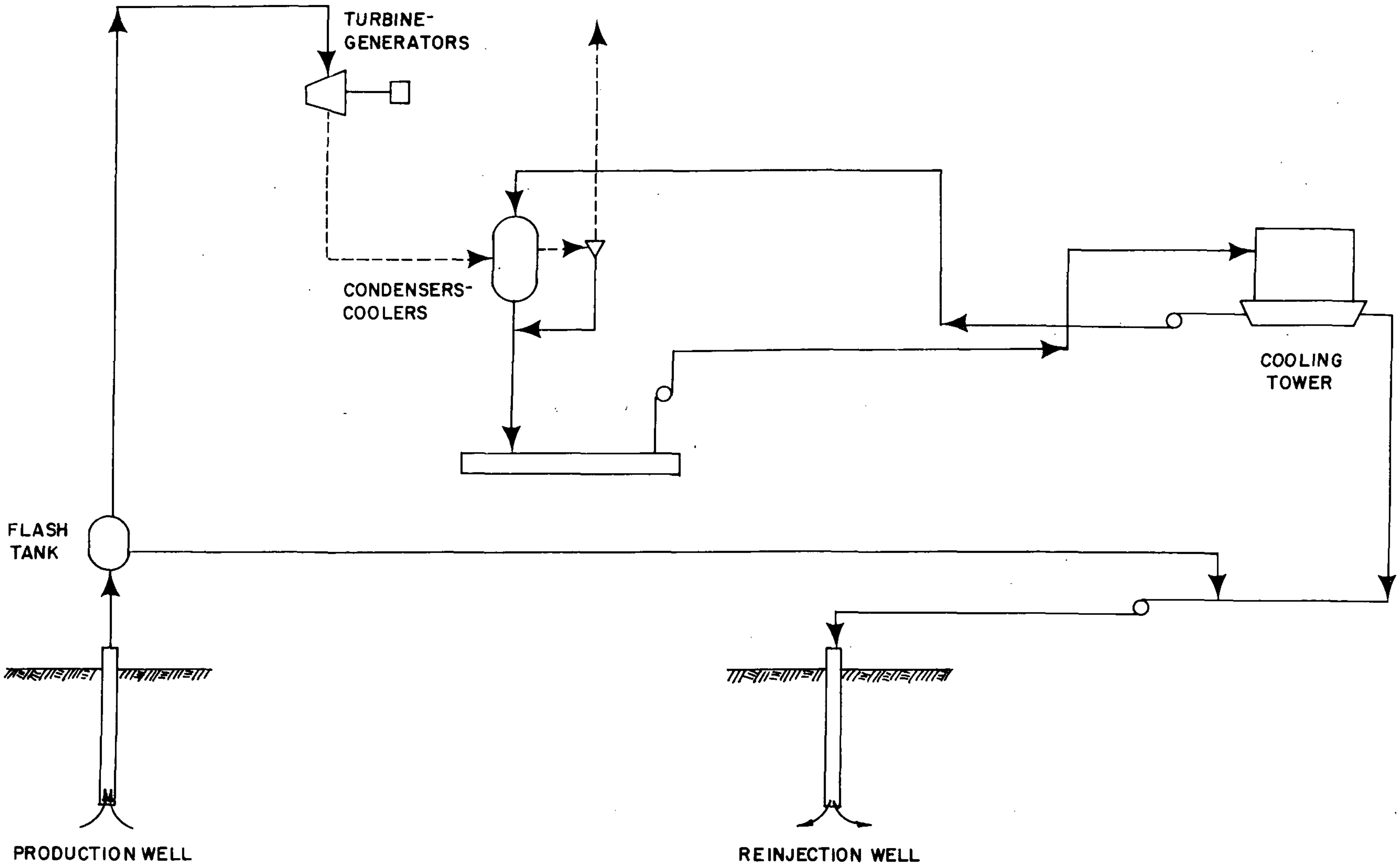
Introduction

The following discussion of the environmental aspects of geothermal resource development comes entirely from the paper presented by R. D. Sadow of Turner Collie & Braden Inc., Houston, Texas. The author has made only a few minor editing changes to the original paper with its comprehensive and concise treatment of the subject.

Geothermal Process Systems

This paper treats the environmental aspects of the two most likely methods of electrical generation. In the flashed steam cycle (Figure 21), fluid is usually received in a liquid state whereby it is flashed by expansion down to a lower pressure, then piped to an expansion turbine driving a generator. The let-down exhaust is condensed, noncondensible gases ejected, and the condensate pumped to a wet-type cooling tower, the blow-down of which is injected back into a suitable geological formation.

The binary fluid cycle (Figure 22) involves transferring heat from the original hot geothermal liquid (unfortunately few simple dry steam fields are available for development) to a closed-loop power fluid using heat exchangers. The power fluid is expanded through a turbine-connected generator. The hydrocarbon-based power fluid is then cooled, condensed, and pumped back to the exchangers. Cooling towers are used for heat reduction loads,



FLASHED STEAM CYCLE

FIGURE 21

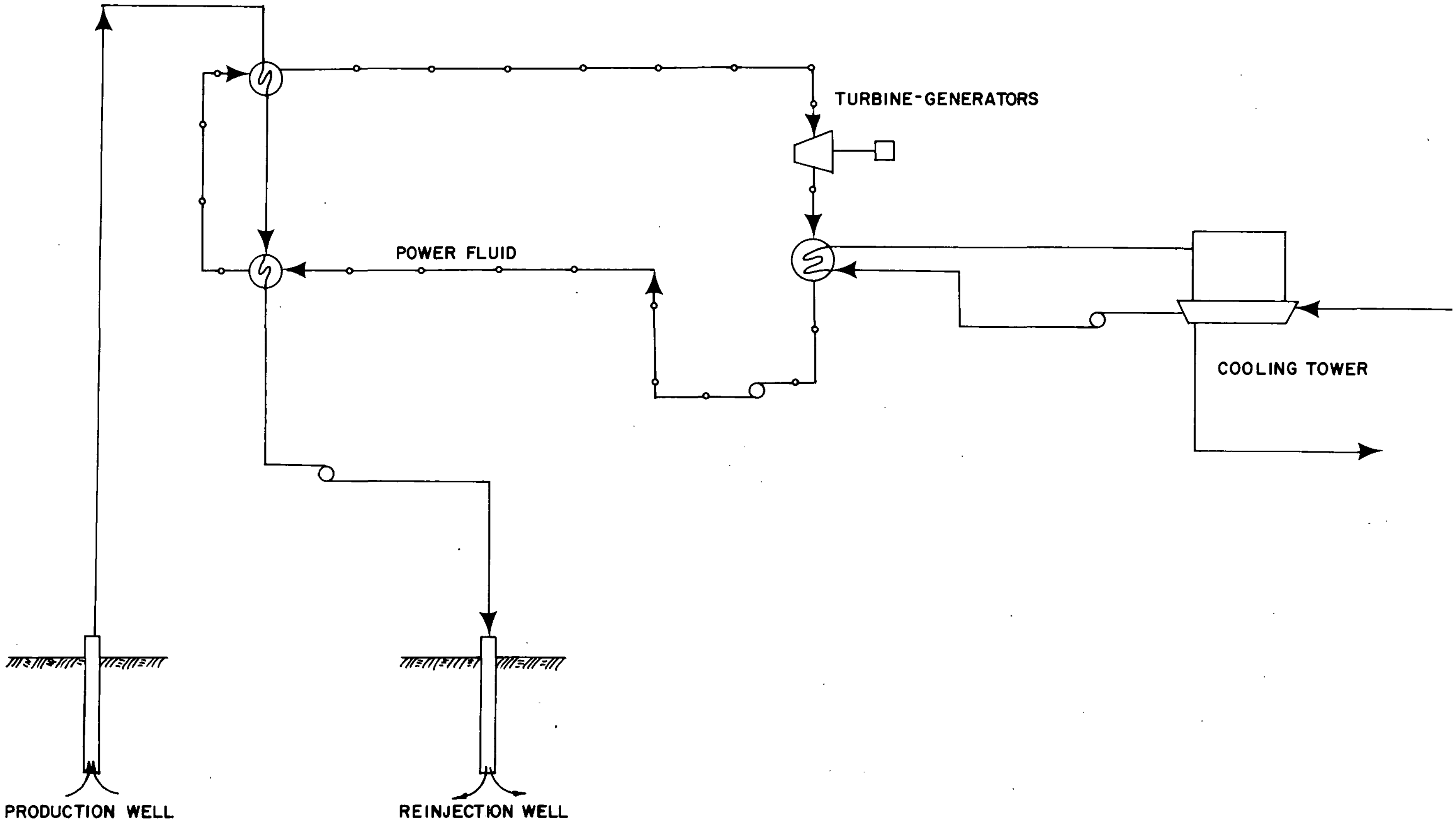


FIGURE 22

BINARY FLUID CYCLE

and the spent geothermal liquid is injected back into the formation. Unlike the flashed steam cycle, no direct contact of geothermal fluid with the turbine and condensing system occurs; however, a source of cooling water (if wet towers are used) is required.

Environmental Influences

Certainly the further development of geothermal energy in the United States gives rise to various regulatory, institutional, and environmental difficulties.

Lists have been developed in the past involving real, probable, or even imaginary environmental impacts. Rather than dwell only on these prognostications, this paper will attempt to categorize and mention the techniques that may be applied to ameliorate them. Evaluations of the actual impacts, their magnitude, and type of applicable recognition and control is needed for each new situation. In most cases existing technology for monitoring and minimizing their adversities is now available.

Water

Inherent in the use of connate or natural hot waters is the fact that these highly mineralized liquids and vapors are not compatible with above-ground environments or even conventional liquid steam-handling equipment.

Various amounts of sulfates, alkaline hydrozides, heavy metals, mixed inorganics, sulfur, carbonaceous, and nitrogeneous compounds are present. High temperatures, exchanger scaling silicates, and related insolubles pose not only significant environmental, but engineering problems as well. Some native fluids range up to 250,000 mg/l (or 250,000 ppm) of the dissolved residues or solids.

In Texas, for instance, receiving waters must not exceed a 85° -98° F (Fahrenheit) temperature (depending on location) nor is a freshwater ambient temperature rise of over 3° -5° F allowable. Heavy metals such as arsenic, boron, barium, lead, mercury, zinc, etc. cannot exceed a range of 0.005 to 5 mg/l concentration in wastewater effluents. Chloride levels depend on location but should not exceed a concentration of 100 to over 5,000 mg/l within the body of water itself. Other states have similar regulations with temperatures and salts being even more restricted in the more northern latitudes.

Both the flashed steam and binary fluid units have a similar potential for receiving water contamination due to their inherent withdrawal and blow-down of formation waters.

Air

Most geothermal waters contain measurable amounts of carbon dioxide, hydrogen sulfide, methane, ammonia, and similar noncondensibles.

Many of these are in trace concentrations that, when discharged from condenser ejectors and wet-type cooling towers of flashed steam plants, do not cause a significant air emission and quality problem.

Due to the ease of recognizing hydrogen sulfide (H_2S) odors (usually at 0.0002 ppm and above) coupled with typical ambient air standards of 0.08 ppm by volume, it is seen that source concentrations of even 30-50 mg/l pose problems. Roughly, two-thirds of the contained sulfides are soluble in the cooling waters of flashed steam plants. This is done by forming elemental sulfur particulate so that none are discharged in the gaseous state from the binary fluid cycle units.

Noise

Besides the rotating equipment involved, the main source of somewhat intensely localized noise levels is from various well head silencers, venting and condenser ejector utilized in the ordinary flashed steam plants. Generally, these are typical noises found in most fossil-based utility plants also.

Geophysical

Subsidence, local geological deformation, and tilting could be the most potentially significant environmental influences brought about by geothermal fluid extraction and utilization systems. In various areas of the world where extensive groundwater withdrawal for domestic uses is practiced, significant and damaging settlement of local formations (some 7-1/2 feet in 30 years just east of Houston, Texas for example) has occurred.

Thus, one concern is whether or not a direct relationship can be expected in geothermal systems between pressure changes induced in the geological lenses and ground deformation that might result. Both horizontal and vertical stresses and strains might occur due to compaction and seismic incidents, and deep tectonic adjustments can result. Even minor stresses or changes can result in serious surface movements.

Geothermal production can result in vast fluid withdrawals (1,000-1,500 gal/min./well) from multiple drilled wells over a relatively large bore field. The possibilities of infringement on existing water rights and related hydrologic elements should also be considered.

Ecological

All resources involving the ambient air, water, and land are affected by geothermal energy production. These may include local wildlife and fishery habitats, air and water quality, domestic grazing, timber (not in Texas), landscape utilization, and allied resource outputs.

Aesthetics

Any man-made alteration of an area raises the subject of visual form or aesthetics. Geothermal energy plants are more like chemical or natural gas-processing installations than a fossil-fueled or nuclear reactor unit. Usually they would be located in rather remote regions, sometimes surrounded by rising, waving plumes of steam and fugitive fogs. Inherently, the natural landscape patterns would be altered by roads, pipelines, pressure relief batteries, power transmission structures, and lines.

Effects and Preliminary Conclusions

The overall prospects for geothermal power and usage relates to technical and economic feasibilities and environmental acceptabilities. This low grade energy source, although diffuse in nature, appears to have significant potential for commercial power and heat transfer applications.

Water

Considering the mineralized, hot effluents involved, it is apparent that ordinary discharge to a receiving body of water such as the Rio Grande, without extensive final treatment, will not be feasible. Both flashed and binary cycle plants share this problem. As practiced in some geothermal installations, wastewater reinjection into compatible receiving formations is required to minimize environmental impacts.

The technology of reinjection is well developed by the oil-gas exploration and chemical industries. There are about 40,000 brine and 1,200 other wells involving groundwater recharge and waste disposal. Over 200 industrial waste injection wells are regulated and operated in Texas alone.

It is necessary that any reinjection process recognize scale build-up tendencies, horizontal permeabilities and backpressure relationships, temperature interfaces and depletions, and ultimate reservoir performance. Given proper conditions supporting a reliable well reinjection program, the overall waterborne implications would seem to be a minimal impact.

Air

There is little opportunity for controlled noxious vapors to be emitted from a binary fluid cycle plant. If wet cooling towers are used (contrasted to air coolers), nearby surface waters are used for tower makeup and local freshwater aerosols are formed.

Flashed steam cycle units utilize both condenser steam jet ejectors and cooling towers (wet or dry, depending upon cooling ranges required) where sulfides and other noncondensibles are discharged to the atmosphere. Hydrogen sulfide gases can be oxidized thermally or with the use of various iron-based catalysts, with ultimate discharge back into the formation after sulfur particulate filtration removal. Thus impacts can be significant for the clashed steam unit if noxious gases are present, but minimal for the binary process.

Noise

Technology exists for muffling, shielding, and accoustically treating emission sources to minimize decibel exposures. Generally these noise minimizations are of most importance to the plant workers. Inherently, the binary fluid cycle plant emits less noise than the flashed steam cycle plant due to the absence of pulsating gas ejector batteries in the binary fluid cycle plant. Thus the overall impacts are not markedly significant.

Geophysical

Potentially, the most severe impact created by either the binary fluid or flashed steam cycle plant is the possibility of local tectonic changes in the earth's crust related to fluid withdrawal. The occurrence of this alteration is related to many factors, including rates and locations of withdrawal, faulting mantle structures, thermal changes, porosities, etc.

Subsidence is the direct result of compacting layers in the substrata and usually assumes an inverted cone shape in intensity. Subsidence, like other earth movements, is essentially irreversible with pressure rebounds of only some 5 percent possible through recharging pressurization.

The results of uneven subsidence, horizontal movements, and other unforeseen events can lead to significant property damage, changes in drainage patterns, and related liabilities. However, geothermal production facilities will frequently be located in relatively uninhabited, rural areas where the effects would not be as severe as in the more populous areas. The subsurface environmental disturbances, with their surface manifestations, can only be guarded against through geological investigations and subsequent control networks and survey monitoring. Predictive assessment remains inexact, but appreciably indicative, and constitutes one of the main considerations of any geothermal project. Balancing aquifer withdrawal with recharge rates is an allied study requirement.

Ecological

The possibility of any significant ecological alterations as a result of geothermal production activity is not considered significant, given the proper handling of effluents. Changes in wildlife patterns, vegetation, and natural resources would be well localized and profound changes would occur only in and around the actual power plant and heat extraction area. (If resource utilization stimulated nonelectric users to relocate in the vicinity, the ecological impacts could be more extensive. Such a contingency would have to be anticipated as development provided more information about the resources.)

Aesthetics

Natural landscape patterns, visual effects, open space shapes, and forms will be altered by any localized development and construction. Initial construction and movement activities could cause the most noticable, although temporary, disruption.

The permanent adverse effects are considered to be fewer than those connected with fossil-fueled plants. The impact is not considered overly significant as long as pleasing design and proper master planning techniques are used.

CHAPTER VII

INSTITUTIONAL PROBLEMS AFFECTING THE DEVELOPMENT OF GEOTHERMAL RESOURCES

A number of institutions can play an important role (either positively or negatively) in the development of geothermal resources. These include federal agencies, state agencies, the geothermal industry, local residents and environmentalists, and foreign institutions. (In the Trans-Pecos area, there is a possibility of geothermal reservoirs which would lie below both sides of the United States-Mexican Border.) The interests of each of these groups would, depending on the circumstances, involve one or more of the various stages of development:

1. resource exploration
2. land acquisition (state owned or private)
3. resource development
4. resource distribution
5. resource consumption

Marlan Blisset, L. B. J. School of Public Affairs, University of Texas at Austin, has raised a number of questions that relate to the institutional considerations involved in development of geothermal resources. He focuses on the gaps in the structure of those institutions which deal with development, on identifying those who have a stake in resource development and use, and on the effort to identify the decision-making apparatus. The most important question he raises at this time in the predevelopment stage is, "What are the inadequacies in the law governing or applicable to geothermal resource development?"

Problems of Definition

Regarding the future of national geothermal resource development, Blissett feels that, "Current statutory definitions of geothermal energy may be inimical to the rapid development of the resource. In fact, the majority of definitions do not encompass one or more of the geological, hydrological, and thermodynamic characteristics associated with geothermal systems."

In reviewing the body of law that governs resource development, there is no agreement among the various states as to what geothermal resources are. As Blissett points out, the various states' laws do not consider the total resource system. What is the resource: water, gas, mineral or something else?

The California law considers the heat of the earth as part of the definition, but it makes no mention of the heat flow rate. Blissett notes, "The Act addresses contaminants of heat transfer media, but apparently excludes the media themselves."

In Oregon the definition of geothermal resources is narrowed to those anomalies where the bottom hole temperature (of the well) is greater than 250° F and the heat is used for the production of heat energy. The State of Washington's statutes are even more narrow. The definition considers only those resources that are practical for commercial production of electricity.

This, of course, would exclude low and moderate temperature resources which might be used in process heating or other activities. The 1970 Federal Geothermal Act did not take into consideration the geopressured geothermal reservoirs, some of which contain relatively large amounts of methane gas.

When considering the statutory problems that could occur if resource development gets underway in the Rio Grande region, precedent does not provide a useful model. Indeed, such examples bear out Blissett's contention that:

> The statutory approach to geothermal energy has been too restrictive, for it has failed to treat the individual elements of the resource as integrated components of a unique resource system. This failure has implications for every aspect of resource development--from questions of resource ownership to the regulation of energy and associated products from geothermal formations.

Resource Ownership

The question of resource definition becomes more than merely academic once resource ownership comes under consideration. In Texas, water resources belong to the surface estate and not the subsurface mineral estate--frequently not owned by the same parties. One additionally complicating factor in Texas is the existence of the geopressured geothermal resources along the Gulf Coast. As mentioned above, methane gas exists in solution in many of these reservoirs. Existing bodies of law would cover the extraction of this mineral resource, but do not treat the potential heat and kinetic energy. However, the hot-water-dominated geothermal systems that are thought to exist in the Rio Grande Region are not the same kind of resource system as the geopressured reservoir systems. This "apples and oranges" aspect might prove to be difficult at a later date.

The Texas Geothermal Resources Act of 1975 placed regulation of geothermal resource exploration, development and production under the Texas Railroad Commission--the agency which regulates the oil and gas industry. In all probability court cases would arise over the ownership of the resource no matter how it is defined.

Before comprehensive laws can be written and regulatory and tax policies made, much more must be known about the resource system. Perhaps experiences in other states will at least provide an example of the pitfalls facing the lawmakers in trying to deal with the Rio Grande Region. Unless the proper planning takes place and the available data are utilized intelligently, future resource development might be hindered even after the technological problems are overcome.

Introduction

"Which way now?" was one of the main topics of discussion in the smaller group meetings held on the second day of the workshop. From these discussions and certain information gathered independent of the conference, a preliminary plan has evolved. This plan attempts to describe a program of research to precede and accompany the development of geothermal resources.

Like the workshop interaction sessions, this research program is divided into two parts: (1) resource exploration and assessment, and (2) demand and utilization of geothermal resources.

Regarding demand for the resource, research projects dealing with specific applications of geothermal energy should follow, in time sequence, confirmation of the existence of an economically viable geothermal resource. On the other hand, there are data needs that are of a generic nature. The "energy crisis" which is already having serious effects in part of the region's irrigated agriculture will spread unless either large quantities of natural gas are made available (price considerations aside), or some alternative energy source is developed. The economic implications of this problem, both nationally and regionally, are serious enough to warrant consideration now rather than later--to avoid the procrastinations of the past.

However, for the most part, questions of resource exploration and assessment are of primary concern. What follows is an attempt to present a sequential plan (see Figure 23). No doubt there is room for improvement in this plan. Constraints preclude a comprehensive treatment. Nonetheless, this plan does offer a preliminary outline of the scope of work within a regional context.

One may assume that most, but not all, of the Phase I field work is intended for the Trans-Pecos area. Although a considerable effort still remains in assessing the geothermal potential in New Mexico, much of the Phase I type of work has already been carried out.

Finally, all of the work presented here is geared to locating, developing, and utilizing economically viable geothermal resources. However, it is quite likely that even if these resources are found, their development will hinge on the matter of power plant construction. Building a geothermal (or any other type) power plant requires enormous capital investments. Development of geothermal resources ultimately may well depend upon the ERDA demonstration power plant program.

Any region that is provided electricity from geothermal power plants is a region that is freeing supplies of natural gas. For this reason, the encouragement of geothermal power plant development is a national concern. In the parlance of the economists, there are positive national externalities

PHASE IV PHASE V

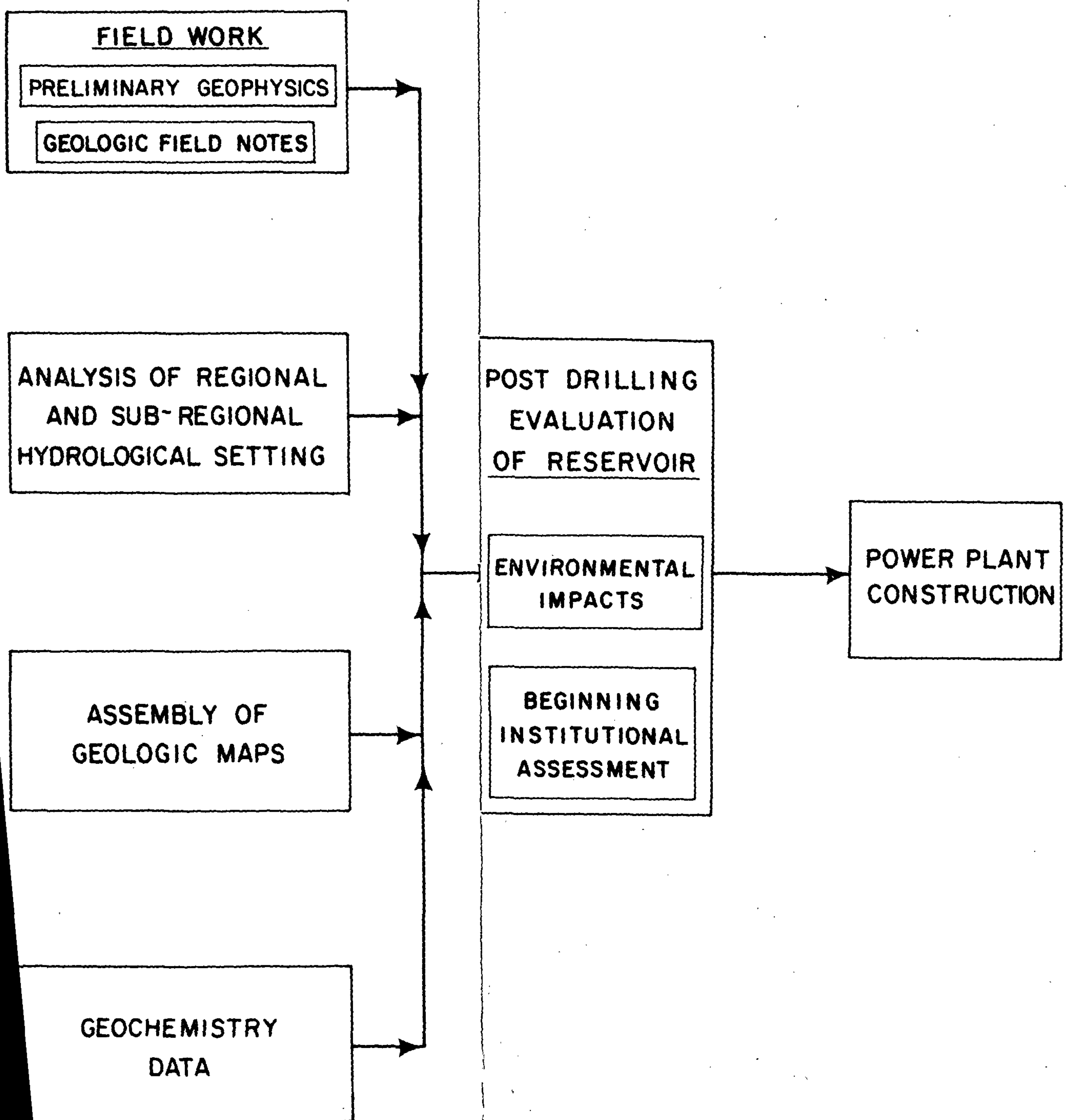


FIGURE 23

resulting from these regional economic activities. Restoration of the demonstration power plant program could be important in the nation's energy future.

Demand and Utilization of Geothermal Resources

What follows is an outline of research needs. There is not an intended implication of time sequence in their order. Also, there is quite probably a certain degree of redundancy in this plan; e.g., certain data pertinent to agricultural operations would also satisfy certain regional economic data requirements.

I. Agricultural assessment - As mentioned earlier in the report, there are certain problems with the existing published data relating to energy use in agriculture. There is available invaluable information that describes how energy is used in agriculture, particularly in the energy intensive irrigation sectors. An assessment of this sector should include the following:

   A. A collection of all the relevant crop data in the region.

      1. Which crops are irrigated; how extensive are they?

      2. How much water do these irrigated crops require? How much will this amount vary seasonally with various rainfall levels?

3. How much energy is used to grow these crops?

4. What are the relevant crop yields?

5. What are the production costs? What portion of these costs is accounted for by energy use (particularly natural gas)? How much will the cost of natural gas increase in the future?

B. Capital requirements for new equipment.

1. How many irrigation pumps will need to be converted from gas-driven to electrically driven?

2. How much will it cost?

3. Should there be tax provisions for these investments?

C. Estimation of agricultural linkages.

1. What are the linkages with other economic sectors in the region?

2. What linkage exists between the agricultural output for the region and the national agricultural output?

II. Develop regional energy data bank.

A. There exists an immediate need for a regional energy data bank to be used for evaluating various aspects of the energy problems in the region.

B. The first step would be to collect and collate all of the relevant published and unpublished energy data pertinent to the region.

C. This could be followed with a determination of the information gaps within the existing data.

D. The next step would be to collect sufficient data to close the determined gaps.

E. Following the data collection, it would be necessary to transpose, scale or employ other suitable data preparation methods so that all of the information is comparable and useful for economic/energy analyses.

III. Macro-economic analyses

A. Understanding the relationships between energy use and economic activity would be improved by establishing (or at least approximating) the various demand elasticities (price, income, gross) for energy under various policy assumptions.

B. There should be an evaluation of the options for conservation and substitution which would alter the elasticity coefficients.

C. Lead time for conservation and substitution policies should be estimated.

D. Examination of population elasticities would prove useful in preparing for long-run energy needs. Climatic changes, increased fuel costs, or the development of alternative energy resources in the region could have considerable effects on the region's growth.

IV. Micro-economic assessment - Because decisions of regional policy makers can have effects on where, how and when resources are developed, a knowledge of the inter-industry (or inter-economic sector) relationships is indispensable. Such an assessment should include the following:

A. Determine the number and types of primary products in the existing regional industrial complex.

B. Determine the type, source, and relative importance of the inputs into the industrial process.

C. Estimate the likely longevity and cost of the future supply of these inputs.

D. Examine the likely changes (growth and decline) of the existing industrial mix and the linkage effects; e.g., basic and service sectors.

E. Determine the under-employed and unemployed resources in the region.

F. Determine which of the unemployed and under-employed resources are needed in other parts of the United States' economy. This would be a beneficial assessment when decisions of power distribution are made. Some economically backward areas might benefit from a dependable energy supply.

G. Examine the cost-effectiveness of stimulating industry relocation by energy-related policies.

H. Determine income, earnings, and population multipliers.

V. Capital requirements - Because of its importance during the beginning of resource development, the matter of capital investment is treated separately from other micro-economic considerations.

A. How much capital investment will be required to bring about a utilization of geothermal resources?

B. What is the likely return on the investment?

C. How long is the "pay-back" period?

D. What is preventing the necessary capital investment from taking place today?

E. What policies should the government pursue to stimulate the necessary investments?

VI. Total resource implications - At some point after economically viable resources are proven to exist (and hopefully prior to development), serious consideration should be paid to the following:

A. Engineering assessment of maximum resource utilization--what types of coterminous activities could exist with power plant operations.

1. Residential and commercial heating.

2. Industrial process heating.

3. Agricultural or experimental agricultural applications.

4. Minerals extraction.

B. What would be the likely environmental impacts of developing geothermal resources?

C. Institutional arrangements - Once the resource is defined, an institutional assessment should be conducted to avoid potential conflicts which would halt development in the future.

Resource Exploration and Assessment

The following outline is intended to present a sequence for development. Obviously, the specific tasks and personnel involved in specific projects will determine the time required to accomplish the work. For a schematic presentation of this outline, see Figure 23.

I. Preliminary assessment

A. Field Work

1. Geophysics

a. Heat flow surveys of the Rio Grande Rift system, based on existing knowledge of "hot" areas.

b. Simultaeous gathering of micro-earthquaking and porosity information gathered by same teams doing heat flow work.

B. Analysis of regional hydrological setting.

C. Assembly of geologic maps. Geologic maps contain a wealth of information. Some of these maps are already published, and some need to be collated from the numerous theses and dissertations dealing with the geology of the region. These maps would need to be checked against field notes.

D. Geochemistry data should be analyzed with regard to the geological and geophysical setting. Such an assessment should include a synthesis of lithology, structure, hydrology, and the entire suite of geochemical elements.

II. Designation of specific sites for test wells.

A. Intensive heat flow and geophysical assessments in small (5 sq. km) areas.

B. Reservoir definition.

C. Determination of well drilling prospects.

II. Site evaluation.

A. Exploratory well drilling.

B. Three-dimensional reservoir modelling.

C. Engineering assessment of well data with regard to energy potential of the reservoir. This would lead to the decision of whether or not to proceed with power plant construction.

IV. Post drilling evaluation of reservoir and pre-power plant construction.

A. Environmental impact analysis.

B. Beginning of institutional assessment.

V. Power plant construction.

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BASE OF THE PERMIAN IN MIDLAND AND DELAWARE BASINS FROM LOGS

Permian Strat Expln Boundaries Strat
Guidebk | Midland & Delaware El Paso Co.
W. Texas Geol Soc 1975

Theodore S. Jones
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Midland, Texas 79701

ABSTRACT

Although the base of the Permian is now generally agreed to be the base of the Schwagerina zone, fusulinids are not available across the contact in the centers of the deep basins. The sea there was too deep during the Late Pennsylvanian for them to live, and too far beyond the slopes for their transported shells to reach. Out past the belt of turbidites the rapidly deposited shale of the basal Wolfcamp and the slowly deposited shale of the Upper Pennsylvanian are not easily distinguished in rotary cuttings. Gamma ray, resistivity, neutron, density, and sonic logs show that the Pennsylvanian shale contains readily correlatable members of radioactive, organic, black shale; the Wolfcamp lacks such shale.

INTRODUCTION

Most geologists working only on the Pennsylvanian and Permian shelves have not seen sufficient faunal or physical evidence to constitute a systemic boundary. However, in the deep basins, where a useful fauna is lacking and a gap in sedimentation does not exist, the evidence for a systemic boundary is clear. Modern stratigraphic principles have helped to find this boundary, and sophisticated borehole tools, developed for purposes other than correlation, make its location a routine matter.

HISTORICAL REVIEW

The erection of the Permian System by Murchison in 1841 after only two summers' field work in a strange country may seem to have been hasty, but it did put a "handle" on the rocks so they could be discussed further. By 1889 Karpinsky had lowered the base of the Permian on the basis of ammonites to where it is today by adding what later proved to be the zone of Schwagerina (lower Leonard and Wolfcamp) to Murchison's original section.

In the meantime the U.S. Geological Survey was organized in 1879, and, in accordance with the thinking of the time, recognized the Permian System. By 1889 experience showed that this recognition had created a problem, and Powell ordered his geologists to include the Permian in the Carboniferous. As Keyes explained in 1899, the fossils which had been found in Kansas since 1858 were somewhat similar to those of the Carboniferous, and the rocks showed no abrupt change or unconformity. It seemed that the Permian might be on its way out.

The third event of 1889 was the issuance of the first annual report of the new Texas Geological Survey. The marine "Coleman-Albany" was placed at the top of the Pennsylvanian, and the continental Wichita with plants and vertebrates was considered basal Permian. Although it was soon demonstrated that the Albany was equivalent to the Wichita, the top of the Coleman Junction, now known to be high in the Wolfcamp, was

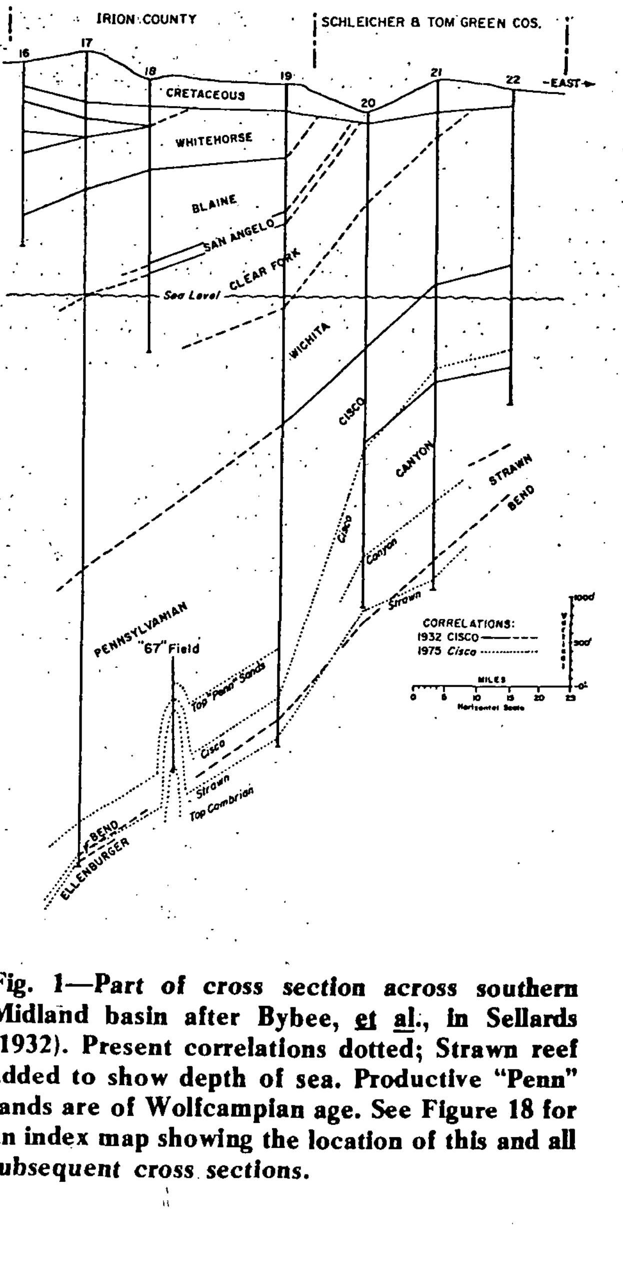

Fig. 1—Part of cross section across southern Midland basin after Bybee, et al., in Sellards (1932). Present correlations dotted; Strawn reef added to show depth of sea. Productive "Penn" sands are of Wolfcampian age. See Figure 18 for an index map showing the location of this and all subsequent cross sections.

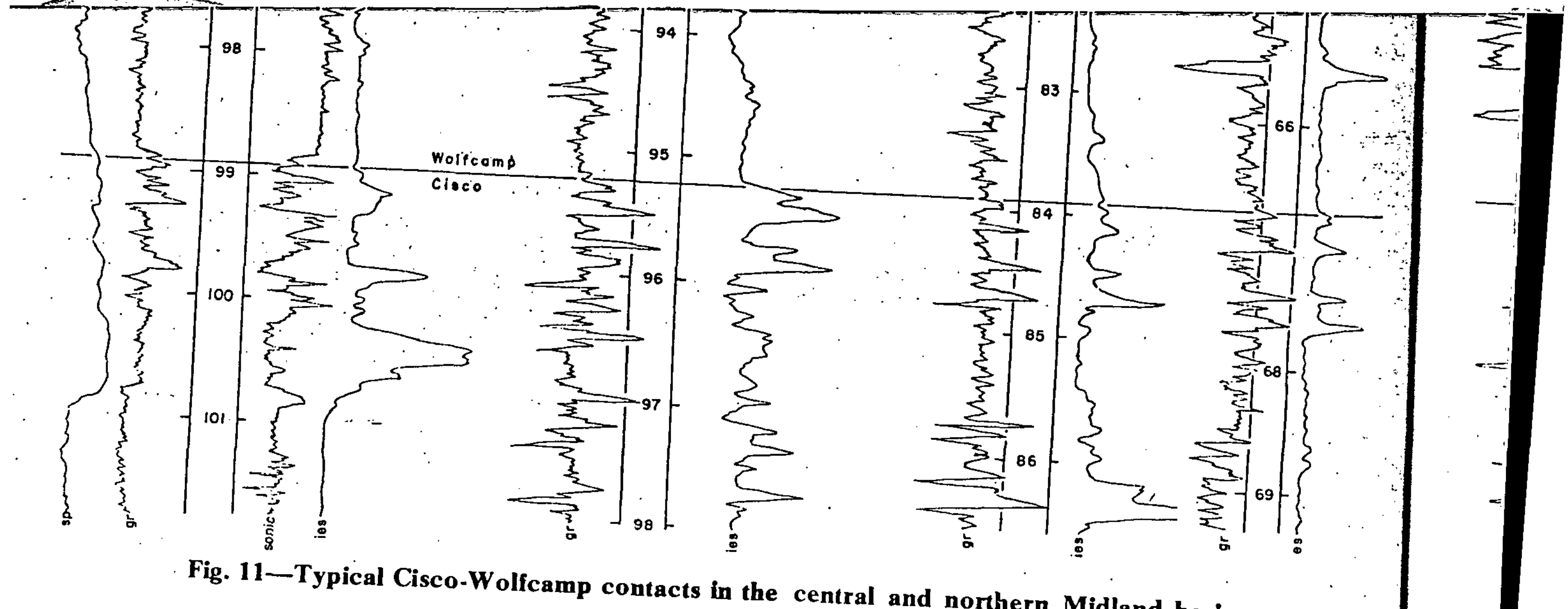

Fig. 11—Typical Cisco-Wolfcamp contacts in the central and northern Midland basin.

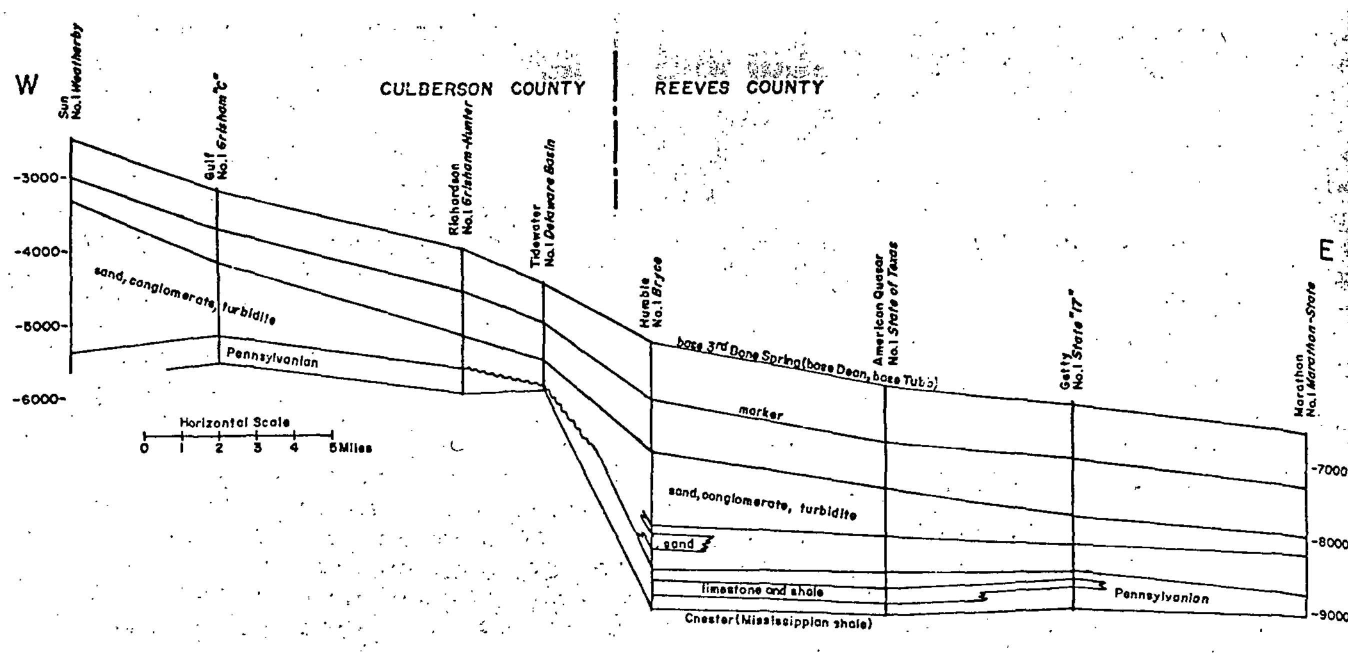

Fig. 17—Cross section in the central Delaware basin.

higher El Paso well actually has a thicker section of shale. The conglomerates reach a thickness of almost 4,000 feet a few miles to the northeast. They wedge out completely in the Magnolia No. 1 Cowden "A" (Fig. 15-A). The deposition of these coarse rocks occupies an extremely brief period of time in the Wolfcamp.

The conglomerates contain pebbles of chert and quartz, limestone, shale, and much sand. It is difficult to guess how much of the shale is in the form of pebbles, but it is certain that the Pennsylvanian fusulinids are either pebbles themselves or contained in pebbles, as the rare cores show. Large boulders or blocks may be common in these turbidites.

The most spectacular slide block lies off the west edge of the Central Basin platform in Pecos County (Guinan, 1971). It covers parts of Rojo Caballo, Coyanosa, and Gomez fields, extending 16 miles from east to west, 9 miles from north to south, and is up to 2,000 feet thick, including a section of Mississippian and Lower Pennsylvanian which is hardly disturbed except for fractures. The block slid seven miles into the basin during early Wolfcamp, and the debris churned up by its toe extends another 20 miles farther west. It is underlain, overlain, and surrounded by Wolfcamp shale and conglomerate. There must be other large blocks in the Delaware basin, some masquerading as fault blocks, but with the wide spacing of the deep gas wells, details will not be easy to obtain.

Obviously one clue to the lower Wolfcamp is its lack of correlatability. Unfortunately, one cannot always tell whether he is dealing with a limestone or a limestone conglomerate, and may try to force through a few correlations that should not be attempted. The depth of the water during the Wolfcampian did not cause a starved basin, because high areas existed around the Delaware basin, and the slopes were steep. Material and transportation made the Wolfcamp a filler.

The Midland basin did not have access to the same volume of debris as the Delaware basin. If the northeast half of the Central Basin platform was exposed at all at the end of the Pennsylvanian, the only result was the solution of limestone. On the Eastern shelf there were no appreciable exposures near the basin, but farther back the geosyncline advancing from the east tilted the land slightly above sea level so that much mud and some sand reached the Midland basin. The coarser sand came to rest on the upper slope, where it may contain a few chert pebbles; the finer sand reached the east edge of the bottom, just as the basal Canyon sands had done previously to a much lesser degree. The Wolfcamp sands are productive in Schleicher, Irion, Coke, Nolan, Fisher, and other counties, where they are usually called Cisco, Canyon, or even Strawn. To most Abilene geologists they were low enough structurally to be Pennsylvanian, especially if one were to use Cisco in the older sense and ignore depositional slopes. To Midland geologists the sands were something different from the shale and lime mudstone of the western Midland basin and might therefore well be Pennsylvanian.

The problem of the Cisco-Wolfcamp contact was naturally not attacked vigorously on the Eastern shelf, where the two series are so similar that a solution would have no economic value. The depositional slopes were recognized by some in such fine articles as Rall and Rall (1958), Van Siclen (1958), Jackson (1964), and Galloway and Brown (1973). However, these authors were well aware that the available information on fusulinds was hardly sufficient to define the contact. Therefore they employed local names and composite terms.

CONCLUSION

A study of the great mass of date on the radioactivity,

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used as the base of the Permian for many years. Even when Beede and Kniker (1924), working in Kansas, stated that the base of the Schwagerina zone was the base of the Permian, there was no immediate impact in central Texas because the genus had not been collected there yet.

The discovery of Ordovician oil in Big Lake field in 1928 stimulated deep drilling in the Midland basin. Figure 1 shows an early attempt to correlate the basin with the Eastern shelf. As was customary then, the base of the Permian was picked too high on the shelf; in the basin an attempt was made to go below the lowest Schwagerina, but the lowest Wolfcamp is barren shale there, and since the holes were drilled with cable tools, the Wolfcamp fossils did not cave downward as they do today. Consequently the top of the Pennsylvanian was picked much too high in the basin also.

In 1939 a committee of west Texas geologists headed by J.E. Adams advocated that the Permian be ranked as a system, and divided it into four series. Noteworthy was the recommendation that if any older rocks with Schwagerina should be found north of the thin surface section of Wolfcamp, they should be included in it also. The wisdom of this became apparent when a nearby well spudded in Devonian chert of the Dugout Mountain thrust encountered an additional 6500 feet of Wolfcamp below it, older than the type section (Hall, 1956). One result of the stratigraphic work of that period was that the U.S.G.S. finally conceded in 1941 that the Permian was a system, although the Wolfcamp was classified as questionably Permian until 1951.

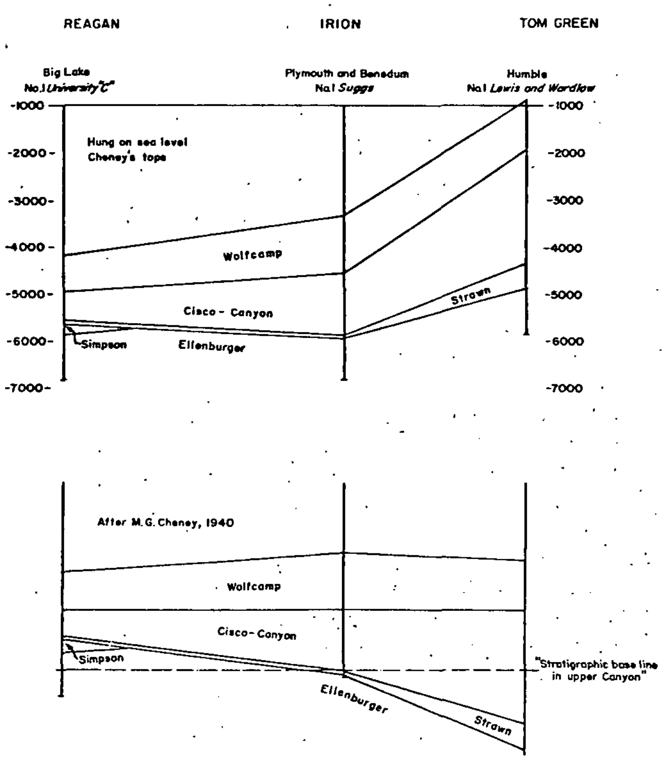

Fig. 2—Simplified cross sections through southern Midland basin. Lower version by Cheney (1940) on a nebulous datum implies thinning in basin due to uplift at Big Lake. Modern version above, using same points but hung on sea level structural datum, shows thinning was unrelated to uplift.

A cross section indicating the early thinking was constructed by Cheney (1940) (Fig. 2). He felt that if the Pennsylvanian was thicker on the shelf, the water must have been deeper there. Now, using the same points but with sea level for a datum, the opposite conclusion is reached. A cross section by a committee of the West Texas Geological Society in 1940 showed some basinward thinning of the Pennsylvanian, but not as much as actually existed because of lack of control. The W.T.G.S. cross section of 1949 suffered from the same defect in Nolan County (Fig. 3). However, where

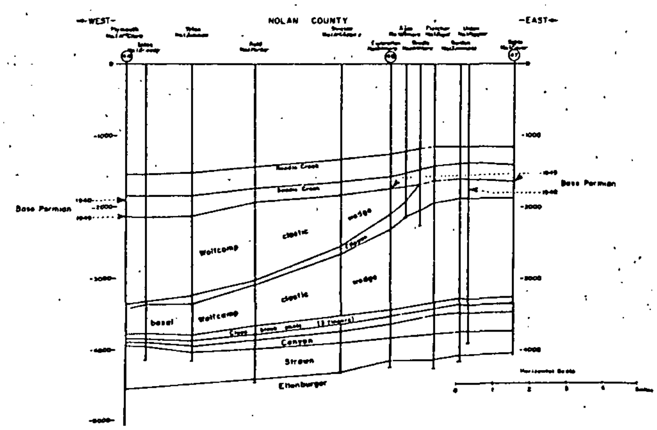

Fig. 3—Cross section through northern Nolan County, Texas, showing changes in interpretation from the 1940 and 1949 sections of the West Texas Geological Society. Numbered wells were on the 1949 section; only 44 and the Union well were on the 1940 section.

the 1940 section included both Pennsylvanian and Wolfcamp shale in the Pennsylvanian, the 1949 committee had additional "information." This consisted of the fact that rotary cuttings contained Wolfcamp fusulinids right down to the top of the Strawn Limestone, so an imaginary unconformity was drawn to make the shale in the western Midland basin all Wolfcamp. The theory was that after a regional uplift the shale in the basins was removed more easily than the limestones on the shelves. Although this idea was not especially palatable, it appeared preferable to calling all the shale Pennsylvanian when it "obviously" contained Wolfcamp fossils.

The guidebook for the 1950 field trip of the Abilene Geological Society included a controversial cross section from Brown to Schleicher County (Fig. 4). At the evening discussion at the First Christian Church in Brady on November 3, someone doubted that the Pennsylvanian could thin so abruptly from the Eastern shelf to the Midland basin. The answer was that the correlation was based on Schwagerina cored in the Honolulu No. 1 Tisdale near the cross section. After

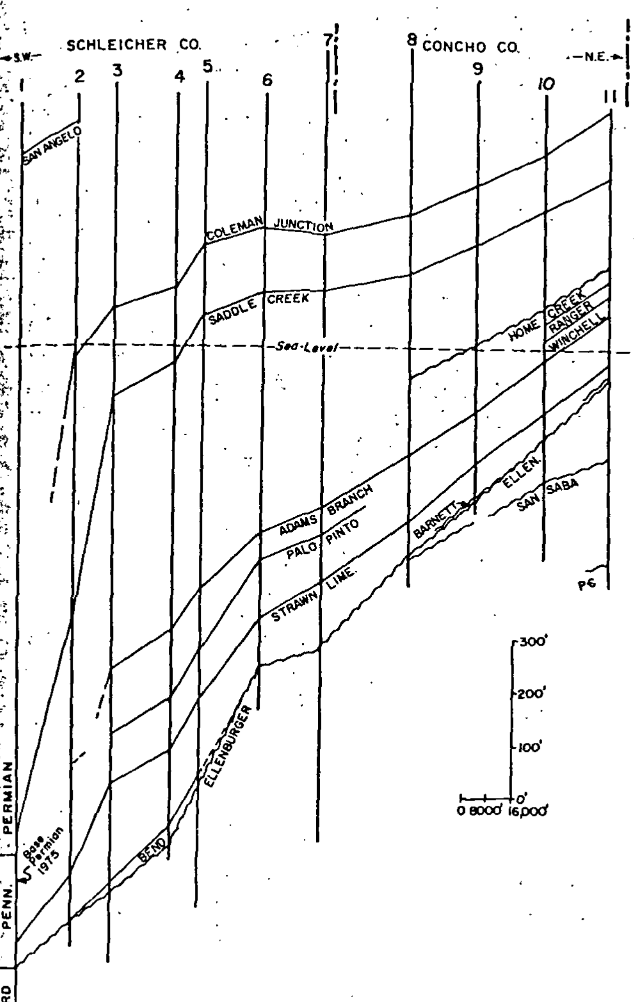

Fig. 4—Simplification of cross section by M.L. Rhodes and others in 1950, first modern interpretation of shelf to basin relationships.

further protest that this was illogical, J.E. Adams arose and presented the "starved basin" theory, subsequently published in the A.A.P.G. Bulletin for December, 1951 (Fig. 5). This has been the foundation of our shelf-to-basin correlations ever since. Acceptance of the idea was put into print when the 1953 Stratigraphic Problems Committee of the West Texas Geological Society agreed that Adams was right and the 1949 cross section wrong (Jones, 1953).

Even before Adams expounded the hypothesis, John Rich had been working on the problem of shelf and basin environments from another point of view. Fine exposures of crumpled slope beds had been known in Wales for years. Rich integrated this information into a classification of shelf, slope, and bottom deposits which he presented to the 1949 A.A.P.G. convention (Rich, 1950, 1951). At the same time Ph. Kuenen was demonstrating how turbidity currents operated. Nevertheless, on the 1951 fall field trip of the West Texas Geological Society geologists viewed the Rader "breccia" in the Delaware Mountains as a phenomenon of uncertain origin unlikely to be encountered again. Over the next dozen years turbidites gradually became accepted, but even now many geologists are reluctant to identify a turbidite on a log in the Delaware basin.

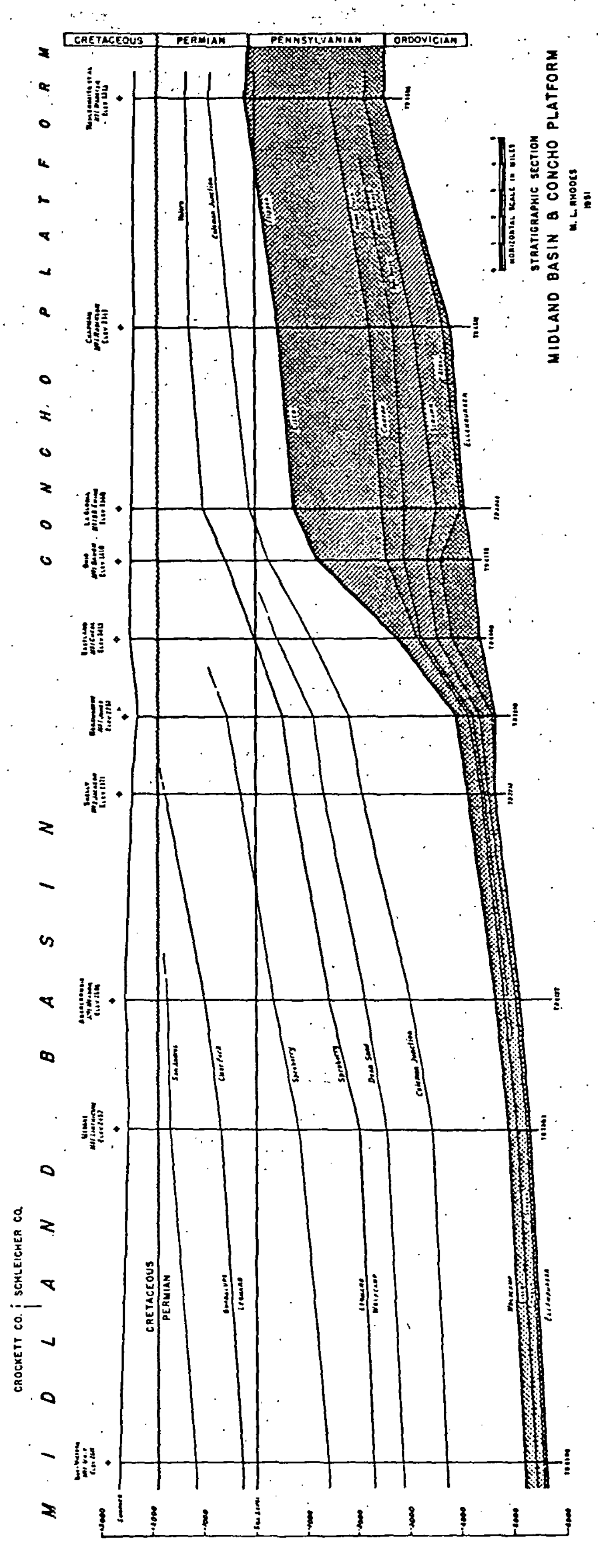

Fig. 5—Cross section by M.L. Rhodes appearing with 1951 article on the starved Midland basin.

EARLY GEOLOGIC HISTORY OF THE BASINS

The problem of the Pennsylvanian-Permian contact in the basins is more easily understood if one has a picture of their earlier history. Although well control in the older formations is more sparse, they are relatively simple to map on account of the absence of real orogeny in the Lower Paleozoic. Those who have worked with the basins in Oklahoma, Illinois, and Michigan also have a great advantage.

A single basin, named Tobosa by John Galley (1958), formerly occupied the site of the Midland and Delaware basins. It was formed at the end of Ellenburger time as a notch in the south edge of the Texas craton, opening southward into the Marathon-Ouachita geosyncline (Fig. 6). The predominantly clastic Simpson, the basal deposit of the Tippecanoe sequence, partly filled the trough, so that the succeeding, more widespread Montoya carbonate thickened only a small amount into the center of the Tobosa basin. Next, the Lower Silurian limestone, made up of the shells of more depth-sensitive organisms, thinned into the basin. In Late Silurian time subsidence was more rapid so that a shelf of thick dolomite partly encircled the thin silty limestone deposited in 1500 feet of water. The Lower Devonian, restricted in area as in most of the United States, is more calcareous where it laps high against the Silurian shelf than in the deep part of the basin, where it consists almost entirely of siliceous skeletons.

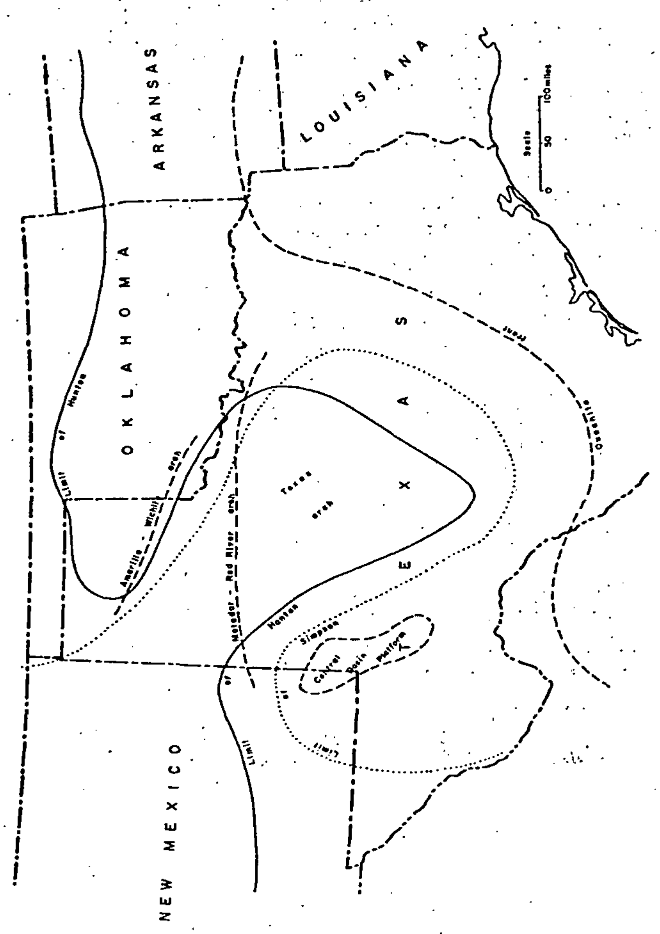

Fig. 6—Sites of early Paleozoic deposition, with location of three major features formed at end of Mississippian time.

The movements of Middle Devonian time were regional in nature so that the first formation of the Kaskaskia sequence, the Upper Devonian Woodford Shale, although more widespread than the older formations, still revealed the existence of the Tobosa basin by thickening into it, but without any conspicuous lithologic change. In fact, this peculiar shale is remarkably uniform over a large part of the east-central U.S., where a lack of current in the sea permitted the growth of a mat of floating plants. The abundance of plants and the slow deposition caused the accumulation of rotting material on the foul bottom, resulting in the incorporation of much organic matter in the Woodford and the adsorption of uranium compounds on the surface of clay particles. It is important to realize that the high radioactivity and organic content of the Woodford Shale, which may overlie solution-creviced Silurian limestone, was not the result of a great depth of water, as it was later on in seas with better circulation.

Although the Mississippian sea was very widespread, the Tobosa basin was still recognizable in it. However, the general pattern is that the "Mississippian limestone" of Kinderhook, Osage, and Meramec age grades from shallow-water, light-colored fossiliferous limestone on the north to exceedingly thin, dark, impure limestone deposited in the deeper water (as much as 2500 feet) farther south. The Chester limestone and shale grade completely into shale southwards and thin also, but not in as great a proportion as the "Mississippian limestone." This Chester shale can be distinguished in rotary cuttings only with difficulty from the overlying Pennsylvanian shale, but rather easily on borehole logs by its characteristic pattern of radioactive and organic members. The term "Barnett" for the basinal Chester has been imported from central Texas. Unfortunately some workers have picked the top of the "Barnett" from cuttings at the top of the lower Morrow (Springer) shale section. In extreme cases the top of the Mississippian has even been picked well up in the Wolfcamp (Vertrees, 1963) resulting in thicknesses as great at 3000 feet (Adams, 1965) for the Mississippian shale. Such thicknesses are, of course, inconsistent with the history of the basin because the Mississippian is pre-orogenic; it is not a basal clastic following an orogeny.

PENNSYLVANIAN

At the end of the Mississippian the first orogeny of the Paleozoic occurred on the craton. Both the Oklahoma and Tobosa basins were divided into two unequal parts by uplifts, with the steeper sides facing the deeper parts of the older basins. The slope of the east flank of the Tobosa basin was not changed much; it was merely interrupted by the Central Basin platform, so that the Midland basin was shallower than the Delaware basin. In fact, only the western part of the

Midland basin remained continually under water and received Morrow shale. Similar shale was carried into the Delaware basin where it has sometimes been confused with Chester shale. This miscorrelated section should not be called "Barnett", but rather "Springer." On the northwest part of the Delaware basin a thick section of limestone and sand in the upper ¾ of the Morrow is easily recognized as such.

The Atoka, or Bend, which name has precedence, is likewise a filler in most of the basinal area, although it has more limestone and less sand than the Morrow because the uplifts had been somewhat worn down. Either the sea was still too muddy or the proper organisms had not evolved, because Bend (Atokan) limestone does not form "reefs" comparable to the later ones. The Bend in the eastern part of the southern Midland basin is very thin, present only in the lows; in the western part it is thicker and productive. In the Delaware basin the Bend Limestone is thickest in the northwestern part. It thins southeastward and loses its diagnostic fusulinids, leaving only the smaller, long-ranged millerellids. In the deepest part of the basin the Bend is practically indistinguishable.

Paleontologically, the Strawn can be classified with the Lower Pennsylvanian, which means that the chance of confusing a Strawn fusulinid with a Bend fusulinid in poor material is certainly much greater than of misidentifying it as post-Strawn. Time-wise the Strawn probably belongs in the earliest half of the Pennsylvanian. Lithologically, it more closely resembles the Bend in the basins. However, the Strawn is often more closely allied with the later Pennsylvanian in thickness; it was a builder rather than a filler where the depth of water allowed it to be. Whether to call the Strawn Upper or Lower Pennsylvanian is really a matter of taste.

Less clastics were available to the Midland and Delaware basins in Strawn, Canyon, and Cisco times. The deepest areas would have received the least sediment; so the problem is to map the relative depth of the sea. One rough way is to map the present structure, which ignores post-Pennsylvanian uplifts. Another is to use limestone, since most organisms with calcareous parts lived in shallow (sunlit) water during the Pennsylvanian just as they do today. Thickness of limestone by itself does not indicate whether the limestone is a reef or a local low. Limestone percentages generally reflect only what intervals were selected. Purity of the limestone is difficult to determine precisely enough. Therefore an attempt is made here to see if the presence of fusulinids can be used to indicate depths and outline basins.

The shortcomings of the method are conceded; a list of identifications will suffice only as a starter. Obviously fusulinids cannot be expected in red beds deposited on land. Eroded areas must be recognized. Identifications are not usually made when the specimens are silicified, dolomitized, or recrystallized. Finely ground cuttings can be a hazard, if one is not aware of the situation. Misidentifications do happen, but not often enough to alter the results. More serious is misnumbering of samples, lag, recirculation, and caving. The best, and sometimes the only identifiable specimens, are not those which have been ground up by the bit, but those which have caved, or been reamed, or knocked off by whipping of the drill stem. Cores are rarely available, so small cuttings brought up with a fresh-water mud may not show that Pennsylvanian fusulinids are part of a Wolfcamp conglomerate.

More control would certainly make the maps (Fig. 7) more accurate, but the outlines would not necessarily

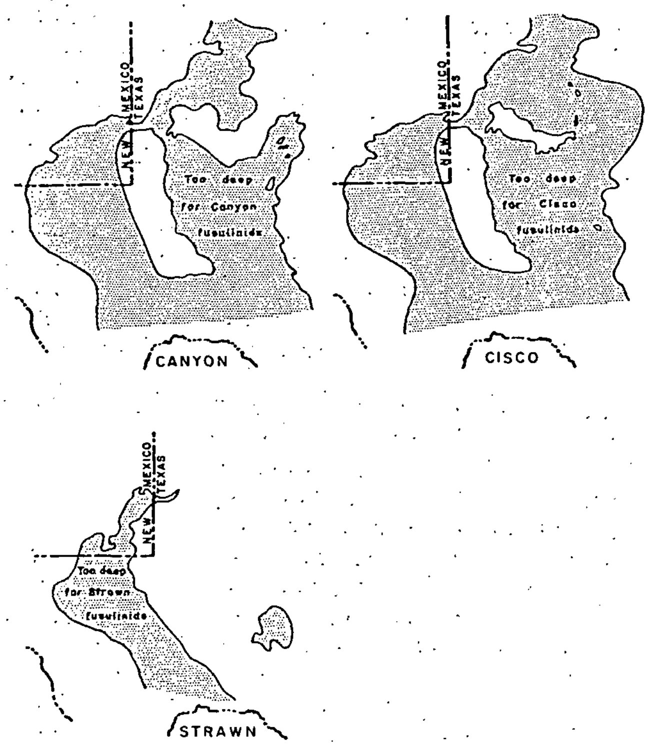

Fig. 7—Stippled areas represent absence of fusulinids due to depth of sea. Comparison shows gradual expansion of deep water through Upper Pennsylvanian.

be more regular. A ridge projecting from the shelf into the basin would extend the area of fusulinids. On the other hand, a ridge in the edge of the basin, but not projecting up into shallow water or connecting with the shelf, would be devoid of fusulinids because they could not live there and could not be transported up onto it.

The Strawn map shows that the Delaware basin, which is deeper than the Midland basin by present structure, previous history, and lithology, is barren of fusulinids over most of its extent, including a part of Lea and Eddy Counties, New Mexico, in which it still serves as an excellent limestone marker. In the Midland basin only a patch in the middle around the common corners of Schleicher, Irion, Reagan, and Crockett Counties lacks fusulinids. At the Barnhart field in the southeast corner of Reagan County Wolfcamp was once thought to overlie Ordovician. If fusulinids could have lived in the surrounding area, they certainly could have lived on the structure. The absolute depth of the Strawn sea in the southern Midland basin can best be calculated at the Sixty-seven field (Fig. 1), where an uplift at the beginning of Pennsylvanian time caused erosion down to Cambrian sandy beds. A "reef" built on the knob maintained itself at the surface of the water until the end of Strawn time, when it was 1,000 feet above the surrounding sea bottom and level with the Eastern shelf. Its position at that time is indicated by the thinning of Canyon and Cisco shale over it, and the submarine lapping out of basal Wolfcamp around it. It was drowned at the end of the Strawn.

The map of Canyon fusulinids shows that the subsidence of the basins at the end of the Strawn not only kept fusulinids from living there, but also prevented their shells from being carried very far from the shelves. A rough rule is that if a limestone has a good self-potential it contains fusulinids. At any rate, the Central Basin platform is completely defined by the absence of fusulinids around it. The main part of the Horseshoe atoll is also apparent, although the low northern segment had already drowned. Some of the Strawn "reefs" on the west edge of the Eastern shelf of that time (Concho platform of some) had been submerged, although a few, such as Jameson in Coke County, stayed alive. Nothing new appeared in the Delaware basin because, regardless of whether or not some local structures might have been growing, the net movement was downward.

How much submergence is necessary to kill a Pennsylvanian "reef"? The total subsidence during Canyon time can be measrued as the thickness of a Canyon "reef" directly over a Strawn reef, which assumes of course that both reached almost to the surface of the sea. It also assumes that there is no tectonic influence, which eliminates the Central Basin platform as a yardstick. Farther east it should be easier, but the Canyon cannot always be distinguished accurately in a carbonate mass, especially if part of it is dolomitized. In such a mass the highest Canyon may not always overlie the highest Strawn. The range is still from about 600 to 900 feet.

These figures are merely a guide in limiting the amount of subsidence which must have taken place at the beginning of Canyon time when some strawn reefs died, because the stratigraphy of the area demonstrates that subsidence of the Eastern shelf continued throughout Canyon time. It is true that a lowering of sea level due to glaciation could have killed the Strawn "reefs," and the difference between Strawn and Canyon fusulinids might be used as some evidence, but the returning sea failed to re-establish the "reefs" in such places as the Sixty-seven Field, so a brief rapid subsidence after Strawn time is necessary anyway. The conclusion is that the Pennsylvanian lime-building animals and plants lived in very shallow water, and could not tolerate an appreciable deepening of the sea.

Continued subsidence of the old Tobosa region caused the Cisco sea to be the deepest of Pennsylvanian time, according to the fusulinid map (Fig. 7). The Horseshoe atoll was further reduced in area, with several peaks remaining in Scurry and Kent Counties. The gap through the Matador arch, or archipelago, was somewhat wider than in Canyon time, and the trough, which was actually the northern segment of the Midland basin, extended between the Amarillo arch and the Bravo dome into the south part of the Dalhart basin (Fig. 8). The surface of the Central Basin platform

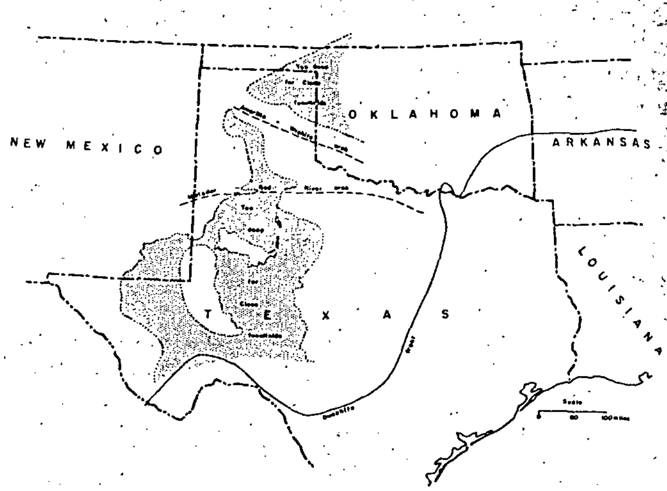

Fig. 8—Maximum extent of deep water in Pennsylvanian time. Stippled area shows where the Pennsylvanian-Permian contact cannot be picked by fusulinids.

was maintained near sea level by limestone deposition; the shale in the bottom of the Delaware basin accumulated more slowly, so the basin deepened.

The main point of contention is the location of the edge of the shallow water of the Eastern shelf in Cisco time, which depends on correlations and ages of rocks. Field designations by the Railroad Commission and "industry" tops in this part of the column do not always match geological tops. The "picks" often are mere "rock-stratigraphic" terms, carried over from a time when the Permian was not clearly defined in Texas. The 1949 W.T.G.S. cross section was laid out to tie with work of the Abilene Geological Society, but more logically should have extended to the limestone masses farther east. Thus, the east end of the cross section began in the basin of Late Pennsylvanain time, although well back on the Eastern shelf of Middle Permian time.

In order to show the age of the sloping limestone tongue and the "Three Fingers" on figure 3, another section (Fig. 9) was drawn in northern Coke County, beginning at the Blackwell "reef". It proves that the main Cisco limestone grades basinward into the "Three Fingers." The Flippen does not become radioactive, because it occupies so little geologic time; it merely becomes indistinct basinward.

The depth of water in Nolan County was about 1500 feet at the end of the Cisco (Fig. 3), in Coke County (Fig. 9) 1400 feet, and in Irion County (Fig. 1) 1300 feet. The sea was deeper farther out in the Midland basin, and was certainly over 2500 feet in the Delaware basin. In Oklahoma sufficient clastic material poured in from the north to almost fill the Anadarko basin while the basins in Texas were still deep.

While it is true that the Upper Pennsylvanian in the Midland and Delaware basins is thin for the amount of time involved, the word "starved" should ideally be restricted to the dark, organic, radioactive layers. For example, on the east edge of the Midland basin are basal Canyon sands deposited at a normal rate; most of the shales were deposited slowly, but not remarkably so. Neither of these rocks has an age equivalent in the nearest "reefs," although both do farther east. The starved rocks are the organic shales, equivalent in age to "reef" limestone, which could only be deposited in deep quiet water.

The upper Cisco contains two pairs of radioactive shales. They form a characteristic pattern and are the shales that concern us in this article. If these shales outcropped or were cored, their peculiar nature would be obvious; but since this is not the case, their distinctive qualities must be deduced from certain types of borehole logs. No values are shown on these logs because the curves have been separated for greater legibility. The values will be discussed later.

The southernmost limit of these organic shales in the Midland basin is in central Sutton County. Southward the sea was shallower, as could be anticipated from the map of Strawn fusulinids (Fig. 7). The radioactive shales in the Shell No. 1 Johnson (Fig. 10-A) at Sonora do not occur down in the Canyon or Strawn as farther north, but are restricted to the upper Cisco. The resistance is the easiest means of identification, although the velocity is slowed down somewhat by the organic content, indicating that the rock is indeed a shale, as the cuttings show. Sandstone is not developed in the basal Wolfcamp here.

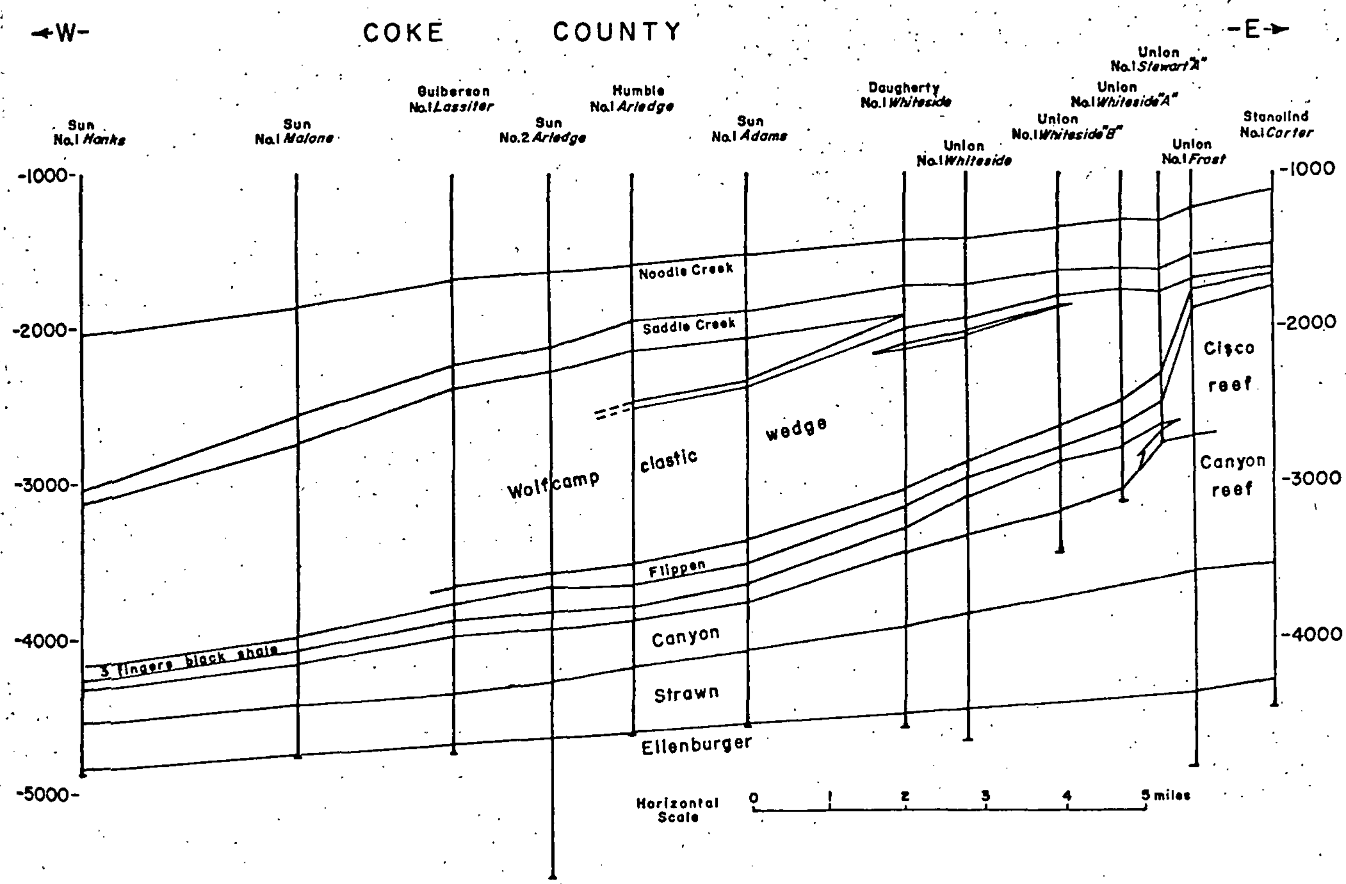

Fig. 9—Cross section from shelf to basin in northern Coke County, Texas.

In Schleicher County, the upper Cisco shales are conspicuous in the Delta No. 2 Jackson (Fig. 10-B) in the Eldorado field one and three-quarters miles northeast of the Skelly No. 1 Jackson, which lies at the west end of figure 4 and is also on figure 5. Although the shale seems to have only two beds, they each bifurcate northward. As the log indicates, productive sand is only a short distance above the Cisco. Four hundred and eighty feet above the Cisco is a bed of limestone correlative with one in the Skelly No. 1 Jackson and also in the Honolulu No. 1 Tisdale, seven miles to the northeast where Schwagerina was cored. Between these two latter wells the limestone varies from 50 feet to almost zero, suggesting that it is a turbidite; it is

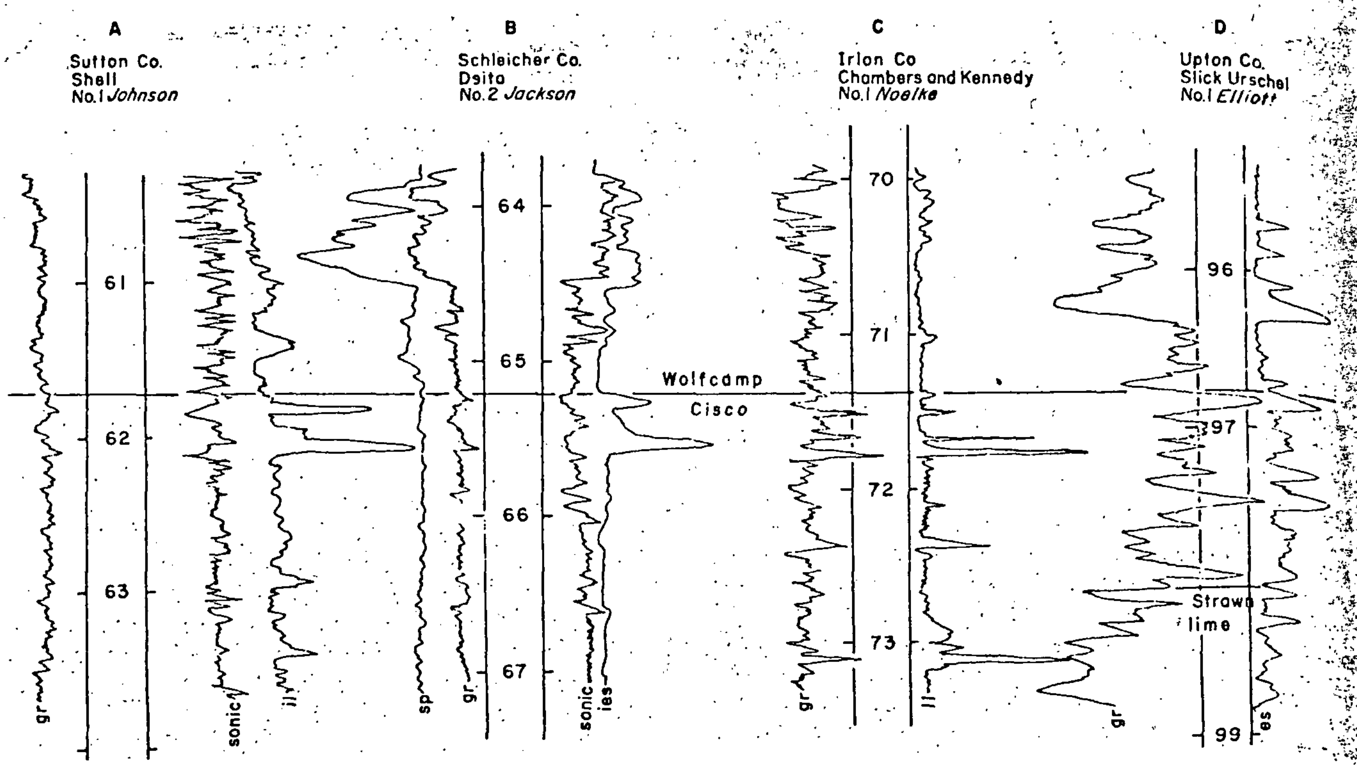

Fig. 10—Typical Cisco-Wolfcamp contacts in the southern Midland basin.

older than the Saddle Creek of early Wolfcampian age.

In Irion County a laterolog of the Chambers and Kennedy No. 1 Noelke (Fig. 10-C), two miles southwest of the Sixty-seven reef sketched on figure 1, presents the familiar pattern. To the northwest in Sterling County, the discovery well of the Credo Wolfcamp field (Fig. 11-C) is similar. Further west on the Benedum structure in Upton County, productive from a thick distillate column in Ellenburger dolomite, the upper Cisco is very thin (Fig. 10-D). There has been no erosion here; the thinner Cisco of the western Midland basin thins even more over a pre-existing high.

In Nolan County (Fig. 11-D) is a typical section 16 miles southwest of the west end of figure 3 and 11 miles north of the west end of figure 9. Westward in Martin County (Fig. 11-B) no difference exists. A well in northeast Terry County (Fig. 11-A) is nearest to the Northwest shelf, proving that the same environment

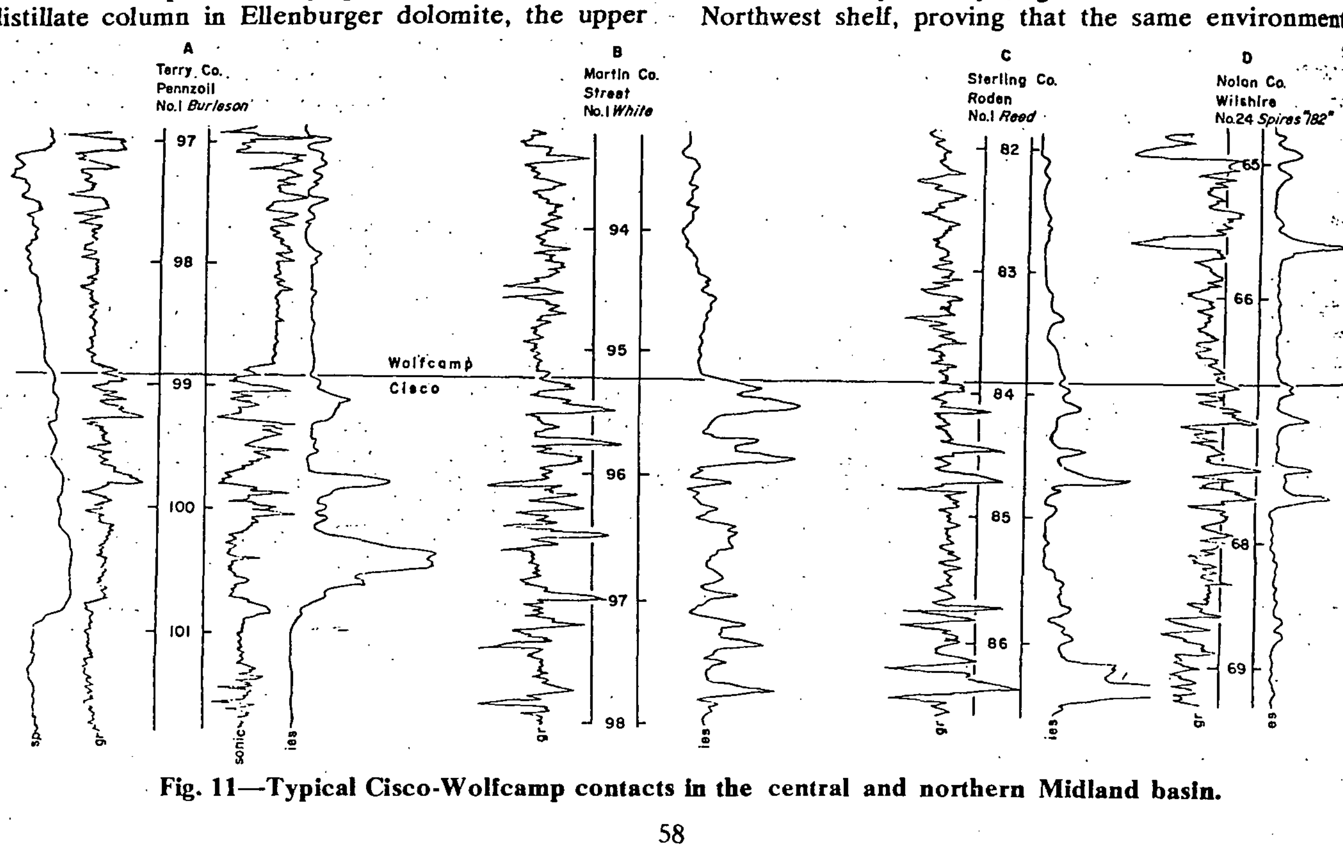

Fig. 11—Typical Cisco-Wolfcamp contacts in the central and northern Midland basin.

existed over the whole Midland basin, and that the source of the shale is not the critical factor. In this well the basal Wolfcamp is a tight, fine-grained, glauconitic sandstone; below the black shales the self potential suggests more sand, but sample logs record it as shale. Evidently this silty shale was rapidly deposited.

The organic black shales at the top of the Cisco in the Midland basin were laid down during a quiet interval when "reefs" could grow, and very little clay mud reached the basin. Similar conditions should be expected in the Delaware basin. The area of best control in the Delaware basin is around Carlsbad in Eddy County, New Mexico. Figure 12 is "hung" on top of the

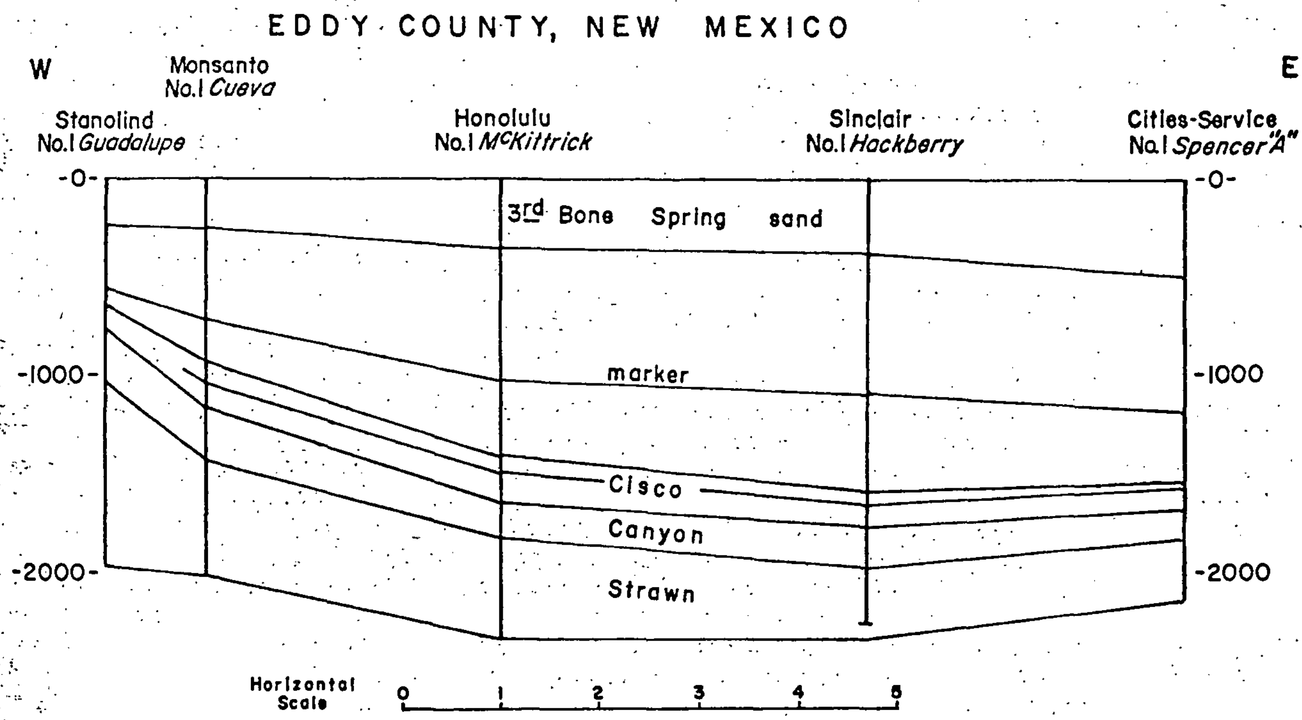

Fig. 12—Cross section from shelf to basin in Eddy County, N.M., near Carlsbad.

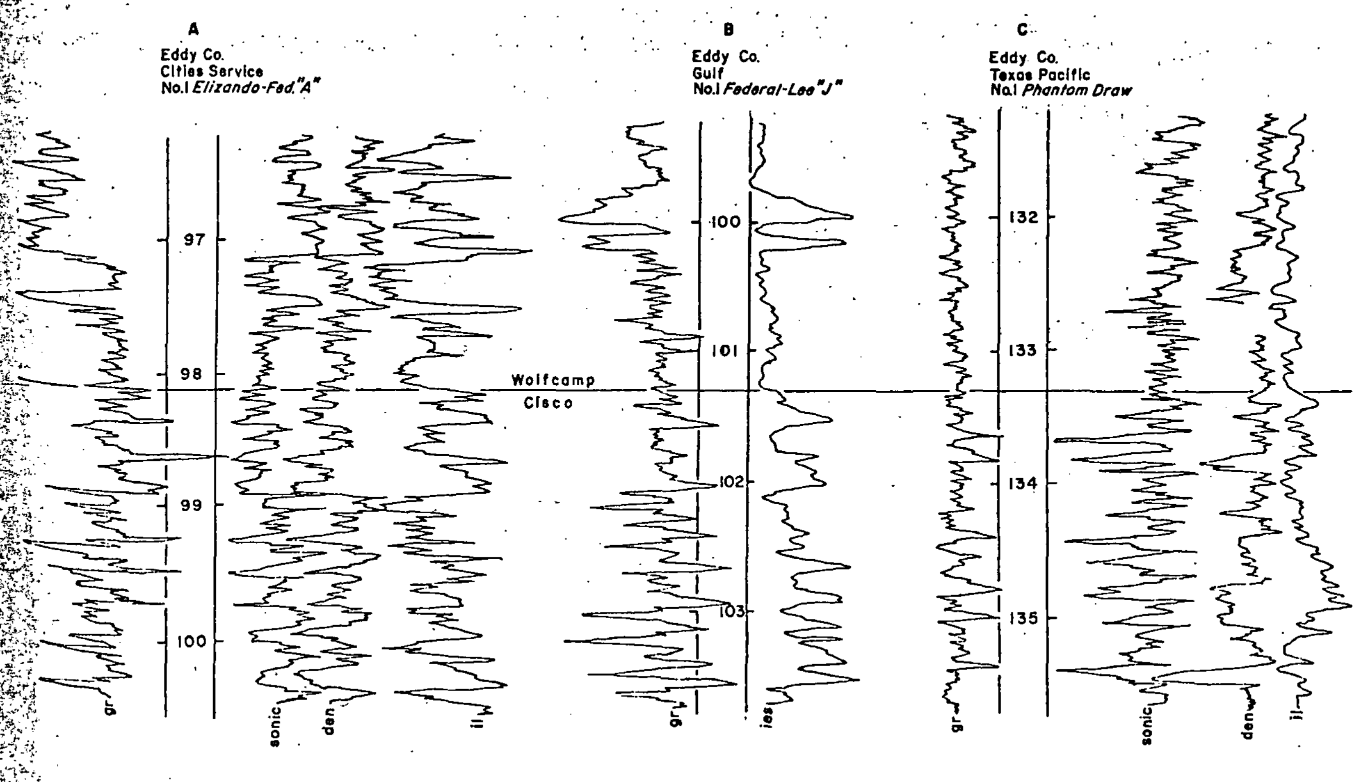

Fig. 13—Typical Cisco-Wolfcamp contacts in the northwestern Delaware basin.

Third Bone Spring sand (Dean of the Midland basin, Tubb of the shelves) because the present regional dip is too strong to permit use of a structural datum. This sand was surely not absolutely flat during deposition, but the cross section does furnish us minimum water depths. The Cisco and Canyon are clean limestone at the west end, but deteriorate rapidly eastward, where they can be traced but do not contain fusulinids. On strike with the east end of the cross section and six miles north of it is the Cities Service No. 1 Elizando-Federal "A" (Fig. 13-A), where the gamma ray, lateral, and sonic curves have the same pattern as logs in the Midland basin. In addition, a density curve indicates that the shales are organic by their light weight. This feature can be used without any others to identify the top of the Pennsylvanian.

Eleven miles southwest of the cross section the gamma ray and induction curves of the Gulf No. 1 Federal-Lee "J" (Fig. 13-B) are also very similar to those on Midland basin logs. In the southeast corner of the county the curves on the Texas Pacific No. 1 Phantom Draw (Fig. 13-C) are adequate to point out the top of the Cisco, although the gamma ray and sonic curves would need some study if the others were not available.

In Culberson County, Texas, the Magnolia No. 1 Cowden "A" (Fig. 15-A) suggests some uplift, although

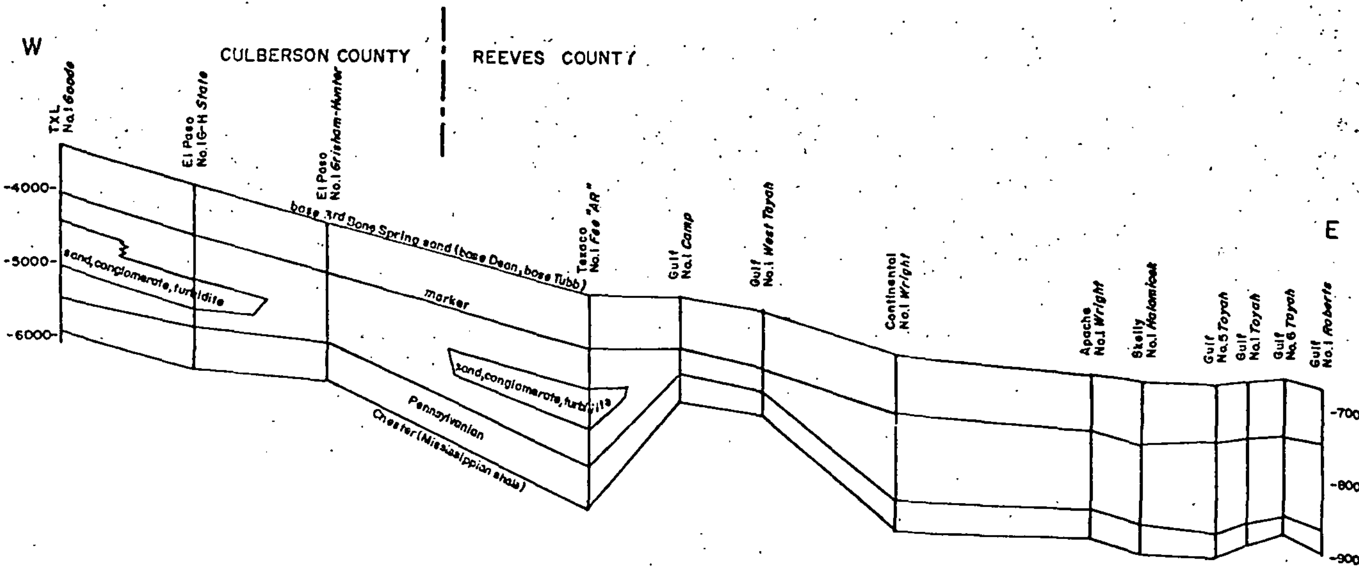

Fig. 14—Cross section in the central Delaware basin.

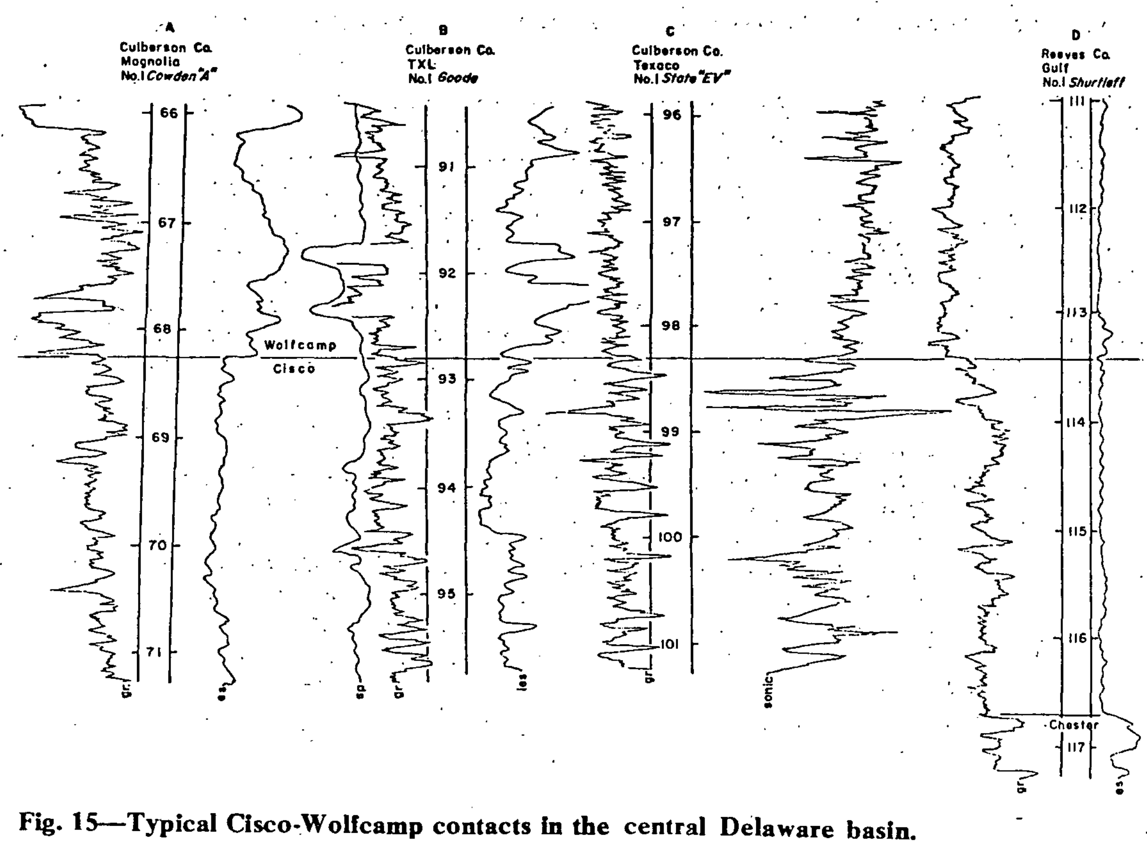

Fig. 15—Typical Cisco-Wolfcamp contacts in the central Delaware basin.

not near the surface of the sea, after Cisco time, because the Cisco shale is overlain directly by limestone. Ten miles southeast of this well, the Texaco No. 1 State "EV" (Fig. 15-C) was situated in a lower structural position, because the main Wolfcamp is 390 feet thicker, but there is also a wedge of 1710 feet composed mostly of sand and conglomerate. It would be unthinkable to include that kind of material in the Pennsylvanian, especially since the normal pattern of basinal Cisco appears below it.

Farther south, at the west end of figure 14, the TXL No. 1 Goode (Fig. 15-B) also has a section of conglomerate. One is tempted to call the base of the Wolfcamp at the base of the conglomerate, and include some limestone with Pennsylvanian fusulinids and self potential around 9200 feet in the Pennsylvanian. However, both of these features are incongruous with the Pennsylvanian of this locality. It is obvious that the "limestone" is a conglomerate, and the Cisco is called where the shale is both radioactive and resistant.

Eastward in deeper water the conglomerate thins, and in high wells only a few thin sands may be present in the Wolfcamp. Near the east end of Figure 14 the log of the Gulf No. 1 Shurtleff (Fig. 15-D- shows a sand body overlying the relatively radioactive Pennsylvanian shale. Unfortunately, this basal Wolfcamp sand has not been identified on sample logs in the Toyah field, but since it produces in several wells its presence may be assumed. The Chester (Mississippian) shale is more radioactive than the Pennsylvanian, and the Woodford Shale below it even more so. This well was shown on the 1963 cross section of the West Texas Geological Society (Vertrees, 1964), but the top of the Mississippian was selected at 10,570 feet after a close vote. The explanation offered was that the dark shale below could not be distinguished from the Mississippian by cuttings, which may have been true enough, but, in the opinion of the writer, was a powerful argument for the proper use of electric logs.

Farther east and south in the Delaware basin and farther from fusulinid control the base of the Wolfcamp is less easy to find. Some of the presently popular sonic logs cannot be read through part of the Pennsylvanian, even on the scale of five inches per 100 feet, let alone be traced. Washouts, cycle skipping, and sticking of the tool are hazards to correlation. Nevertheless, the three logs on figure 16 from the Hershey, Mi Vida, and Pike's Peak fields, reading from left to right, are useful illustrations of the base of the Wolfcamp. In the Superior well the resistance at the top of the Pennsylvanian may seem low, but the uppermost black shale is a very thin peak which is high for shale, but is not conspicuous against the immediately overlying coarse clastic section. In the Texas Pacific well the density curve is the one that really clinches the point. In working with logs in this part of the basin the use of several types is desirable, and the large scale must be

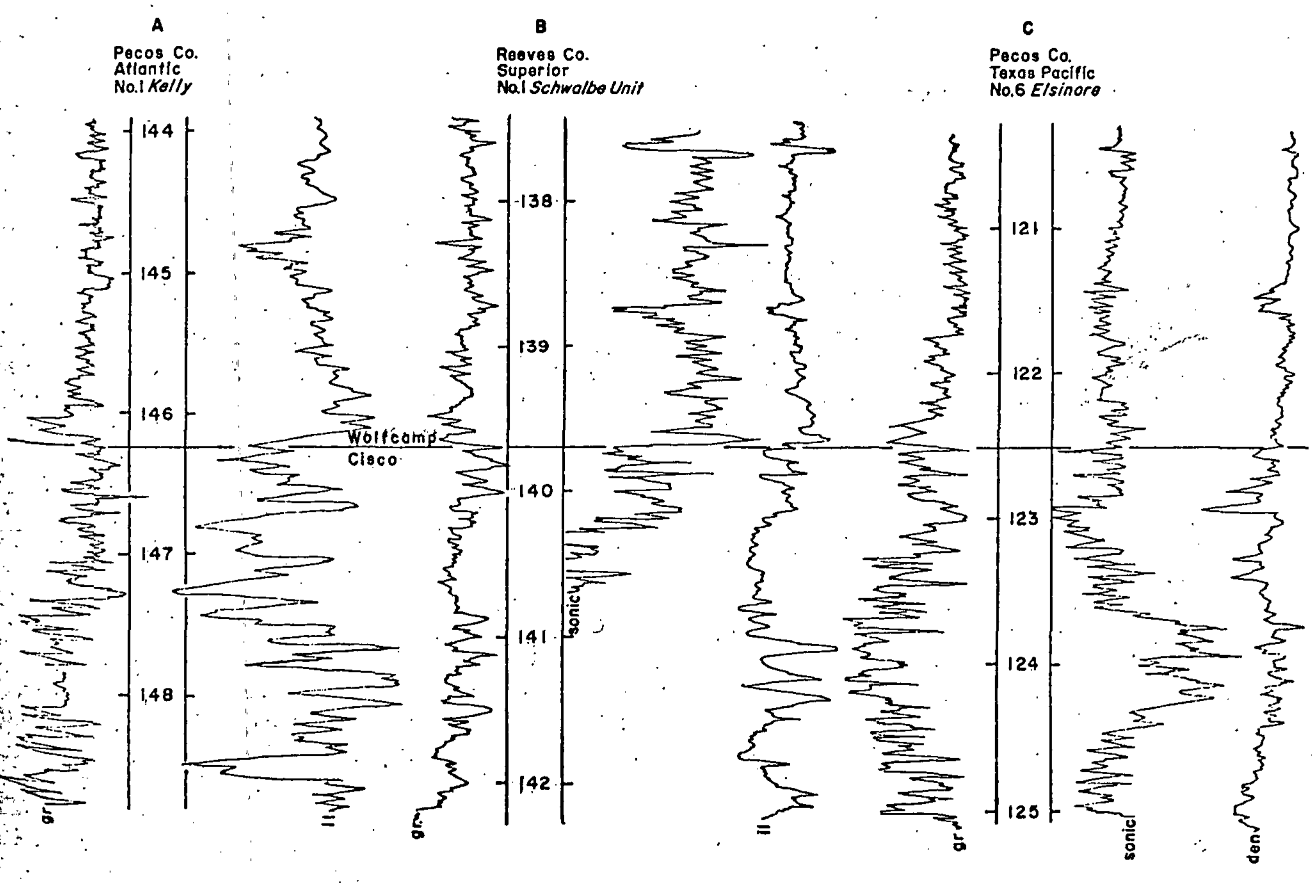

Fig. 16—Typical Cisco-Wolfcamp contacts in central and southern Delaware basin.

used to see the precise relationship of the curves. Even so, success is not nearly as certain as in Eddy County, New Mexico, and the Midland basin.

LOG VALUES OF UPPER CISCO SHALES

Gamma Ray

The gamma ray curve is the simplest and most reliable means of distinguishing the peculiar basinal shale members of the Cisco from the basal Wolfcamp shale. For comparison, the Woodford, probably contains about .01 per cent uranium here, as elsewhere, which is 33 micrograms of radium equivalent per ton of formation. Since the left half of the log is scaled to read a total of anywhere from 6 to 14 micrograms, the complete curve of the Woodford cannot be shown. Next most radioactive are the organic members of the basinal Chester shale, which contain 10 to 13 micrograms. The Cisco shales are less radioactive than the Chester shales, and the basal Wolfcamp is the least radioactive of all. This might suggest that a source of uranium uncovered after the uplifts in the middle of the Devonian was becoming exhausted, but the rate of deposition and the amount of organic matter on the sea bottom are likely more important, and certainly much more important in a comparison of Cisco and Wolfcamp values.

Precise quantitative determinations are not always possible. A few older logs have the appearance of having been run too fast. Perhaps unusually thin members in the bottom of the Delaware basin are overlooked by the tool. Statistical variations can be averaged out, but borehole conditions, such as hole diameter, mud weight, cement and casing (if any) can affect the reading considerably if they are not standard. Corrections can be made but the conditions are not always known. On some logs the scale is not shown and the tool is not specified. A sampling of logs suggests that 6.3 micrograms might be an average for the basal Wolfcamp shale and 8.1 for the Cisco peaks. This difference is easily discernible on the log and there is rarely an overlap. In the eastern Midland basin values seem to be higher but the proportion is similar.

Sonic

The sonic log indicates zones of low velocity, which in a carbonate rock are deduced to contain oil, gas, or water. Since the identity of the substance cannot be determined without further information, the device is classed as merely a porosity tool. In a shale section the rock is already known to have high porosity containing all salt water, unless the velocity is low, in which case some residual organic matter is present.

The Woodford Shale, with up to 20 per cent organic matter, might be expected to have the highest transit time, especially the middle member. However, the middle member also contains the most chert and pyrite and therefore reads only 60 to 75 microseconds per foot compared to 82 to 90 in the top and bottom. The Chester organic shales, consisting entirely of shale, read 103 to 118 microseconds. Peaks in the Cisco organic shales are from 95 to 102 microseconds. It is hardly possible to calculate the amount of organic matter there without knowing its composition and the salinity and amount of water also in the shale. The basal Wolfcamp shale averages about 85 microseconds.

Of course, where there has been unusual compaction due to great depth, and squeezing due to tectonism, sonic values will be different.

Density

One might reason that the density of the upper Cisco shales should be higher than that of the basal Wolfcamp shale because of greater depth, greater age, higher uranium content, and finer texture. However, these factors are overriden by the high organic content, and the density pattern faithfully follows the others. The Woodford, Mississippian, and Cisco shales seem to have about the same maximum density. The lightest Cisco black shale members average 2.40 and the heaviest ones 2.55; the lower pair are generally the lightest ones. The basal Wolfcamp shales are surprisingly uniform, averaging 2.60. While these differences may seem small, they are quite consistent, and appear large on field prints.

Some figures from other areas may be of some interest because of recent discussions of the possibility of the commercial extraction of oil from oil shale in this country. In the Woodford equivalent in Kentucky, where pyrite is the greatest source of error, the oil yield was zero at a specific gravity of 2.679, and 24 gallons per ton of rock at 2.077. The organic matter had a gravity of 1, normal mineral matter 2.7, and pyrite 5.

In the Green River Formation of the Piceance basin in Colorado experiments in density logging revealed that "shale" with a density of 2.4 yields 12½ gallons per ton. The famous Mahogany ledge is 60 feet thick and would yield 34 gallons of "oil" per ton; density of this rock would be 2.025. The Green River can hardly be called a shale, furthermore, it was deposited rapidly in very shallow water.

Self Potential

This curve is of less value today in many of the deeper wells because of the drilling muds used now. It should show a very slight positive (to the right) deflection, attributed to the organic content of the shale. A strong negative deflection means that someone has mistaken a Wolfcamp limestone or sandstone for a Cisco shale.

Resistivity

The many kinds of resistivity logs used in the last several decades under various conditions all record a similar pattern of peaks for the Cisco black shales, resembling the maxima in the Chester and Woodford organic shales and higher than anything in the Wolfcamp shale. These Cisco peaks coincide with the anomalies on the gamma ray, sonic, and density logs; they do not indicate a calcareous element, but rather the presence of a non-conductive substance in place of part of the salt water tightly held in the shale. The actual values of the apparent resistivities are of little importance because it is not possible to determine the amounts of water and hydrocarbon in the shale due to lack of knowledge of the resistivity of the formation water. On the older conventional logs the peaks are three or four times as high as the Wolfcamp shale, and about one third as high as Pennsylvanian limestone.

Laterologs, reading closer to the true resistivity of the shale, show greater relief for the Cisco members, unless plotted on a logarithmic scale. The microlog device, mounted on a pad in contact with the shale, also records greater contrast, and is often accompanied by a caliper survey which sows the black shales do not cave like the ordinary shales above and below.
The Athabasca tar sands are evaluated for their hydrocarbon content by a combination of density, gamma ray, sidewall neutron, and laterolog surveys. These agree quite well with the abundant information from cores, the main difference being in the shaly sections. Similar core information on the Cisco black shales would be very helpful in setting up parameters for electric logs, but cores and micrologs are hardly appropriate in this uneconomic part of the section.

WOLFCAMP

That the Wolfcamp in the basins looks like the Pennsylvanian is too general a statement to be of value. The Wolfcamp, if we could see it on the outcrop, would not resemble the upper part of the Pennsylvanian; it would remind us of the Morrow. The Morrow of the basins has a lower section of shale which has been confused in well cuttings with the much more slowly deposited Chester, characterized by radioactive shale members. This lower shale of the Morrow is succeeded by coarse clastics, indicating deeper erosion of the source of the sediment. What has made the Wolfcamp a more difficult problem than the Morrow is the abundant caving of the long-ranged genus Schwagerina through the lower barren shale and across the systemic boundary. The electric log curves can be easily misinterpreted.

The event that causes the Wolfcamp sedimentation to differ from that of the Late Pennsylvanian is the orogeny that occurred in a number of places in the United States, usually as a resumption of activity that began at the start of the Pennsylvanian. In the region under discussion the most important uplifts were the Amarillo-Wichita arch, the Matador-Red River arch, the Pedernal-Diablo trend, the Ouachita-Marathon geosyncline, the Central Basin platform, and an uplift along the southwest margin of the Delaware basin. These elements rose simultaneously, also vertically, according to some who have studied the subject more than the writer, except for the advancing Ouachita-Marathon geosyncline.

The latter structure continued to be thrust toward the craton until late in Wolfcamp time, so that in Pecos County it overlies most of the thick Wolfcamp section. Its north edge is only 5 or 10 miles south of pre-Mississippian gas production, and can be approximated by a thick wedge of green and red shale of Wolfcamp age derived from the thrust, containing pieces of rock as old as Ordovician, and some huge slabs of Pennsylvanian shale. The original thickness of the wedge is uncertain because the original steep dips have been modified by continued shoving from the south. Surely some of the beds are turbidites, reworked from older turbidites. The base of the lower Wolfcamp is far below this wedge and well below the thrust itself and can be discussed along with the country to the north.

The maximum thickness of Wolfcamp in the Permian basin was derived from Pennsylvanian and older sediments of the folded and overthrust geosyncline moving northward; it thus tends to parallel the geosyncline. This thick Wolfcamp is called the Val Verde basin, and merges with the Delaware basin at its west end (Vertrees, et al., 1960). In Val Verde County the Wolfcamp shale with thick wedges of sand is over 14,000 feet thick; since it is truncated by the Cretaceous farther south, the thickness there can only be estimated as being "greater." The southernmost gas well in Pecos County, south of the West Grey Ranch field drilled over 17,000 feet of Wolfcamp clastics. Probably a large part of the Wolfcamp is dipping steeply, but some of the dip is undoubtedly depositional.

As mentioned previously, the basal Wolfcamp shale may superficially resemble the Upper Pennsylvanian shale in the Delaware basin, because the basinal Pennsylvanian shale was uplifted, eroded, and redeposited in the southwest part of the basin, as at the Tidewater well on figure 17. Furthermore, the Mississippian shale was exposed not only there but also over the Central Basin platform, from which it was largely removed. Logs can distinguish the two, but the danger is that one will be distracted by a coarsely clastic Wolfcamp member overlying Wolfcamp shale. Some people have thought that such clastics would have to be subaerial deposits, and that the contact represents a subaerial unconformity. Study of the deepwater channels and turbidites exposed in the middle Permian outcrops southwest of Carlsbad, New Mexico, should eliminate such notions.

Figure 14 shows two lenses of conglomerate deposited in the lows on either side of the El Paso No. 1 Grisham and Hunter. These turbidites must have cut channels in the lows before filling them, because the

Northern Trans-Pecos magmatic province: Introduction and comparison with the Kenya rift

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ABSTRACT

The Trans-Pecos magmatic province of West Texas and southern New Mexico is a more eroded analogue of the Kenya (Gregory) rift in East Africa. Trans-Pecos alkalic rocks are similar to the basalt-phonolite-trachyte-rhyolite assemblage from fissure and multicenter eruptions, and from some central volcanoes, in the Kenya rift. In both provinces, quartz-normative and nepheline-normative mafic rocks occur, providing likely parents for the entire observed range of silica saturation. Thus, no special mechanism is needed for deriving silica-undersaturated and silica-oversaturated rocks from one another, because both groups evolved independently. The Kenya rocks tend to be more mafic and, at the silicic end of their compositional range, more peralkalic than the Trans-Pecos rocks.

Similarities in tectonic style, extent and duration of magmatism, and igneous rock compositions in the two provinces suggest that the alkalic rocks in both regions were generated by differentiation from quartz- and nepheline-normative parents in the upper parts of elongate mafic or ultramafic intrusions, probably diapiric welts that caused doming and normal faulting.

INTRODUCTION

Cenozoic alkalic rocks occur in a diffuse belt along the eastern margin of the North American Cordillera from Montana to Mexico (see Barker, 1974, for a bibliography and list of occurrences). The Trans-Pecos magmatic province, a segment of this belt, is delimited on the east by the Pecos River, on the south and west by the Rio Grande, and on the north by a line 12 km north of the Texas–New Mexico boundary (Fig. 1). Rocks of the same types and ages as in the Trans-Pecos province extend for at least 200 km southeast into Mexico (Daugherty, 1965; Sewell, 1969; Bloomfield and Cepeda-Davila, 1973; Robin, 1974).

This paper is the first of a series on the Trans-Pecos province (see Barker and Hodges, 1977; Barker and others, 1977), integrating results of field, petrographic, chemical, electron microprobe, experimental and isotopic investigations conducted by staff and students of the University of Texas at Austin. To provide an overview and to point out the petrologic problems to be treated in succeeding, more detailed papers, this introduction compares the northern part of the Trans-Pecos province with a classic intracontinental magmatic province, the Kenya rift.

The Trans-Pecos province, with an area equal to that of Vermont and New Hampshire, contains more than 200 intrusive bodies with outcrop areas exceeding 1 km² and extensive, thick, and stratigraphically complex volcanic sequences. In this project, we have scanted the southern third of the province, specifically the Solitario-Terlingua region (Lonsdale, 1940) and Big Bend National Park (Maxwell and others, 1967; Carman and others, 1975).

STRUCTURE

Faulting and Warping

Cenozoic structural elements and igneous centers of the Kenya rift and the Trans-Pecos province are shown at the same scale in Figure 2. In the Trans-Pecos, north-trending faults are assumed, from their orientation and age, to be basin-and-range faults. At least in part, north-northwest-trending faults and flexures are reactivated Precambrian and Paleozoic dislocations (King, 1965, p. 103–107; Twiss, 1970). Displacement on some faults probably exceeds 1 km (Wiley, 1970, p. 121). Basin-and-range faulting apparently was most ac-

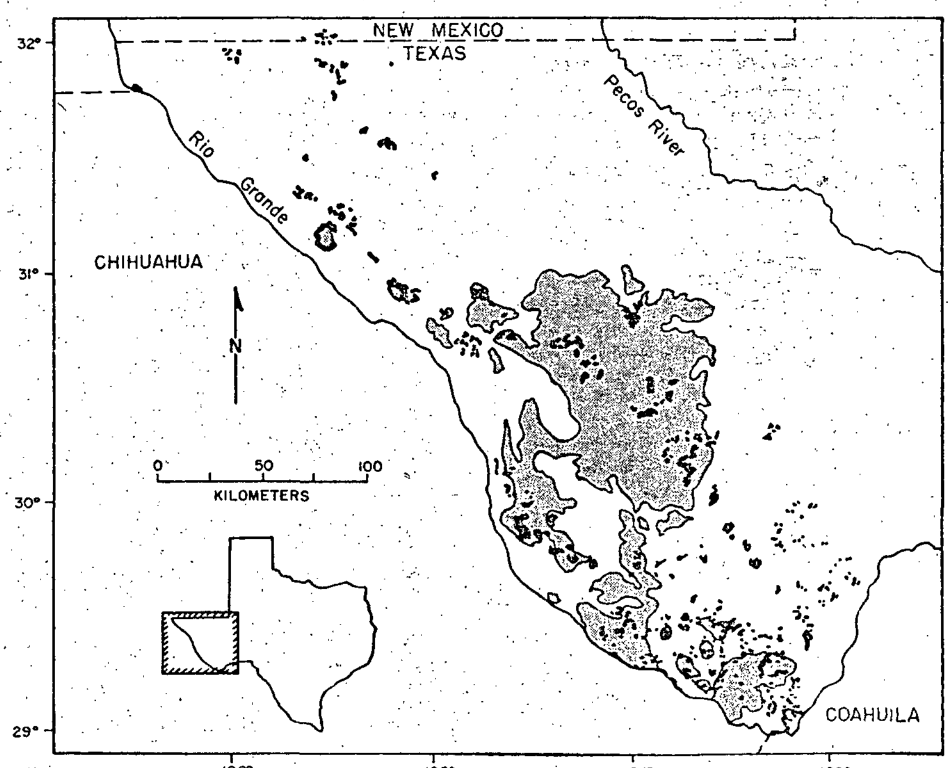
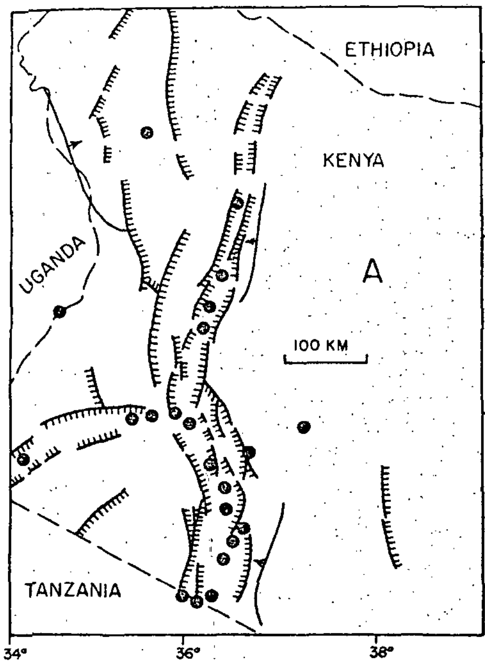


Figure 1. Distribution of Cenozoic igneous rocks, Trans-Pecos magmatic province. Intrusive rocks are shown in black; lavas and pyroclastic rocks are shown by stippled pattern.

Geological Society of America Bulletin, v. 88, p. 1421–1427, 5 figs., October 1977, Doc. no. 71004.



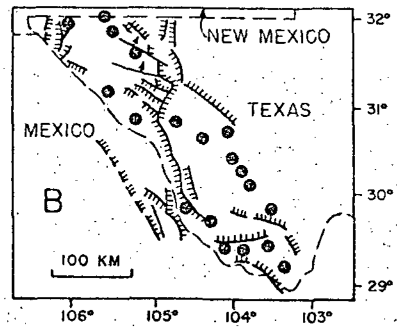


Figure 2. A, Tectonic sketch map of the Kenya rift, generalized from B. H. Baker and others (1971, p. 193) and Baker and Wohlenberg (1971, p. 539). B, Tectonic sketch map of the Trans-Pecos province, generalized from Wiley (1970) and Gries and Haenggi (1970). Solid circles are volcanos in A and major intrusive complexes in B. Hachured lines indicate Cenozoic normal fault (hachured on downthrown side). Arrows indicate monocline.

tive in Miocene time (Stevens, 1969), but earlier Cenozoic and later Quaternary displacements are known (McKnight, 1968; Wilson, 1970; Dasch and others, 1969), and seismic activity continues (Sellards, 1932; J. Dorman, 1975, oral commun.). The Mitchell Mesa ash-flow tuff covered an area originally extending for at least 8,000 km² in the southwestern part of the Trans-Pecos province; at the time (32 m.y. B.P.) that this pyroclastic blanket formed, the underlying surface had not been displaced by basin-and-range faults (Burt, 1970).

C. L. Baker (1934, p. 169), without mentioning the strong petrologic similarities, applied the term "rift valleys" to the Trans-Pecos province, because he considered the structure and physiography to be analogous to those of the Kenya rift. The correspondence is not precise (Fig. 2); the more diffuse Trans-Pecos fault pattern produced discontinuous grabens interrupted by irregular plateaus, not a continuous valley as in Kenya.

Rift faulting in Kenya began in early Pliocene time and is still continuing (B. H. Baker and others, 1972, p. 45). Normal faults of the Kenya rift lie along the crest of a dome 1,000 km wide that rose 300 m in late Miocene time and an additional 1,400 m during late Pliocene to middle Pleistocene time (Baker and Wohlenberg, 1971, p. 538). These faults are locally controlled by Precambrian structural trends. Throws on the major faults are as much as 3 or 4 km (Baker and others, 1972, p. 27).

Doming in East Africa is indicated by upwarping of broad, low-relief erosion surfaces. In the Trans-Pecos province, similar erosion surfaces have locally survived. An "early Tertiary" surface, marked by a thin, widespread, but only locally preserved conglomerate, and another surface created by a Miocene episode of extensive postvolcanic planation have been recognized (R. K. DeFord, 1973, oral commun.). Reconstruction of regional crustal arching will not be feasible until accurate topographic maps are available for the entire area. King (1965, p. 111) cited local and incomplete evidence for broad post-Cretaceous doming in the extreme northern end of the Trans-Pecos province.

Forms of Magmatic Rocks

In the northern third of the Trans-Pecos province, extrusive and pyroclastic rocks are rare; laccoliths, sills, and plugs are the most common forms. To the southeast, volcanic rocks become abundant, and some lavas and pyroclastic units have been traced to their sources in poorly preserved calderas. Fissure and multicenter eruptions have not yet been distinguished, owing to the advanced degree of erosion. One ring dike and two cone sheets have been found, but ring complexes, so characteristic of many alkalic provinces, are surprisingly scarce. Major intrusive complexes (Fig. 2B) are situated in horsts as well as in grabens. Thick bolson fill probably covers other igneous bodies in the down faulted blocks. Thus, in contrast to the situation in Kenya, erosion has bared high-level intrusive bodies and has dissected volcanic sequences, but erosion and deposition have severely obscured or destroyed primary extrusive features.

In the Kenya rift, erosion has not yet exposed intrusive bodies, except for volcanic necks and minor dikes and sills. Magmatic activity is therefore expressed almost entirely by lava and pyroclastic rocks. Fissure and multicenter eruptions are voluminous in the rift and on its flanks, but volcanic edifices built from single centers (Fig. 2A) are confined, with the exception of the two largest, Mount Elgon and Mount Kenya, to the floor of the rift and its westward branch, the Kavirondo graben (Williams, 1972).

Gravity Anomalies

Searle (1970) demonstrated that a positive Bouguer gravity anomaly, as much as 30 to 60 mgal and 40 to 80 km wide, coincides with the long axis of the Kenya rift. These observations are best explained by Searle's model, which incorporates an intrusion 20 km wide that reaches to within 2 km of the rift floor in places and is composed of rocks with a mean density of 2.9 g/cm³ (denser rocks yield poorer calculated fits to the observed gravity profiles). Other model interpretations of the positive axial gravity anomaly include an intrusion 10 km wide or a wider, more diffuse zone of dikes (Baker and others, 1972, p. 45).

Reconnaissance gravity studies in the Trans-Pecos area have failed to reveal a linear positive Bouguer anomaly (Woollard and Joesting, 1964), but an anomaly similar to that in the Kenya rift may be detected by more closely spaced observations. Gravity profiles across the northern end of the Trans-Pecos province, approximately along lat 31°45′N, have been made independently by Decker and Smithson (1975) and by K. A. Cortes (1975, written commun.). Both profiles show a positive Bouguer anomaly of approximately 25 mgal on the trend of Cenozoic intrusions in the Diablo Plateau (Barker and others, 1977). Whether this anomaly truly indicates dense intrusive rock at depth or merely is an edge effect near the major fault bounding the Diablo Plateau horst cannot be resolved without additional traverses across the intrusive belt farther south.

PETROLOGY

Rock Types

The Kenya rift and the Trans-Pecos province exhibit a distinctive assemblage of basaltic and sodium-rich feldspathoidal rocks, trachytes, and rhyolites. Prior (1903, p. 235) and Smith (1931, p. 234–236) pointed out similarities between the sodic rhyolites and phonolites of Kenya and the Trans-Pecos.

Central volcanoes in the Kenya rift contain two suites — the basalt-phonolite-trachyte-rhyolite and the nephelinite-phonolite assemblages (Williams, 1972). Rocks of fissure and multicenter eruptions (the "plateau volcanics") belong almost entirely to the first group (Williams, 1971, p. 443; Saggerson, 1970, p. 40, 73).

Nephelinites and melilite-bearing rocks are not known in the Trans-Pecos province. Neither are carbonatites, which are sparsely present in the nephelinite-phonolite assemblage in Kenya. A nephelinite-phonolite suite does occur in Texas, in the Balcones magmatic province (Spencer, 1969): this province is older (Late Cretaceous), it lies east of the Pecos River, and it trends roughly at right angles to the Trans-Pecos province.

Compositions

Table 1 compares analyses of alkalic rock types in the northern Trans-Pecos province with those of the basalt-phonolite-trachyte-rhyolite assemblage of the Kenya rift floor and plateau volcanic rocks. Averages for the Kenya rocks do not include analyses from central volcanoes of the nephelinite-phonolite suite.

Mafic and intermediate rocks, those with a differentiation index (Thornton and Tuttle, 1960) of less than 64, are divided according to the classification used by P. E. Baker and others (1974). Basalt has normative plagioclase with at least 50% anorthite; hawaiite, 30% to 50% anorthite; and mugearite, 15% to 30% anorthite. Only one analyzed sample in the northern Trans-Pecos province has sufficiently calcic normative plagioclase (Table 1) to be called basalt; similarly, only one of the Kenya samples satisfies the definition of mugearite. The extent to which these disparities in numbers of samples reflect actual differences in abundance is of course unknown.

Of 28 analyzed samples of Trans-Pecos basalt, hawaiite, and mugearite, 16 are nepheline-normative and 7 are quartz-normative. Of 22 similar rocks from Kenya, 9 are nepheline-normative and 7 are quartz-normative. The presence of both silica-oversaturated and silica-undersaturated mafic and intermediate rocks is significant. Parental magmas were available to form silica-oversaturated and silica-undersaturated differentiates. There has been much speculation concerning mechanisms by which quartz-bearing and feldspathoidal rocks might be derived from the same parent at crustal levels (Edgar, 1974). The region of magma generation under intraplate igneous provinces may extend through a large vertical range, tapping magmas with wide variation in silica saturation, perhaps during ascent of a diapir. Later fractionation and mixing of the coexisting magmas could yield the spectrum of rock types observed, from phonolite to rhyolite, without any liquid changing composition across a thermal divide during crystallization.

Phonolites and their intrusive equivalents, abundant and distinctive rocks in both provinces, are not strongly peralkalic on the average, thus contrasting with the rhyolites. Of all the rock types, trachytes show the greatest variation, both within and between provinces.

The Kenya rhyolites are more mafic than the persodic rhyolites of the Trans-Pecos province. A large amount of rhyolitic rock in both regions is in the form of ash-flow tuff. In the Trans-Pecos, rhyolite containing sodic amphibole forms shallow intrusive

TABLE 1. AVERAGE COMPOSITIONS AND CIPW NORMS FOR ALKALIC IGNEOUS ROCKS OF THE NORTHERN TRANS-PECOS PROVINCE AND THE KENYA RIFT

	Basalt		Hawaiite		Mugearite		Phonolite and nepheline syenite		Trachyte and syenite		Rhyolite	
No. of analyses:	T 1	K 12	T 15	K 9	T 12	K 1	T 29	K 32	T 23	K 22	T 12	K 14
SiO_2	45.53	45.79	47.09	49.89	52.71	51.53	58.02	56.53	64.08	61.53	72.32	71.62
TiO_2	2.60	2.77	2.75	2.28	1.93	2.44	0.20	0.74	0.41	0.77	0.16	0.29
Al_2O_3	16.06	16.27	16.28	16.97	16.79	16.63	18.19	17.73	16.59	14.15	12.98	9.72
Fe_2O_3	2.81	3.74	4.83	4.57	4.70	5.53	3.61	3.38	3.18	3.73	2.16	2.03
FeO	7.36	8.16	6.92	5.95	3.80	3.45	2.03	3.32	0.97	4.21	1.17	4.21
MnO	0.17	0.17	0.18	0.24	0.17	0.23	0.27	0.28	0.16	0.29	0.12	0.19
MgO	7.41	6.55	4.76	3.57	2.49	2.44	0.21	0.81	0.28	0.47	0.08	0.10
CaO	9.63	10.76	7.62	7.33	5.30	6.06	1.50	1.99	1.11	1.53	0.29	0.42
Na_2O	4.11	2.71	4.04	3.92	4.93	4.90	7.99	7.24	6.17	6.95	5.22	6.29
K_2O	2.74	0.98	1.82	2.29	3.44	2.83	5.15	5.23	5.30	4.83	4.71	4.41
P_2O_5	0.78	0.49	1.03	0.78	1.30	0.83	0.12	0.18	0.14	0.21	0.03	0.03
q	..	..	..	..	0.29	..	..	..	5.45	0.57	23.81	27.75
or	16.19	5.79	10.75	13.53	20.32	16.72	30.43	30.90	31.31	28.54	27.83	26.06
ab	9.20	22.93	33.58	33.17	41.72	41.46	43.03	40.19	52.21	45.90	40.55	25.45
an	17.28	29.34	20.91	21.95	13.53	15.03	..	0.44	1.92	..	..	..
ne	13.86	..	0.33	..	..	..	11.85	11.42	..	..	..	..
ac	..	..	..	..	..	..	2.39	..	..	10.79	3.19	5.87
ns	..	..	..	..	..	..	..	..	..	0.15	..	4.91
di	20.43	16.84	8.17	7.52	3.34	7.76	4.14	6.89	2.26	5.42	1.08	1.67
wo	..	..	..	..	..	..	0.77	..	..	..	..	..
hy	..	0.83	..	8.25	4.87	0.54	..	..	0.95	5.35	0.87	6.97
ol	11.42	10.84	8.96	0.61	..	3.27	..	0.87	..	..	..	..
mt	4.07	5.42	7.00	6.63	6.81	4.80	4.04	4.90	2.46	..	1.53	..
il	4.94	5.26	5.22	4.33	3.67	4.63	0.38	1.41	0.78	1.46	0.30	0.55
hm	..	..	..	..	..	2.22	..	..	1.48	..	..	..
ap	1.85	1.16	2.44	1.85	3.08	1.97	0.28	0.43	0.33	0.50	0.07	0.07

Note: CIPW norms are in weight percentage. T = northern Trans-Pecos province; K = Kenya rift.

Data for Kenya are taken from analyses in Baker (1958), Bowen (1937), Macdonald and Bailey (1973), Macdonald and others (1970), McCall (1967), McCall and Hornung (1972), Nash and others (1969), Saggerson (1952, 1970), Sceal and Weaver (1971), Smith (1931), and Weaver and others (1972).

Trans-Pecos averages are of analyses in Clarke (1904), Erickson (1953), Goldich and Elms (1949), Meigen and Nachreiner (1925), Osann (1896), Richardson (1909), Twiss (1970), three unpublished analyses by D. A. Schofield and J. Etheredge (Univ. of Texas Bureau of Economic Geology), and 73 new analyses by G. K. Hoops (Barker and others, 1977).

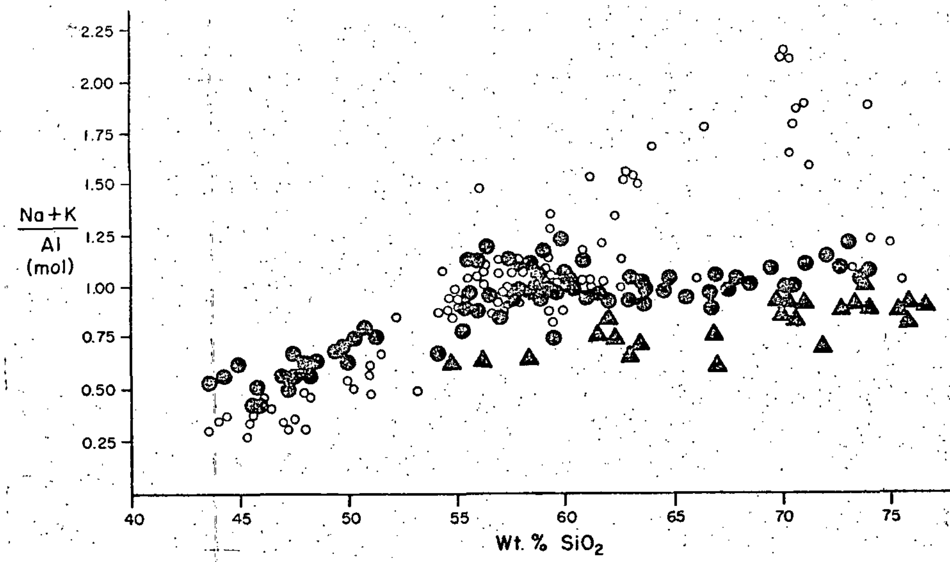
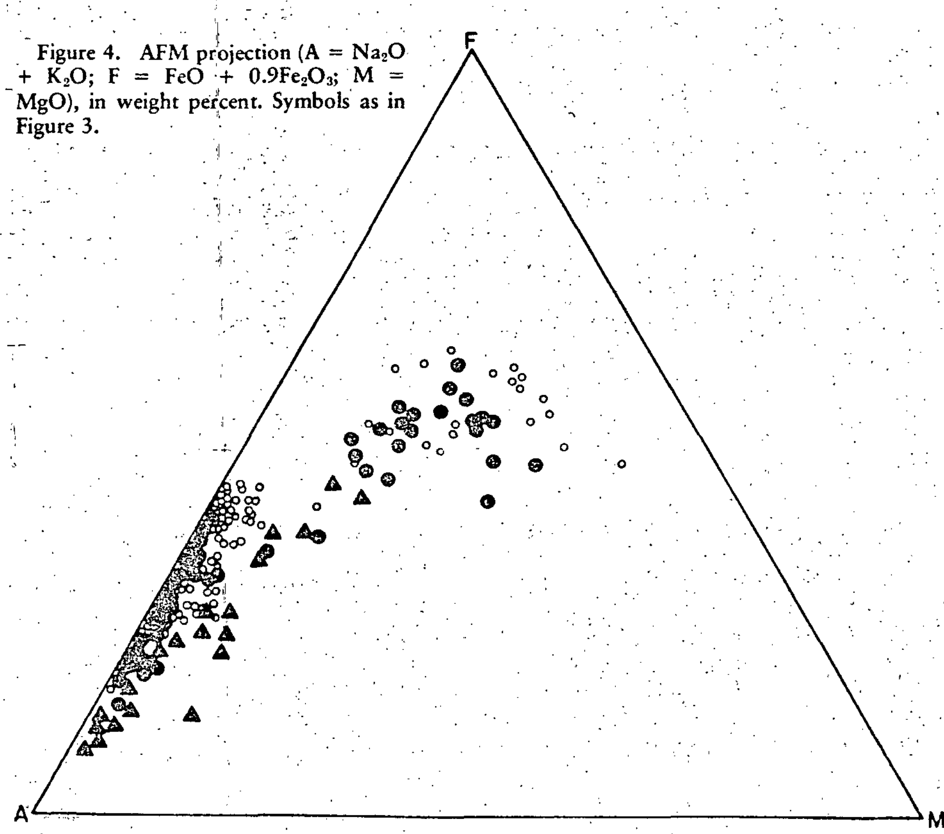


Figure 3. Molecular ratio (Na + K)/Al versus weight percent SiO_2. Open circles = Kenya rift; solid circles = Trans-Pecos alkalic rocks; and triangles = Trans-Pecos metaluminous rocks.

bodies with the same composition as widespread ash-flow tuffs and numerous flows.

Despite differences between the averages in Table 1, there is considerable overlap between individual analyses from the two provinces (Figs. 3, 4). On the (Na + K)/Al versus SiO_2 diagram of Figure 3, the Kenya rocks show a more pronounced and linear increase in peralkalinity with increasing silica. The trends for the two provinces intersect in the compositional range of phonolites (55% to 60% SiO_2 by weight), but the Trans-Pecos mafic and intermediate rocks are more peralkalic, and rhyolites less peralkalic, than the corresponding Kenya rocks. Trans-Pecos samples with more than 60% silica by weight show no significant change in peralkalinity from trachyte to rhyolite. Greater peralkalinity in Kenya rhyolites probably reflects the greater abundance of analyzed glasses. Trans-Pecos rhyolites are more commonly holocrystalline, and the loss of alkalis during crystallization and devitrification has been amply demonstrated (Macdonald and Bailey, 1973). The AFM plot in Figure 4 emphasizes the similarities of the two provinces but shows the greater depletion of Fe and Mg in the Trans-Pecos rocks.

Figure 4. AFM projection (A = $Na_2O + K_2O$; F = FeO + $0.9Fe_2O_3$; M = MgO), in weight percent. Symbols as in Figure 3.



Twenty-four Trans-Pecos analyses plotted in Figures 3 and 4 as triangles are not included in Table 1 because they have no Kenya analogues. They represent a petrologically and geographically distinct group with, relative to the alkalic rocks, lower (Na + K)/Al, Ti, Fe, Mn, and P and higher Si, Al, Mg, and Ca. To distinguish them from the more alkalic rocks, the term "metaluminous" is used (Shand, 1951, p. 50–51) for these rocks in which (Na + K)/Al is less than one, but (Na + K + Ca)/Al exceeds one. None of the Trans-Pecos metaluminous rocks is feldspathoidal.

Initial $^{87}Sr/^{86}Sr$ ratios for alkalic rocks in the northern part of the Trans-Pecos province range upward from 0.703 (Hedge, 1966; Long and others, 1971; Barker and others, 1977). The lower values are similar to those of oceanic basalts and are consistent with magma generation in the mantle. No strontium isotope ratios have been published for the plateau volcanic rocks of the Kenya rift.

Times of Emplacement

Magmatism in the Trans-Pecos province and in the Kenya rift lasted a similar amount of time, from 43 to 16 and 23 to 0 m.y. B.P., respectively. Trans-Pecos ages are given by Parker and McDowell (1973) and Barker and others (1977). Kenya ages are summarized by Baker and others (1971).

Abundances

The Trans-Pecos igneous rocks, although occurring throughout a region nearly as large as the Kenya rift, are much less abundant, probably because erosion, having removed a large portion of the erupted rocks, is now exposing narrow conduits and the tops of small subvolcanic chambers.

Williams (1972) estimated the abundance of rock types in the Kenya rift. Of the plateau volcanic rocks, volumes are 60,000 km³ for basaltic rocks, 25,000 km³ for phonolite, and 20,000 km³ for trachyte and rhyolite. Central volcanoes total a volume of 39,000 km³, but volumes of specific rock types cannot be estimated because flanks of the volcanoes are so little dissected.

In the northern Trans-Pecos province, the intrusive equivalents of phonolite, trachyte, and rhyolite are each estimated to total between 10 and 20 km³ of rock exposed or conservatively inferred at shallow depth. Intrusive basalt, hawaiite, and mugearite form approximately 1 km³. The total preserved volume of lavas and pyroclastic rocks is on the order of 5,000 km³, with rhyolite the most abundant. At least another 20,000 km^3 is represented by volcanic rock fragments in Oligocene and Miocene sedimentary rocks in the Gulf Coast.

Sequence

In the Kenya rift (Williams, 1972), basalt was erupted first among the plateau volcanic rocks (23 to 14 m.y. B.P.), mostly northwest of the subsequently formed graben system, followed by phonolite (13.5 to 11 m.y. B.P.). Smaller quantities of basalt and phonolite continued to erupt into Holocene time. Trachyte and rhyolite, including ash-flow tuff, were dominant in the span 7 to 2.5 m.y. B.P. and were subordinate to basalt from 2.5 m.y. B.P. to the present.

In the Trans-Pecos province, the oldest and youngest flows are mafic to intermediate (Maxwell and others, 1967; Twiss, 1970); mugearite and hawaiite are more common in the younger rocks. Feldspathoidal rocks are younger than some rhyolites and are contemporaneous with some trachyte and quartz syenite. In the Paisano Pass volcanic-intrusive complex (Parker, 1975), the sequence was rhyolite-trachyte-mugearite and phonolite.

Petrogenesis

Few of the central volcanoes of the Kenya rift have erupted all members of the basalt-phonolite-trachyte-rhyolite assemblage. Many show distinctly bimodal abundances of rock types. Sceal and Weaver (1971, p. 331) concluded that the basalts, mugearites, and trachytes of Paka volcano cannot "have originated from independent sources or by different processes." Similarly, McCall and Hornung (1972, p. 100) decided that basalt, phonolite, trachyte, and rhyolite are comagmatic at Silali volcano. Weaver and others (1972, p. 192) inferred that "a dyke-like basaltic body of batholithic proportions" differentiated into more salic liquids in cupolas to produce the diversity observed in Kenya volcanoes.

Whole-rock and mineral compositions (see Barker and others, 1977; Barker and Hodges, 1977) demonstrate genetic links among the Trans-Pecos rocks and suggest that they attained their wide variety of compositions by crystal fractionation within the crust, although oversaturation or undersaturation of silica was predetermined when the parent magmas were generated. Chilled selvages and cognate inclusions, some of the latter with cumulus texture, permit us to follow magmatic evolution from silica-oversaturated and silica-undersaturated hawaiites and mugearites by divergent trends to phonolite and rhyolite.

INFLUENCE OF BASEMENT HETEROGENEITY

The Kenya rift cuts basement rocks that are approximately homogeneous with respect to age and tectonic history (Baker and others, 1972, p. 7). Variations in the basement of the Trans-Pecos province, under a 2- to 3-km section of Paleozoic and Mesozoic sedimentary rocks, may have influenced the composition of Cenozoic igneous rocks. Although the metaluminous rocks were emplaced at the same time as the alkalic rocks, according to K-Ar ages cited by Twiss (1970, p. 150), the two suites occur in separate belts (Fig. 5). Basement beneath the metaluminous strip is the Van Horn tectonic belt (Flawn, 1956), which contains a section at least 6 km thick of metamorphosed sandstone, arkose, and limestone intruded by diorite and granite. About 1,000 m.y. ago, these rocks were folded and thrust against the Texas craton, a fairly homogeneous terrane of granite and rhyolite.

The metaluminous Cenozoic rocks were emplaced only within the area underlain by the Van Horn tectonic belt, and alkalic rocks were emplaced through the Texas craton at the same time. The geographic and compositional differences may reflect variations in parent magmas rather than interaction between mantle-derived magma and crustal rocks.

IMPLICATIONS OF LINEARITY

Exposures of feldspathoidal rocks in the Trans-Pecos province (Fig. 5) lie in a linear array 325 km long. From the northern to the southern ends of this chain, rocks of virtually identical composition and texture crop out, suggesting that one magmatic reservoir, or a series of chambers exhibiting the same distinctive behavior, underlies the alkalic belt. The extent is comparable to that of the reservoir that fed the 25,000 km^3 of phonolite in plateau volcanic rocks of the Kenya rift. No variation in age has yet been recognized from one end of the Trans-Pecos belt to the other, such as would be produced by a lithospheric plate moving over a plume or hot spot.

McCall and Hornung (1972) suggested that a chain of cupolas, probably extending upward from an intrusive body like that inferred by Searle (1970) from the positive Bouguer anomaly, lies under the floor of the Kenya rift and that extreme differentiation produced alkalic magmas from subjacent basaltic liquid. It is possible that the basalt, in turn, was derived from, or served as lubricant for, a diapiric welt of mantle rock.

Perhaps fortuitously, the Trans-Pecos belt of alkalic magmatism is parallel to the nearest boundary of the American plate, and this magmatism was contemporaneous with the most rapid Cenozoic spreading on the Pacific-Farallon plate boundary (Larson and Pitman, 1972, p. 3655).

Nevertheless, the relationship of Trans-Pecos igneous activity to subduction remains obscure. Lipman and others (1972, p. 235) estimated a depth of 400 km to an Oligocene Benioff zone under West Texas. Many more rock analyses are now available than were used by them in estimating the K_2O content at a given silica percentage, but their result (5.0% K_2O normalized at 60% SiO_2) is not changed by the newer data. Correlation of potassium content with depth of magma generation is suspect, as Lipman and others (1972) recognized, because the Trans-Pecos rocks are certainly not akin to circum-Pacific calc-alkalic island-arc lavas, on which the depth estimate is based (Hatherton and Dickinson, 1969).

Christiansen and Lipman (1972, p. 254) used an estimated time of transition (30 to

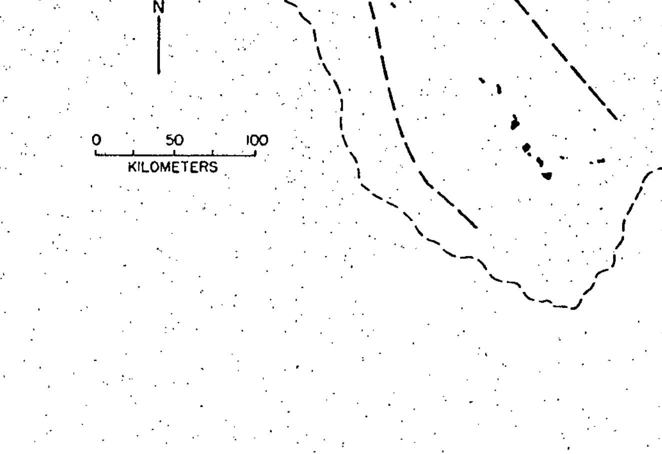


Figure 5. Tentative boundary between alkalic and metaluminous Cenozoic intrusions, Trans-Pecos magmatic province. Outcrops of phonolite and nepheline syenite are shown in black.

23 m.y. ago) from "andesitic calc-alkalic volcanism" to bimodal basalt-rhyolite volcanism in Trans-Pecos Texas as one data point in their plate tectonic model. This "transition" is difficult to distinguish in the Trans-Pecos province, where the "andesites" are alkalic mugearite and trachyte.

The Trans-Pecos province may resemble the Kenya rift in its independence from a subduction zone. The relationship of alkalic magmatism to tectonism remains a matter of debate (Bailey, 1972; Barker, 1970; Bass, 1970). Intracontinental igneous rock provinces do tend to associate with extensional faulting, but the fractures may be an effect of magmatism rather than a cause. Perhaps doming, magmatism, and faulting are all symptoms of mantle diapirism, as suggested by Koide and Bhattacharji (1975). Certainly in the Kenya rift and the Trans-Pecos province, the time of greatest faulting followed the period of maximum extrusion.

Similar rock suites, including basalt-mugearite-phonolite-trachyte and even sodic rhyolite assemblages, are known within oceanic portions of lithospheric plates (for example, see Bishop and others, 1973).

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VERTEBRATE BIOSTRATIGRAPHY OF TRANS PECOS TEXAS

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1970 in Geol Framework of the Chihuahua Tectonic Belt: Western Tx Geol Soc.

INTRODUCTION

[he volcanic series, which has been shown to be ; than the Laramide orogency, is at present very ıtisfactorily dated by fossil evidence." So, wrote the geologist, C. L. Baker in volume 11 of **The ılogy of Texas**. He went on to say "The series ;ains abundant tuffs, lake deposits, and some ₃lomerates which probably will afford a con- rable amount of fossil evidence to collectors of ȷuate experience, but the search for fossils is still to ındertaken" (Baker , 1935, p. 151).

aker himself was a collector of adequate ex- ence; I followed him to several East Texas localities, asota, and Cold Spring for example, but I am glad he carefully picked his way between the West as vertebrate fossil localities he so accurately licted would be found and left them for later kers.

was led into the vertebrate biostratigraphy of West as by Ronald K. DeFord. It was on the West Texas ılogical Society Fall Field Trip, 1948. I can vividly ıll Ronald energetically directing traffic; asking inent, provocative questions and talking about the o-Mitchell State No. 1. It was on the first day of that l trip, October 29, at the lunch stop at Cottonwood k that I made my first contact with fossil bone in ıt Texas. The long line of cars bunched up close to Schlumberger source of supply; the cloud of dust lually began to settle and the leader of the day ured and hollered at the top of his voice, "Men go -a-way, ladies go that-a-way." I followed direction perly and in the process of helping to settle the ı, it came to me: "— ——, that's bone!" Such was of the wonderful discoveries of science. If the field leader, however, had faced in the opposite ction, certain fundamental differences in mam- ian anatomy make it highly improbable that fossil es would have been found that day.

hat was my first day in the field with Ronald. There e many others to follow. It was a one-sided cation - from Orla to Toyah, to Kent, to Porvenir; aught me an enormous amount about the geology Vest Texas. As a teacher, I was a failure; I could er get his eye trained to find a bone.

ıst to prove that my first discovery of Tertiary bone West Texas was not accidental, let me briefly ›unt the discovery of the only section of continental iliferous Paleocene and Early and Middle Eocene Texas. Ross Maxwell was Superintendent of Big d National Park and in 1950 I stopped to ask him ctions so that I could show the students on that summer's field course what a dinasaur looked like in the raw. Ross directed me toward the McKinney Hills and we took off. But unknown to Ross was the fact that the road crew had just changed a detour and we wound up on Tornillo Flat. The badlands there smelled good and within a few minutes the students came up with a **Coryphodon** lower jaw. **Coryphodon** is characteristic of the Early Eocene. If the detour hadn't been changed, we would have gone to the McKinney Hills where there are only dinosaurs.

ACKNOWLEDGMENTS

I acknowledge the help Dr. Stephen E. Clabaugh has given me in the identification of the igneous rocks. I am grateful to Drs. R. L. Folk and E. F. McBride for profitable discussions on the sedimentary petrology and to Dr. Wann Langston for discussion on correlation of the dinosaurs. Dr. Ross A. Maxwell encouraged my work in Big Bend National Park. Many employees of the National Park Service and ranch owners from the Vieja to the Agua Fria have been most cooperative; a total list would be impossible. Some of this work was carried on with aid from NSF Grants G 13270 and GP1050, and grants from the University Research Institute. However, I especially want to acknowledge the Geology Foundation of the University of Texas and those who have supported it.

Vertebrate fossil collecting has been moderately successful in two areas (fig. 1) of highly dissected country close to the Rio Grande and its major tributaries. The more northerly is the Rim Rock Country between the Sierra Vieja and the Rio Grande for a distance of about 50 miles north of the village of Candelaria. The southern area includes Big Bend National Park and the dissected country between it and the Bofecillo Mts. Late Cretaceous dinosaur-bearing sections are known in the northern and southern areas (Chart 1, localities 4, 6, 7, 11, 13, 16, 18) and a vertebrate fossiliferous section that is unique to Texas extending from Middle Paleocene to Middle Eocene is found in the Park (Chart 1, localities 8, 9, 10, 13). From Late Eocene to Middle Oligocene over the Big Bend area in general volcanic activity spread a succession of flow rocks and ignimbrites, some of which have been dated by the potassium-argon method as shown on Chart 1 and in Wilson et al. (1968), between which are intercalated tuffaceous sediments which also contain vertebrate fossils (Charts 1, localities 1, 2, 3, 5, 10, 14, 17, 19, 20, 21, 22, 23). The distinctive lithology of the extrusive rocks has helped determine the order of superposition particularly in the faulted areas and thereby has aided in verifying the temporal succession of the local faunas.

Many groups of mammals evolved rapidly and because the most significant evolutionary changes are recorded on their teeth, the hardest parts of their anatomy, they make excellent stratigraphic tools for dating. They furnish a finely calibrated clock that in my opinion can be read to smaller units than the radiometric clock. A succession of mammalian faunas extending from Middle Paleocene to Early Miocene Ages have been discovered in West Texas and furnish a key to the geochronology (Chart 1).

Because my audience is more geologically than biologically oriented, let me quickly discuss the composition of the vertebrate faunas, where they are found and then turn to my interpretation of the chronology of some geologic events for which the vertebrate fossils furnish the basis.

Dinosaur-bearing late Cretaceous sediments are found in Big Bend National Park, the Rim Rock country and at various localities in northeastern Mexico. In the Park, the lower part of the Aguja Formation is very near shore; according to Hopkins (1965), who studied the sedimentology, it was deposited in a lower tidal flat evironment. Marine invertebrates, including **Placenticeras, Exogyra** and **Inoceramus,** are observable in the alternating yellowish

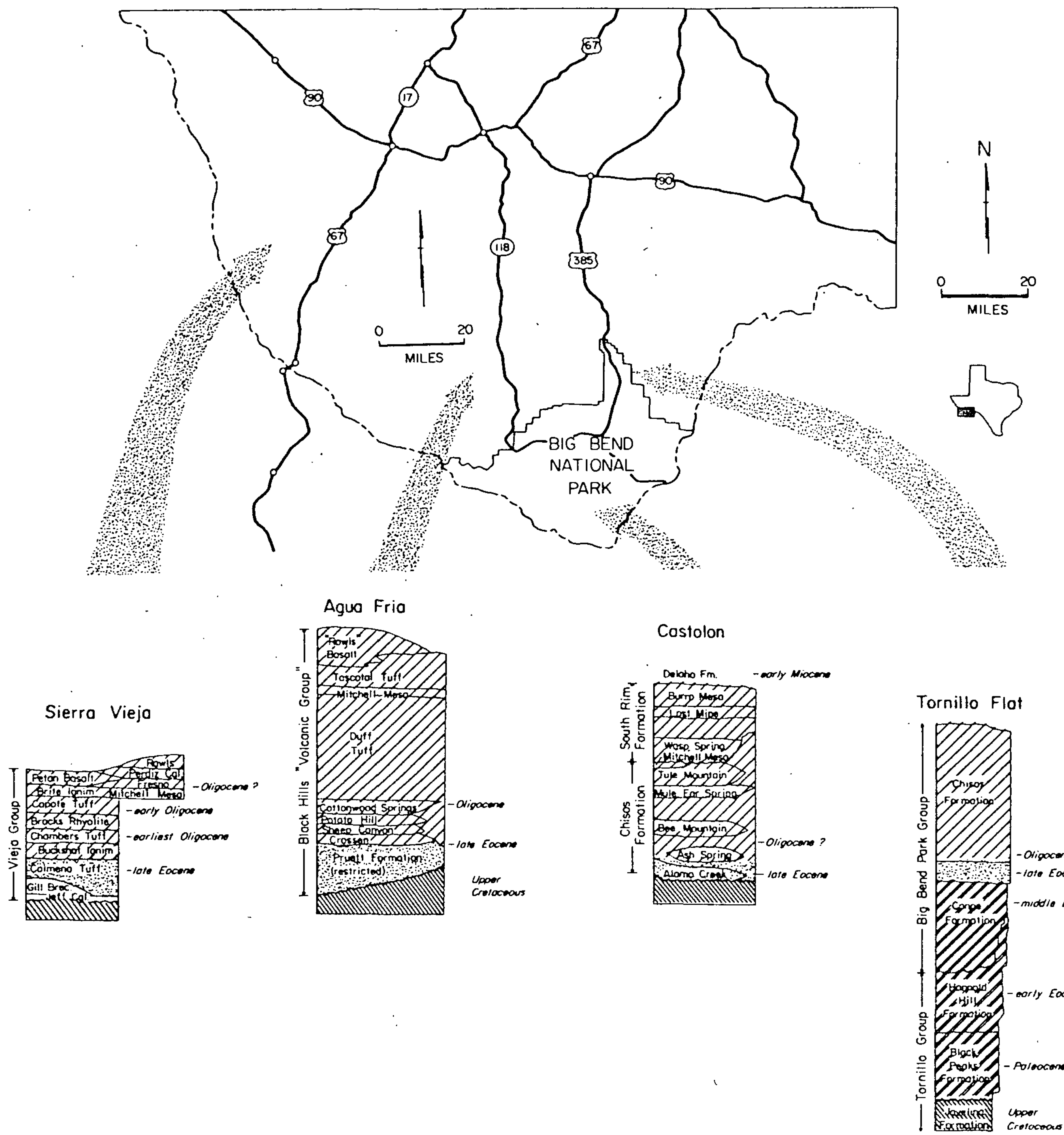


Fig. 1. Some Early Tertiary vertebrate bearing sections, Trans-Pecos Texas. Not to scale. Partly after McKnight, (1970).

ıy teeth, marine turtles, the large suchus, disarticulated dinosaur ıdance of petrified wood. In the lored part of the Aguja, dinosaur logs and stumps replace the near- ıvertebrates.

ına is poorly known. As Dr. Wann xas Memorial Museum could tell fragments are abundant, but ar- · very scarce.. Nonetheless, all of f Late Cretaceous dinosaurs have n isolated bones. Ceratopsians, but adrosaurs, small and large car- saurs are present (Langston, per- ɪn, September 1970).

'auna of the overlying Javelina ig Bend National Park is more mous sauropod, **Alamosaurus,** and yet, the only ones identified.

ccurrence of Paleocene vertebrate ı the Black Peaks Formation, Big It was the southern-most in North ılifornians discovered a small n Baja California, Mexico. A ıan fauna of small, medium, and taeniodont and phenacodontids l Late Paleocene, or Torrejonian espectively. Micromammals have ıcking up likely looking dirt and ; it in the laboratory. About 150 ws have been recovered. Good by this I mean skulls or jaws with of single teeth, have only shown wo summers. Judith Schiebout, d her study of the fauna, should be ıarisons with Paleocene faunas of to the north.

ne or Wasatchian age is well ıe presence of **Coryphodon,** **racotherium** found in the Hanold sed on Tornillo Flat in the Park. e correlation is shaky and rests on one lower jaw as **Helohyus lentus.** collection was more than doubled discovery of a new quarry in the ar Agua Fria Mt. A carnivore, artiodactyl, **Leptotragulus,** and a now permit me to tie together Colmena Tuff of the Vieja Group is the most common form, the uck Hill Group and an unnamed ve the Alamo Creek Basalt in the to identify these local faunas as tàn (fig. 2).

the succession of Early Oligocene ocal faunas that are found within been a slow and exasperating task

ved garfish scales are found at all ies and are just like garfish scales d the Recent. Fragments of turtle tributed and occasionally a well- is found but turtles like the garfish time and of little value for

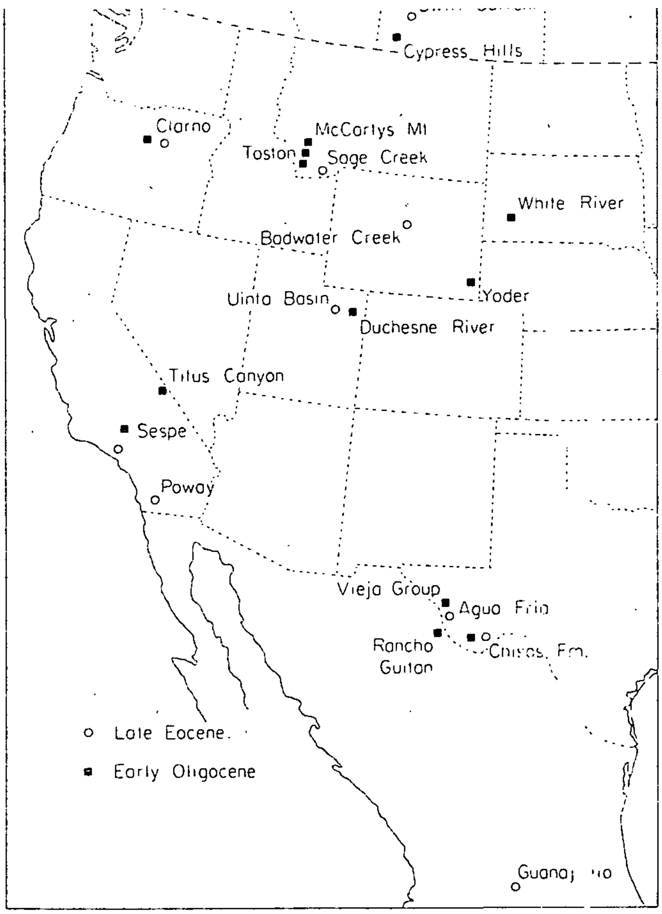


Fig. 2. Some Late Eocene and Early Oligocene vertebrate localities in western North America.

correlation.

In addition, my prize of all prize specimens, the skull of the lemuroid **Rooneyia viejaensis,** is the only Oligocene primate skull from North America. There is nothing to compare it with. Late Eocene primates are also very rare and mostly lower jaws.

Nonetheless, some excellent material has come from widely separate but prolific localities. The Reeves Bonebed has produced skulls and jaws of the small oreodont **Bathygenys.** A higher locality in the Capote Mt. Tuff produced camels, carnivores and another oreodont, **Limnenetes.**

The faunas in the Vieja Group span the Early Oligocene and furnish a control so that isolated fossil remains from the base of the section in the Mc-Cutcheon Group (Chart 1, locality 1) and the Pruett Tuff on the 02 Ranch at Cottonwood Tank (Chart 1, locality 3) can be correlated.

The discovery of an Early Miocene vertebrate fauna near Castolon came as kind of a shock. When you look for bones and teeth, your eyes are focused on an area no more than a few inches from the toes of your boots, so when I found a fragment of a large oreodont jaw in beds I thought were Late Eocene, it was almost as surprising as if I had found a trilobite. Retracing my steps later, I am surprised I didn't trip over the fault. The Castolon local fauna from the Delaho Fm. (Stevens et al., 1969) is the highest Tertiary vertebrate fauna known in the Big Bend area.

As a result of our knowledge of the vertebrate faunas, together with a study of the petrology of the sediments in which they are found, we can rather precisely date the time of occurrence of five major geologic events that occurred late in the history of West Texas: 1) the withdrawal of the Cretaceous sea, 2) the Laramide Orogeny, 3) the beginning of volcanic activity, 4) the end of volcanic activity and 5) the time of the beginning of Basin and Range faulting.

Let us examine the stratigraphic and paleontologic evidence for the first of the aforementioned events in West Texas and adjacent areas.

Toward the close of the Cretaceous, the epicontinental sea began to retreat toward the east and the south. Hopkins (1965) in his study on the "Sedimentology of the Aguja Formation, Big Bend National Park" interprets a shift of environments from tidal flats, marshes, lagoons, and beaches to rivers and estuaries. He draws an analogy with deposits of the Wadden Sea, the Netherlands, as reported by Van Stratten (1954).

The overlying Javelina Fm. is predominantly clay but there are occasional cross-bedded channel sandstones. It represents swampy, nearshore conditions on the continental side of the shore line.

Continental dinosaur-bearing Late Cretaceous sediments of the Picacho Formation are exposed near Ojinaga and in the Rim Rock Country. I am unable to distinguish them lithologically from the Aguja and Javelina Formations of Big Bend National Park. In fact, the Late Cretaceous continental deposits can be found (fig. 3) from the eastern part of the Park westward to the vicinity of Agua Fria Mt., south to Lajitas, around the south and west flanks of the Sierra del Mulato (Del Arenal, 1964) across the Rio Grande from the Boficillos Mts. and north to the Ojinaga and Rim Rock areas. During the late Cretaceous and early Tertiary this area might have been one continuous basin, like the San Jaun Basin, New Mexico (fig. 4). But unlike the San Juan Basin, its original extent has been masked by the igneous activity of the Oligocene and the block faulting of the Miocene.

The dinosaur faunas in the Aguja, Javelina and Picacho Formations, according to personal communication of Dr. Langston, are correlatable with those of the Ojo Alamo Formation of the San Juan Basin, New Mexico, and the Judith River Formation of Montana. These continental formations are in turn approximately correlated with the marine Austin Chalk Formation and are of Senonian Age. A latest Cretaceous, Maestrichtian, **Triceratops** fauna has not been found in West Texas or northern Mexico. If a **Triceratops** fauna was present in Big Bend, it is now represented by a lacuna between the Javelina Fm. and the Black Peaks Fm. (fig. 5). It is possible, however, that the **Triceratops** fauna was a northern one and did not reach as far south as Big Bend. But the absence of an Early Paleocene or Puercan Age fauna adds to the problem. There is no geologic reason to suppose a barrier existed to prevent the migration of either land reptiles or land mammals from the north to New Mexico and the Big Bend during

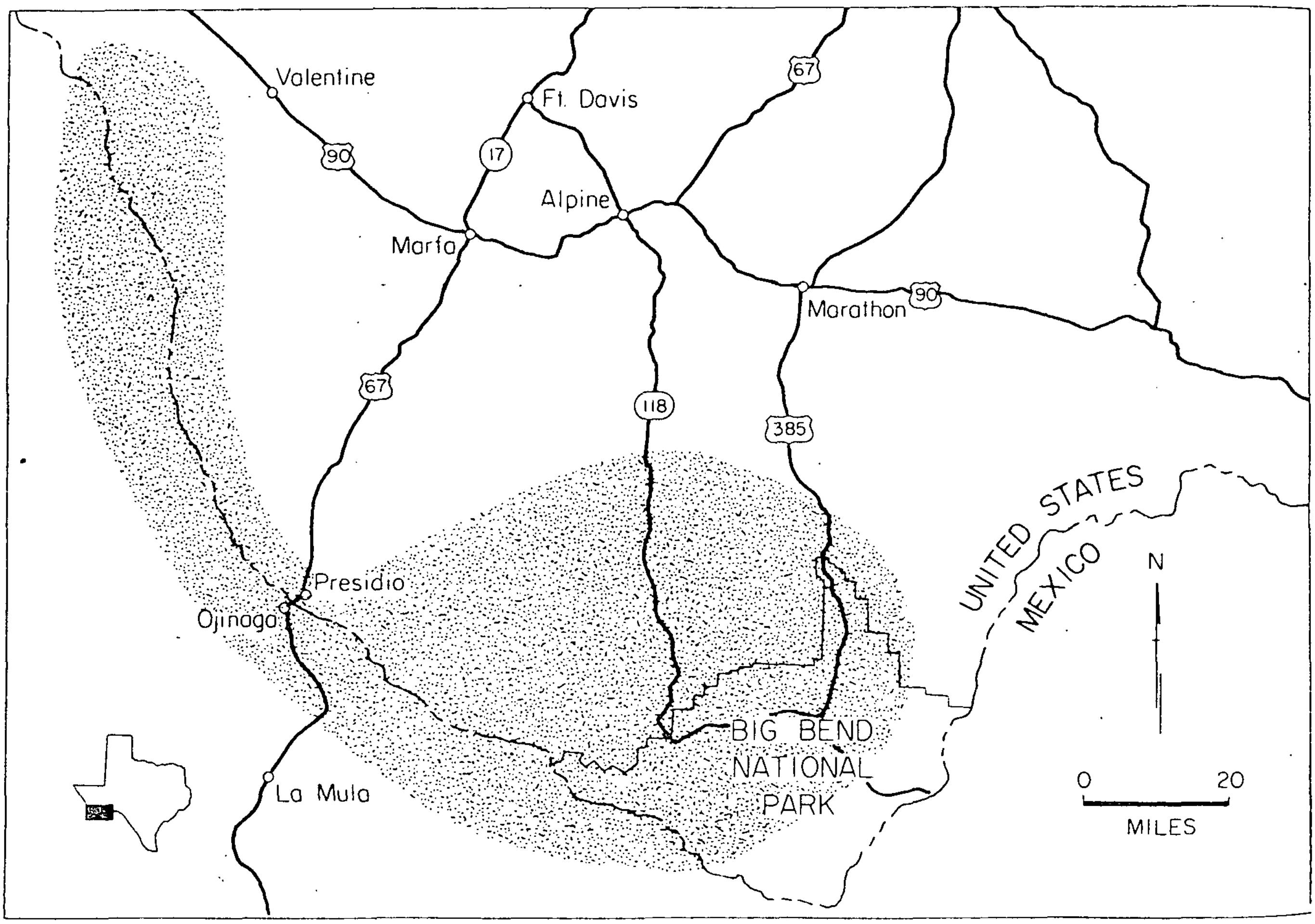
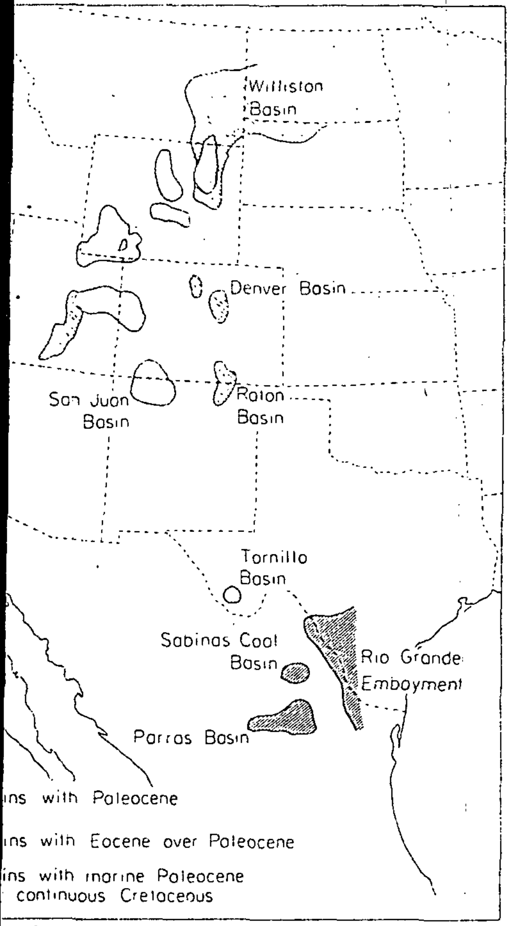


Fig. 3. Approximate area of Late Cretaceous continental deposits in Trans-Pecos Texas and northern Mexico.



ne structural basins in western North
h Early Tertiary fill.

eous and Early Paleocene time. Without ndent dates it seems best to postulate a luring which no accumulation of sediment lace.

io Grande embayment, the Olmos For- Piedras Negras Eagle Pass areas is a coal- nation and represents a very nearshore out so far no identifiable dinosaur remains have been recovered from that area. The ver, is correlated with the Aguja, Javelina Formations to the north and west. oal swamp conditions did not last very long rande Embayment because the Olmos is the marine Escondito Formation which **Sphenodiscus** fauna (Cooper, personal on, Sept. 1970). The **Sphenodiscus** Zone according to Jeletsky (1960) is followed by **tops** zone of the Lance Formation ents latest Cretaceous. The **Triceratops** e represented by a lacuna between the n. and Midway Group in the Rio Grande

uth in the eastern part of the Parras Basin, narine faunas alternate with near-shore aunas. I have seen dinosaur remains that ered by Dr. Grover E. Murray and his four or five localities near Saltillo. a sizable collection of dinosaur bones that ought in by ranchers and students from the of the Parras Basin.

PERIOD	LIFE	ENVIRONMENT		TIME	STRATA
TERTIARY	Mammals	Back levee Swamp Stream	-Continental-	Puercan Age	Black Peaks Fm.
		Lacuna including		Puercan Age *Triceratops* Chronozone (continental) *Sphenodiscus* Chronozone (marine)	
CRETACEOUS	Dinosaurs	River Estuaries	-Continental-		Javelina Fm
	Oysters	Marsh Lagoon	-Near-shore-		Upper Aguja Fm
	Ammonites	Tidal flat	-Marine-		Lower Aguja Fm

Fig. 5. Cretaceous Tertiary transition in Big Bend National Park, Texas.

In the Sabinas Coal Basin a well-preserved articulated ceratopsian was discovered near Palau by students of the School of Mines at Nueva Rosita, but where it fits in the Late Cretaceous section with respect to the **Sphenodiscus** Zone, I do not know. Someday I hope a dinosaur expert and a Cretaceous invertebrate paleontologist will cooperate on a faunal study of the interbedded marine and non-marine formations of northeastern Mexico.

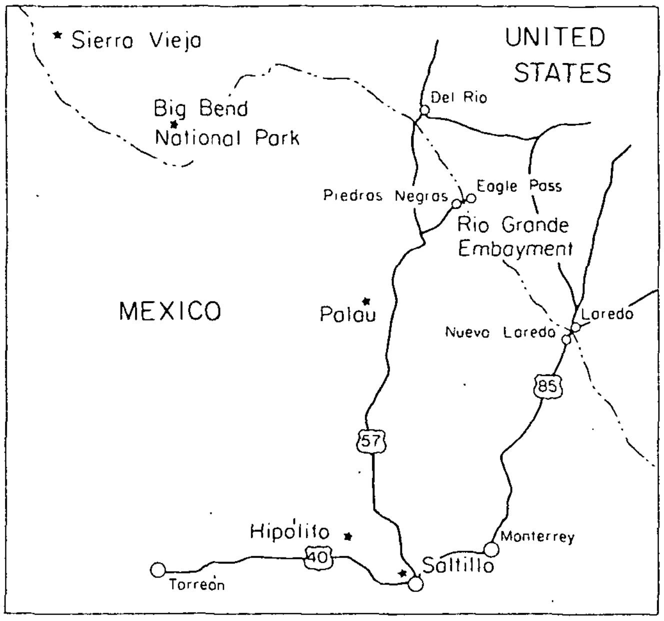


Fig. 6. Late Cretaceous dinosaur localities in northern Mexico.

The first of the geologic events I mentioned earlier, the withdrawal of the Cretaceous sea, occurred in West Texas before the extinction of the dinosaurs and in Big Bend and the Rim Rock Country, the withdrawal was permanent. In the upper Rio Grande embayment near Eagle Pass-Piedras Negras, and in the Sabinas and Parras Basins, the withdrawal was only temporary. A latest Cretaceous and Paleocene Midway sea returned to those areas (Murray et al., 1959) and it is not until Oligocene time that marine water finally retreated from the Gulf Coastal Plain of Texas.

The second major geologic event listed was the Laramide Orogeny. Evidence for its date is paleontologic, and sedimentologic as well as structural. A regional unconformity separates Cretaceous from Tertiary rock in West Texas and northern Mexico. It varies from a sharp angular unconformity between folded Cretaceous marine limestone and almost horizontal Early Oligocene volcanic tuffs, to a disconformity in Big Bend National Park between Late Cretaceous and Middle Paleocene. In the Rio Grande Embayment marine Late Cretaceous of the Escondito Formation is conformably overlain by the marine Midway Group. The same stratigraphic relations are found within the Difunta Group in the eastern Parras Basin. The area from Big Bend west was affected by the Laramide Orogeny; the Rio Grande Embayment and Coastal Plain, of course, were not (fig. 7).

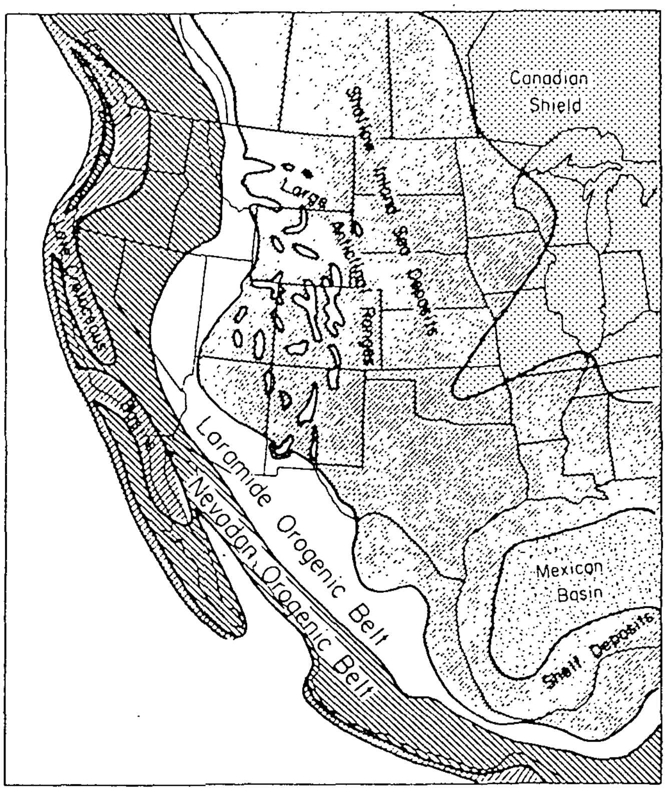


Fig. 7. Tectonic map of Late cretaceous Early Tertiary of western North America, (after Eardley, 1969).

In the Park, there is no sharp lithologic break between Cretaceous and Paleocene in spite of its being an erathem boundary and in spite of a long lacuna. Udden (1907) had placed all of the Tornillo Group on Tornillo Flat in the Cretaceous. The time change was recognized only after the discovery of mammals.

Classically the Laramide Orogeny was used to separate Cretaceous from Tertiary. It is so used by Maxwell and Dietrich (1965) and Maxwell et al. (1967).

Their interpretation places the main deformation of the Laramide Orogeny during a time following the close of deposition of the Javelina Formation (Late Cretaceous) and prior to the deposition of the Black Peaks Formation (Middle Paleocene).

Sedimentologic studies of the Aguja and Black Peaks Formations show no distinct differences between them. A comparison of the grain size of the sandstones shows that ". . .the grain size in the Aguja sandstones ranges from very fine sand to medium sand. The coarsest-grained sediments are confined chiefly to the upper part of the formation, although very fine sandstone beds occur throughout the formation." (Hopkins, 1965, p. 66). For the Black Peaks Formation "most samples examined are fine sandstones, very fine sandstones or very fine muddy sandstones." (Schiebout, 1970, p. 43). There is no significant change in grain size from Aguja to Black Peaks. Schiebout (1970, p. 92) summarized her interpretation of the environment of deposition of the Black Peaks Formation as follows: "Western Tornillo Flat lay on an alluvial plain far from sources of coarse sediment. At least two separate sources contributed material to the formation, a volcanic source outside the Big Bend region and older sdeimentary rocks within the region." The environmental interpretation based on an analysis of the sediments of the Black Peaks Formation tones down the structural interpretation of Maxwell and Dietrich (1965) and Maxwell in Maxwell et al. (1967). It seems highly unlikely to me that strong folding and deep erosion could have occurred prior to the accumulation of, or even during the accumulation of the Black Peaks Formation.

It also seems highly unlikely that only sills of the same general rock type as the Tertiary were intruded at the close of the Cretaceous. The fact that they are concordant with broadly folded beds does not necessarily mean that the intrusion had to occur prior to the folding, but, alternatively, could mean that the intrusion followed the bedding planes and occurred after the folding.

In my opinion conditions did not change much at the close of the Cretaceous in West Texas. Gentle warping accompanied uplift of the area as the sea withdrew and provided basins for the slow accumulation of continental Cretaceous and Paleocene rocks. In the areas between the basins, removal of Late Cretaceous Javelina and Aguja took place. The very fine to medium sand and clay of these formations was reworked into the Black Peaks Fm.

The first indication of deep erosion is the occurrence of reworked Comanchean limestone pebbles in the Early Eocene Exhibit Sandstone Member of the Hanold Hill Formation which is exposed only on Tornillo Flat in the Park.

Elsewhere in West Texas the earliest Tertiary is sometimes a basal conglomerate which underlies the volcanic section. It was named the Jeff Conglomerate by Eifler (1951) in his study of the Barilla Mts. Since then it has been correlated with a conglomerate in a similar position in the northern Davis Mts., the Rim Rock Country and the Bofecillos Mts. In addition, Moon (1953) mapped the "basal conglomerate" of the Buck Hill Volcanic Group which is similar in appearance and lithology to the basal Tertiary conglomerate near Lajitas that McKnight (1970) correlates with the Jeff.

If the Jeff is correlatable into the Early Tertiary l the Park the most similar lithologic unit is the ow Sandstone Member of the Canoe For- t lies at the base of the volcanic section on Tornillo Flat, contains some igneous material, ded black chert pebbles and large cobbles of ean limestone as does the Jeff in the Northern s. If this tentative correlation is correct, the ırt at least , could be Middle Eocene.

de folding seems best dated as the Middle or ımide Orogeny as classified by Eardley (1951) he orogeny began with gentle warping during taceous and the Paleocene, but the major ccurred in the Early and Middle Eocene.

hird major geologic event, volcanic activity, l the rocks that today hold up some of the most lar and familiar scenery in West Texas. /e flows and ignimbrites have provided units to help unravel a very complex picture furnished samples for radiometric dates. The ng tuffaceous sediments have, as Baker (1935) l, afforded " a considerable amount of fossil "

Eocene vertebrates occur in tuffaceous s of the Canoe Formation in the Park. The ıglomerate of this formation, the Big Yellow contains igneous pebbles. The lowest igneous : in place, however, is a basalt about 250 ft. laxwell et al., 1967, p. 108) It is the presence of :anic products that give a lithologic unity to 3end Park Group and distinguish it from the l-volcanic continental sediments of the Tor- ıup below.

ic sections rest directly on Cretaceous rocks tolon, Lajitas and the Rim Rock Country. In hern Davis Mts. a rhino tooth collected by 935) low in the section dates the initiation of activity there as Early Oligocene. A sizeable ım the Colmena Tuff close to the base of the roup in the Rim Rock Country is Latest The new discovery last summer of well d vertebrate fossils in bentonitic sediments low ruett Formation of the Buck Hill Volcanic ates the commencement of volcanism there as ene also. This fauna also dates the lowest tuffs ıstolon areas of the Park and the maroon and ; exposed near the base of Lajitas Mesa.

ɔw possible to confidently state that volcanic ɔegan in the Park in Middle Eocene, in the a and Vieja areas in the Late Eocene, and in nern Davis Mts. in Early Oligocene.

ive volcanic activity in the Park, at least, was by Early Miocene; the fourth geologic event. ısive igneous rock overlies the Delaho Fm. ɔf the various rock types of the South Rim ın the highest unit containing volcanic flow recognizable in the Delaho. The South Rim ın, however, is intruded by the Chisos Moun- on. Stevens (1969) in his study of the Castolon ıld not demonstrate igneous intrusive rocks ıe Early Miocene Delaho Fm. Nonetheless, the s mass of conglomeratic material in the upper he Delaho Formation must be the result of intrusion of the Chisos Mountains.

and Clabaugh (1969) published a radiometric 3 and 23 m.y., Early Miocene, for a dike swarm in the Rim Rock Country.

The last geologic event I wish to discuss is the time of the Basin and Range faulting. The fault I should have tripped over near Castolon has Late Eocene on the up side and Early Miocene on the down side. It is one of Maxwell's (Maxwell et al., 1967) Terlingua Abaha fault group and parallels the well-known Terlingua fault that forms the face of Sierra Ponce and the mouth of Santa Elena Canyon. The Terlingua fault, in turn, is part of the general northwest-southeast grain of West Texas produced by Basin and Range faulting (fig. 8). The deeply excavated valley of the Rio Grande at Castolon exposes the down-faulted fossiliferous Early Miocene on the east side of Cerro Castellan. Cross-sections in Stevens (1969) show the position of the Delaho Fm. in fault blocks that step down in a southwest direction from the Chisos Mts. to the Rio Grande. From the evidence of the vertebrate fauna in the Delaho Fm., Basin and Range faulting began in post-Arikareean or post-Early Miocene time. From the Valentine earthquake (Sellars, 1933), we may assume it is still going on.

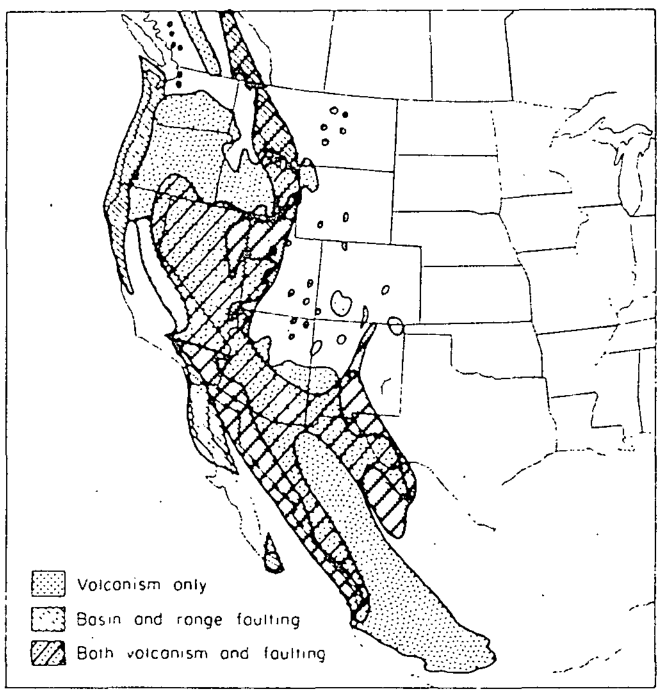


Fig. 8. Tectonic map of Middle and Late Tertiary of western North America, (after Eardley, 1965).

In summary, vertebrate fossils have provided evidence for the presence of a structural intermontane basin, the Tornillo Basin, similar to those farther north and containing a thick early Tertiary section. The original extent of the basin, however, has been masked by volcanism and block faulting. The dating of vertebrates has fixed the time of withdrawal of the Cretaceous sea as Senonian, the Laramide Orogeny folding as Early and Middle Eocene, the beginning of volcanic activity as Middle Eocene to Early Oligocene depending on what area is considered, the extrusive volcanic activity had ended by Early Miocene and preceded the beginning of Basin and Range Faulting.

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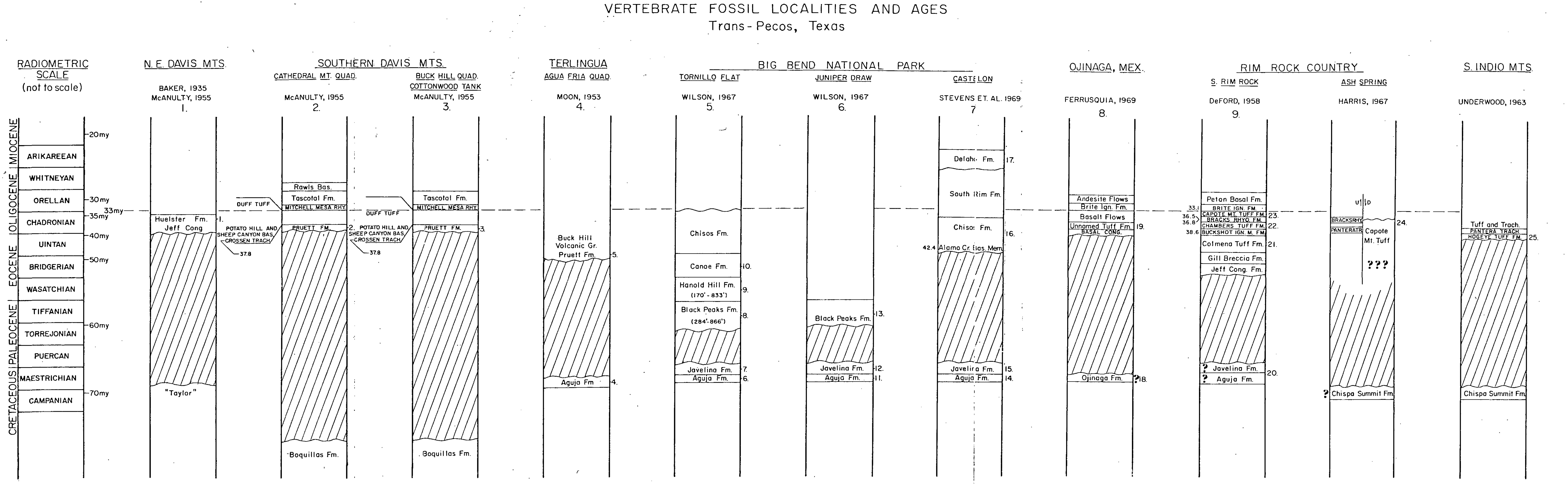
Chart 1. Correlation of vertebrate bearing formations, trans-Pecos, Texas. Numbers to left of column represent K-Ar dates numbers to right of column represent known occurrences of vertebrate fossils.



Zeolitic Diagenesis in Oligocene Volcanic Sediments, Trans-Pecos Texas

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ABSTRACT

Volcanic sedimentary rocks of the Vieja Group of Trans-Pecos Texas contain zeolite, montmorillonite, and silica minerals that formed during diagenesis in an open hydrologic system. Volcanic glass shards dissolved in ground water to provide constituents for authigenic minerals. Diagenic mineral zones, from top to bottom, are (1) montmorillonite-opal-glass, (2a) montmorillonite-opal-clinoptilolite, (2b) montmorillonite-quartz-clinoptilolite, (3a) montmorillonite-quartz-analcime, and (3b) analcime-quartz. During diagenesis the original vitroclastic texture of volcanic sediment was preserved. Montmorillonite formed coatings on glass shards that preserved their outline during replacement by clinoptilolite. Clay or clinoptilolite cement filled much of the remaining intergranular space. Analcime replaced both pseudomorphs of shards and interstitial cement that first formed as clinoptilolite. All authigenic minerals formed at low temperature and low pressure at burial depths no greater than a few hundred meters. Rocks in each zone were buried less deeply, and boundaries between zones are stratigraphically higher in the northeastern than in the southwestern part of the area. Distribution of clinoptilolite and analcime were controlled locally by permeability of the host rocks. Diagenesis converted sediment with an original composition similar to that of rhyolite into rock composed of Na_2O, CaO, Al_2O_3, and SiO_2, but relatively depleted in K_2O. Field evidence shows that diagenesis occurred in early Oligocene time, but zeolites began to form only after a critical thickness of a few hundred meters of sediment had accumulated. *Key words: geochemistry, zeolites, sedimentary petrology, volcanic sediments, diagenesis.*

INTRODUCTION

Clinoptilolite, analcime, montmorillonite, opal, and quartz formed in volcanic sediments of the Chambers and Capote Mountain formations from constituents dissolved from volcanic glass. The formations are exposed along the western edge of the Trans-Pecos volcanic field in southwestern Texas (Fig. 1).

The stratigraphic units are shown in Figure 2. Though they consist mostly of stream-deposited sediment, both the Chambers and Capote Mountain formations were given the lithologic designation "tuff" by DeFord (1958). Modern usage restricts tuff to volcanogenic material that has not been transported after its initial deposition. Normal terrigenous classification schemes are used to describe rocks composed of volcanogenic material reworked by normal transport processes (Pettijohn and others, 1973, p. 268). For this reason I have used the lithologic modifier "formation" for the Chambers and Capote Mountain rocks to indicate that they are diverse sequences of sedimentary rocks.

Radiometric age determinations and fossil mammal faunas date the entire succession from the Chambers formation to the Mitchell Mesa as early Oligocene (Wilson and others, 1968; F. McDowell, 1972, personal commun.).

The Chambers and Capote Mountain formations of the study area were deposited between two volcanic centers. The Van Horn Mountains eruptive center, 65 km north of Candelaria, was most active during deposition of the Chambers. The Pinto Canyon–Chinati Mountains center, 20 to 30 km southeast of Candelaria, was the source of most of the material in the Capote Mountain formation. Streams carried detritus into the study area from volcanos to the north and south and from mountains to the west. The streams coalesced in the northern part of the area to form larger rivers, which flowed out of the Rim Rock Country (Fig. 1) across the volcanic field to the east. Accumulation of debris around the northern volcanic center forced the axis of stream activity southward as the Chambers formed. With growth of the southern center, during deposition of the Capote Mountain, detritus spread northward, gradually shifting the courses of the east-flowing streams northward and burying their earlier deposits.

The Chambers formation ranges in thickness from 30 m at the southern edge of the area to more than 200 m 15 km to the north. The thicker, stream-deposited facies contains fining-upward sequences: conglomerate made up of volcanic rock fragments and carbonate rock fragments; coarse sandstones comprising rounded quartz, sanidine, and some volcanic rock fragments; and fine sandstones containing glass shards and pumice fragments (Fig. 3a). Overbank deposits are composed primarily of glass shards, most of which are now pseudomorphed by zeolite. The overbank deposits are extensively root mottled, contain calcite concretions, and are marked by paleosoil horizons. The thinner southern facies contain channel deposits and airfall material from various sources.

The Capote Mountain formation ranges from 400 m thick at the southern boundary of the area to nearly 550 m at Capote Peak. Its upper part has been eroded in the northern one-third of the area. Like the Chambers formation, it has distinct northern and southern facies. The northern one is similar to the immediately underlying Chambers, except that it contains more plagioclase in coarse sandstones. It represents deposits of the through-flowing streams. The southern facies is the apron of material spread out from the Pinto Canyon–Chinati Mountain eruptive center. Coarse rocks contain abundant volcanic rock fragments, and fine rocks contain primarily shards (Fig. 3b). Quartz, sanidine, and plagioclase are present in most rocks and abundant in medium sandstones but are less rounded than in the northern facies. To the south, the Capote Mountain formation thins and interfingers with extrusive rocks of the Shely Group (Maxwell and Dietrich, 1970).

DIAGENETIC MINERALS

Glass shards and pumice fragments are the most abundant original constituents of the Chambers and Capote Mountain formations. They also contain abundant volcanic rock fragments, crystals of various sorts, and some carbonate rock fragments. Action of ground water has resulted in solution, recrystallization, or replacement of much of the volcanic glass and in cementation of the

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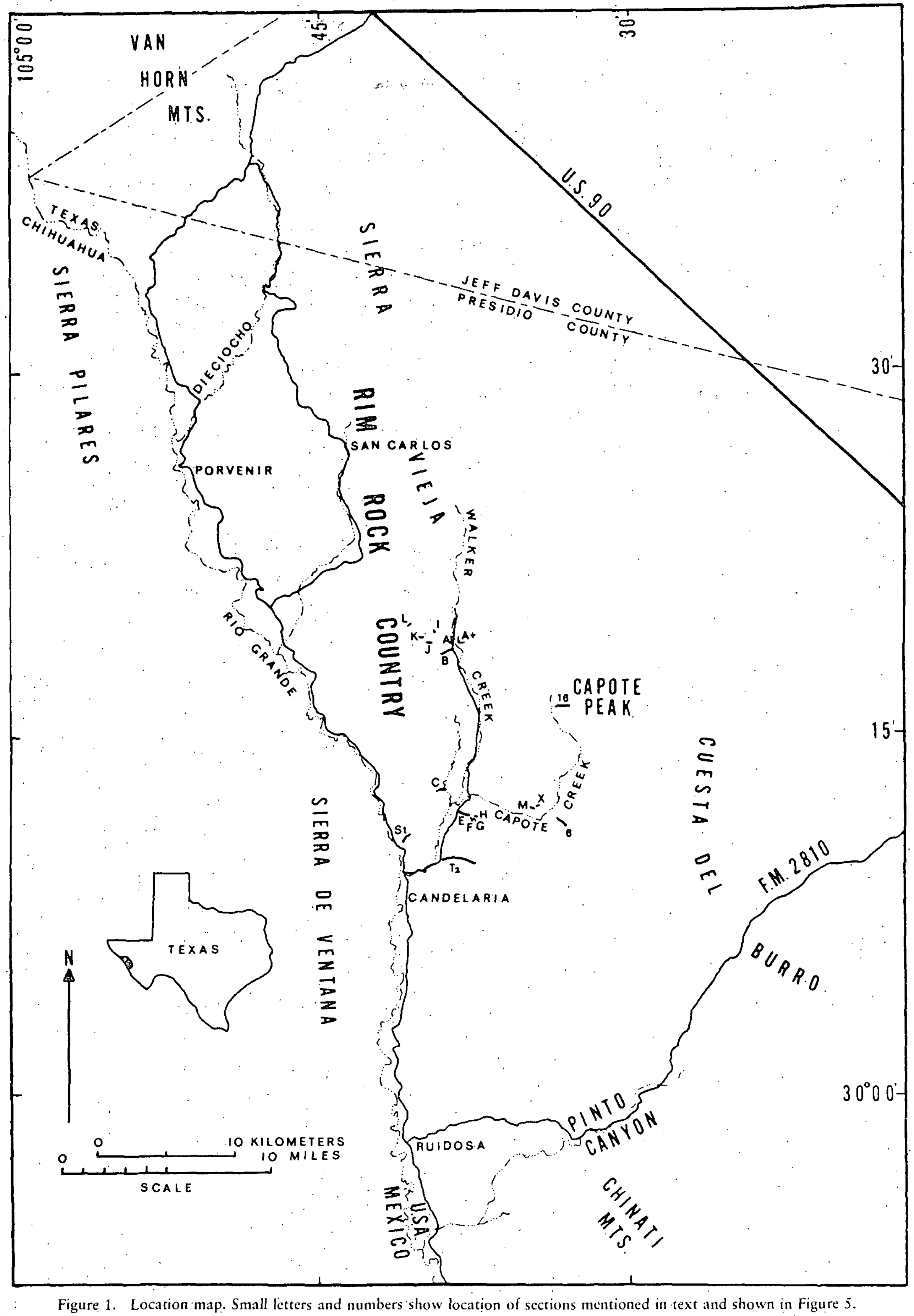

Figure 1. Location map. Small letters and numbers show location of sections mentioned in text and shown in Figure 5.

rock. Minerals formed by reaction with ground water include opal, quartz, montmorillonite, clinoptilolite, and analcime. Calcite, iron oxides, manganese oxides, and other nonsilicates also formed.

Opal

Opal occurs in the upper part of the section as microscopic spheres coating glass shards. Some rocks that contain abundant clay but no microscopically visible opal show a strong diffraction pattern of disordered cristobalite such as is commonly produced by opal (Flörke, 1955). Presumably, opal in these samples is masked by masses of clay that surround it. No opal was visible within ghosts of glass shards except in a few large shards in one sample, which had cores of opal surrounded by inward-radiating crystals of clinoptilolite.

Montmorillonite

Clay that coats shards, fills pumice tubes and bubbles, and forms irregular nodules within shards is montmorillonite. X-ray diffraction traces of oriented aggregates of the <2-μ fraction of most Vieja Group rocks had maxima close to 12.4 Å, indicating that sodium is probably the dominant interlayer cation. Some traces had maxima in the vicinity of 15 Å and were either more hydrated sodium montmorillonite or calcium montmorillonite. Clay coatings on shards are among the first diagenetic products to form.

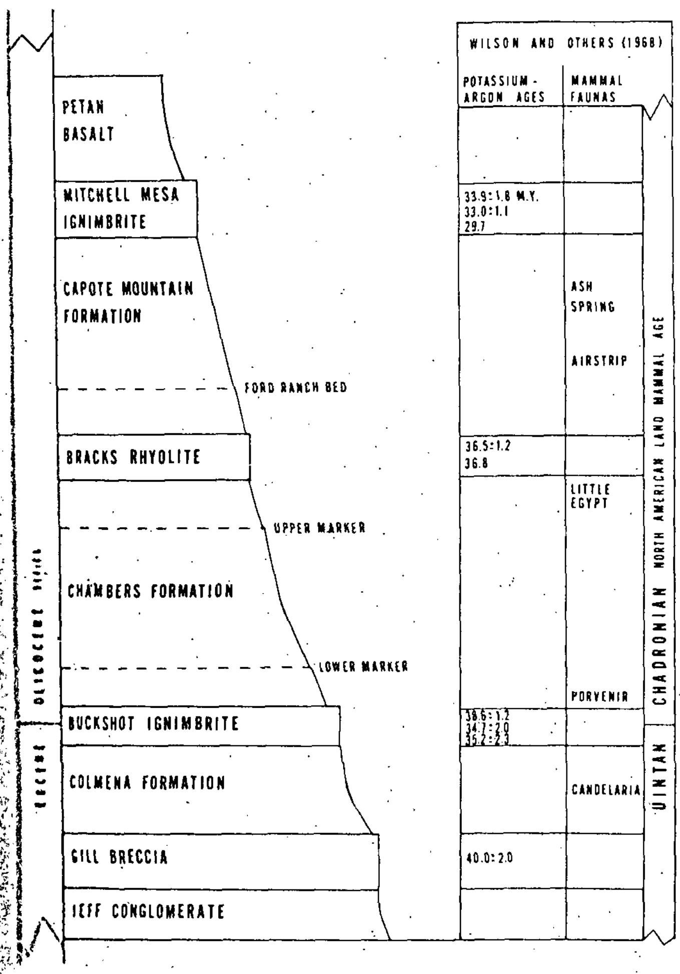

Figure 2. Stratigraphy of Vieja Group. Formation names are from DeFord (1958), as used in Walton (1972). Mammal faunas are those mentioned by Wilson and others (1968). Potassium-argon dates from Wilson and others (1968).

Within them, clay plates have preferred orientation parallel shard surfaces. In rocks containing glass, the coatings are a i microns thick at most. In rocks containing shards replaced clinoptilolite, clay coatings are as much as 0.015 mm thick, aver. ing 0.005 to 0.010 mm. Within any one thin section, coatings of uniform thickness on all shards, but are thinner or nonexist on crystal or lithic grains. Montmorillonite fills pumice tubes t have diameters on the order of 0.010 mm. These observations su gest that montmorillonite formed at grain surfaces where it found now rather than depositing from suspension after transp. from some other place of formation. Some of the constituents the clay may have come from glass quite near the site of precipi tion and some probably from elsewhere in the diagenetic syst but the proportions from each source cannot be assessed.

Clinoptilolite

The clinoptilolite in the Vieja Group has a mean index of refr. tion that ranges from 1.476 to 1.488. Its x-ray diffraction pattern quite similar to that given by Wise and others (1969) for clinopti lite from Agoura, California (Table 1). Whole-rock analyses samples containing nearly pure clinoptilolite show that sodium a potassium predominate among the cations present, and the zeol contains a high percentage of silica. For example, sample A+4 contains 5.9 percent $K_2O + Na_2O$ and 1.5 percent CaO, and it h a ratio of Si/Si+Al of 0.84 (Table 2).

Clinoptilolite that replaces shards occurs in two habits. A fibro fringe, 0.005 to 0.020 mm thick, replaces the outer part of t shard. The inner part of most large shards is replaced by large re tangular crystals, up to 0.05 mm long and one-sixth to one-third wide, that radiate inward from the sharp or gradational cont. with the fibrous fringe (Fig. 4a). Clinoptilolite cement also fibrous, but the fibers are in radiating masses unlike either of t habits found within shards. Rocks containing clinoptilolite are o viously volcanic sedimentary rocks; the outlines of undistort shards are clearly visible.

Quartz

Diagenetic quartz is commonly visible in thin sections of roc from the lower Chambers formation in the northern part of t study area (Fig. 1, secs. J and K). It occurs as mosaics of microcry talline anhedra and as singly terminated crystals that project in shard ghosts that also contain analcime.

Quartz maxima are by far the strongest in x-ray diffractogra of most samples from the rest of the stratigraphic sections in t northern part of the area (Fig. 1, secs. B, A, A+, and I) and in sa ples from the entire Chambers and lower Capote Mountain form tions to the south (sec. C and lower 30 m of sec. E). But in the rocks, visible quartz, all detrital, makes up only a small fraction the material. The rest of the quartz must be in minute crystals co cealed among clay. Such small crystals of quartz, in sediment of fi sand size or coarser, must be authigenic. Its cryptic habit is simil. to that of opal that occurs higher in the Capote Mountain (secs. G, and T_2).

Analcime

Analcime occurs in samples from the northern and central par of the area as pseudomorphs after shards and as cement, in th same mode of occurrence as clinoptilolite. Some analcime-replace shards have ghosts within them that resemble the texture of clino tilolite that replaces shards elsewhere in the section (Fig. 4b). In few rocks, analcime forms equant 2- to 3-mm concretions, repla ing both shards and cement and preserving the vitroclastic textur of the rock but surrounded by rock composed of clinoptilolite an montmorillonite. These textural relations suggest that analcim

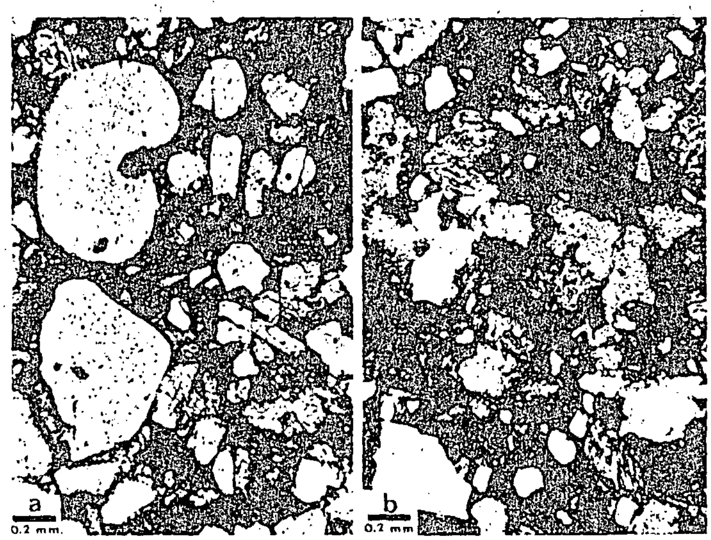

Figure 3. a. Photomicrograph of upper Chambers stream-deposited facies, section 1 (Fig. 1). Medium sandstone composed of well-rounded quartz and sanidine grains with a few volcanic rock fragments. Plane polarized light. b. Photomicrograph of Capote Mountain sandstone derived from Pinto Canyon–Chinati Mountain sources south of study area. Medium sandstone from section E (Fig. 1) composed of angular and subangular quartz, plagioclase, sanidine, and volcanic rock fragments. Plane polarized light.

Figure 4. Diagenetic textures of Chambers and Capote Mountain roc[k] a. Shard coated with thin layer of montmorillonite (arrow) and replaced [b] fibrous and rectangular crystals of clinoptilolite. Capote Mountain form[a]tion, section E (Fig. 1). Plane polarized light. b. Shard pseudomorph [in] which analcime has replaced clinoptilolite but preserved texture of cli[no]ptilolite. Chambers formation, section J (Fig. 1). Plane polarized light.

replaces clinoptilolite rather than forming directly from solution or directly replacing glass. Sheppard (1971) reported that most analcime in sedimentary rocks replaces other zeolites. The analcime that appears to replace clinoptilolite has a ratio of Si/Si+Al of about 0.72, whereas other analcime in the Vieja Group that formed as crystals lining joints and vugs has a Si/Si+Al ratio between 0.69 and 0.71, according to electron-probe and rapid-method analyses (Tables 2, 3). This agrees with the results of Sheppard and Gude (1969) and Boles (1971), who showed that starting material influences the composition of analcime.

Diagenetic Assemblages

Diagenetic minerals in the Vieja Group occur in three distinct assemblages, two of which each include two subassemblages. From

TABLE 1. X-RAY DIFFRACTOMETER DATA FOR CLINOPTILOLITE IN SAMPLE E-121, CAPOTE MOUNTAIN FORMATION

Sample E-121		Clinoptilolite from Agoura, Calif.*		
$d_{obs.}$ (Å)	I/I_0†	$d_{obs.}$ (Å)	I/I_0	hkl
9.02	S	8.92	100	020
7.97	M	7.97	3	002
6.81	M	6.78	2	$10\bar{1}$
5.95	W			
		5.61	2	031
5.13	M	5.15	7	112
4.67	M	4.65	14	130
4.37	W	4.35	2	$10\bar{3}$
3.99	S	3.964	55	132
		3.964	55	004
3.85	M	3.897	57	042
		3.74	7	$14\bar{1}$
3.56	MW	3.55	6	$21\bar{1}$
3.47	W	3.48	3	$051, 11\bar{4}$
3.43	MW	3.419	16	220
		3.324	4	202
		3.168	14	$22\bar{2}$
3.13	W	3.119	15	222
3.08	W	3.07	8	231
2.98	MW	2.974	80	044
2.80	M	2.793	15	035
		2.793	15	$12\bar{5}$
2.73	MW	2.728	33	$16\bar{1}$

* Wise and others, 1969.
† S = strong diffraction intensity, M = moderate, W = weak.

top to bottom the assemblages are (1) montmorillonite-opal-gla[ss] (2a) montmorillonite-opal-clinoptilolite, (2b) montmorilloni[te-]quartz-clinoptilolite, (3a) montmorillonite-quartz-analcime, [and] (3b) analcime-quartz. Except for the absence of mordenite and Ca-clinoptilolite, the progression with depth is similar to the [first] three stages and part of the fourth stage of the progression in [the] Niigata Oil Field, Japan, as described by Iijima and Utada (19[7-]. Potassium feldspar, laumontite, and phyllosilicates present in [the] lowest part of the Niigata occurrence are not known in the Si[erra] Vieja.

In rocks containing the first assemblage, a thin film of m[ont]morillonite or spherical masses of opal coat hydrated but still [iso]tropic glass shards. Some rocks have calcite cement. This as[sem]blage occurs in the Capote Mountain formation in the upper [part] of the southern section of the study area. At section H (Fig. 1), [the] assemblage is about 220 m thick, and it thins to the north. No f[resh] glass occurs in the complete section on Capote Peak itself (Fi[g.] sec. 16).

Montmorillonite coats shards altered to clinoptilolite, [and] montmorillonite and clinoptilolite fill pore spaces in rocks con[tain]ing the second assemblage. In the upper part of the interval, w[here] clinoptilolite predominates, opal is cryptically distributed in [the] rock, presumably mixed with clinoptilolite and montmorill[onite] cements. Below the opal-rich subassemblage, quartz is presen[t in]stead of opal. In the southern Candelaria area, the clinoptil[olite-]rich assemblage occurs in both the Chambers and Capote M[oun]tain formations, stratigraphically below the fresh glass assembl[age.] In the northern part of the area, it occurs only in the highest p[art of] the Capote Mountain formation, in rocks deposited con[tem]poraneously with those containing only fresh glass in the sou[thern] part of the area. The opal-rich subassemblage (2a) of the clino[ptilo]lite assemblage is found only in the southern part of the area i[n the] Capote Mountain formation. The uppermost part of the C[apote] Mountain in the northern part of the area, where one would e[xpect] to find the opal-rich subassemblage, has been eroded, and it [is not] known whether this subassemblage occurred there. The quart[z] subassemblage (2b) occurs in the Chambers and lowest C[apote] Mountain rocks in the southern part of the area and in the hi[ghest] preserved Capote Mountain beds exposed in the north.

In the third zone, clinoptilolite is replaced by analcime in shards and cement. In rocks from the upper part of this zone

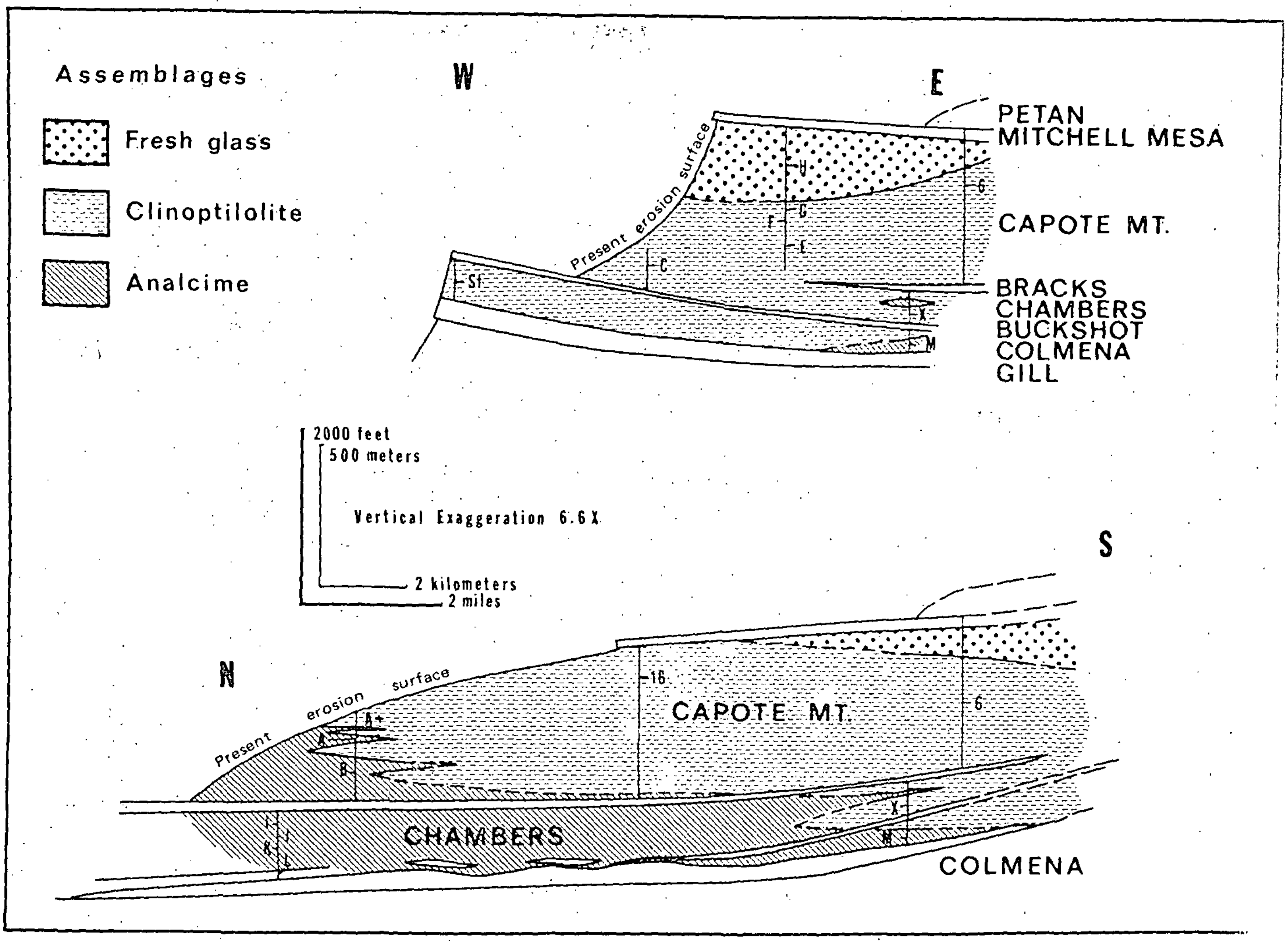

Figure 5. Schematic cross section of Vieja Group in Candelaria area of southern Rim Rock Country, drawn to remove effects of Miocene and l faulting. Distribution of diagenetic assemblages was determined by x-ray and thin section studies of samples from lettered sections and isolated sar between. Dashed lines extrapolate boundaries beyond areas of intensive control. For sections 6 and 16 (Fig. 1), thickness data are from Peterson (1' and position of diagenetic assemblage boundary corresponds to sharp change from unlithified to lithified rock in section 6.

gives 0.83. Perhaps the lower ratio is the result of the small percentage of Al-rich montmorillonite in H-236.

Sample T_2-1136 contains larger amounts of montmorillonite than H-236, some opal, and small amounts of detrital quartz and feldspar, but it is mostly fresh glass. It shows increase of water, soda, lime, magnesia, and ferrous and ferric iron, and some increase in alumina, but decreases in silica and potash (Table 2). Such changes are consistent with its increased content of sodium montmorillonite if the clay has a noticeable magnesium content.

Sample A+405 is a vitric volcanic arenite that contains montmorillonite, clinoptilolite as cement, and pseudomorphs after shards, but no glass. It contains less potash than either fresh glass or glass-montmorillonite rocks; the small decrease in silica may be insignificant (Table 2). Its alumina content is lower than that of rocks containing glass. Its content of soda and lime is greater than that of fresh glass, even when calcium is adjusted to allow for its carbonate content. It contains more water than do rocks containing glass.

The next step in diagenesis is represented by sample K-160, from the lower marker horizon of the Chambers formation in the northern part of the area. This horizon is anomalous because it contains no analcime at section K, even though it is there overlain by several hundred meters of sedimentary rock that contains analcime. Though it may be from a hydrologically similar but distinct system, its initial composition of nearly pure glass resembles that o other samples considered. There is no reason to believe that ch cal interaction between glass grains of this marker and the tained solutions were different from those of other Vieja G. rocks. It thus can be compared to the other samples. K-160 tains abundant quartz and clinoptilolite and some montmo nite. Its chemical composition is consistent with its minera compared to A+405, which contains no quartz, it has more and less alumina. This sample has the greatest calcium cont any of the analyzed rocks; the calcium may be in either the c the zeolite.

Sample J-69.5 consists almost entirely of quartz and anal Silica and soda are concentrated in such rocks, but alum somewhat depleted (Table 2). In quartz-analcime rocks, the r oxides is a function of the ratio of quartz to analcime; ana rich rocks should contain less silica and more soda and al than do quartz-rich rocks. Calcium would be present as cal these rocks; J-69.5 was selected because it contained little c Potash is reduced by a factor greater than three from its v H-236. The H_2O content, which is less than that of other containing zeolite, indicates the lower H_2O content of analcime rocks.

Although the diagenetic process has retained all other ma ides in proportions approximately equal to those in the

Substantiation of the influence of the ratio of alkali to hydrogen ions in controlling the solid phase formed from solution during diagenesis of volcanic sediment should include an equation that can be used to determine solution composition at the time montmorillonite ceases to form and clinoptilolite begins to form:

$$\underset{\text{montmorillonite}}{NaAl_5Si_7O_{20}(OH)_4} + 4Na^+ + 13\,H_4SiO_4 + 4H_2O = \underset{\text{clinoptilolite}}{5Na\,AlSi_4O_{10} \cdot 6H_2O} + 4H^+ . \qquad (2)$$

In this equation, the formulas for solid phases have been simplified. Taking as unity the activity of solid phases and water, the equilibrium constant for equation (2) is written

$$K = \frac{(a_{H^+})^4}{(a_{H_4SiO_4})^{13} \cdot (a_{Na^+})^4}.$$

Assuming the system to contain some fixed concentration of silicic acid, such as an amount in equilibrium with amorphous silica, the equation can be simplified further and can be inverted:

$$K = \frac{a_{Na^+}}{a_{H^+}}, \qquad (3)$$

implying that the activity ratio is a crucial variable.

Equation (2) is really a sum of two equations:

$$\underset{\text{montmorillonite}}{NaAl_5\,Si_7O_{20}(OH)_4} + 4OH + 20H_2O = Na^+ + 5Al(OH)_4^- + 7H_4SiO_4 \qquad (4)$$

and

$$Na^+ + Al(OH)_4^- + 4H_4SiO_4 = \underset{\text{clinoptilolite}}{NaAlSi_4O_{10} \cdot 6H_2O} + 4H_2O . \qquad (5)$$

The equilibrium constant of equation (4), again assuming an activity of unity for solid phases and water, is

$$K = \frac{(a_{Na^+}) \cdot (a_{Al(OH)_4^-})^5 \cdot (a_{H_4SiO_4})^7}{(a_{OH^-})^4}. \qquad (6)$$

At pH below the dissociation of silicic acid and in places where clinoptilolite is not forming, the concentration of silica is controlled in glass-containing systems like the Vieja volcanic sediments by relations with some solid phase. Which of the possible silica-containing phases — glass, montmorillonite, opal, or some precursor of opal — controls the abundance of silica is not important for now; the fact that silica is not independently variable *is* important. As montmorillonite forms during diagenesis in an open system, dissolution of glass and hydrolysis of its constituent silica and alumina cause a constant rise of pH and an accumulation of cations in solution. Because pH is rising, the amount of aluminate in solution must increase, as indicated by equations (4) and (5), if montmorillonite formation is to continue. Evidence exists that the solubility of silicic acid is inversely related to the amount of aluminate present (Walton, 1973). The amount of silica in solution may actually decrease as pH rises, and aluminate becomes more common until the pH is reached at which silicic acid dissociates.

Equation (2) assumes that aluminum is conserved — all that the aluminum present in montmorillonite that dissolves is converted into clinoptilolite or vice versa. Equation (4) shows that the amount of aluminate in solution in equilibrium with montmorillonite is a function of pH. Because pH can change as the reaction described in equation (2) proceeds, aluminate need not be conserved during the process, and equation (2) is not an accurate description of the conversion. Therefore, equation (3), the equilibrium constant, is not a complete description of the chemical controls on solid phases formed during diagenesis of volcanic sediment.

The equilibrium constant for equation (5) is

$$K = \frac{1}{(a_{Na^+}) \cdot (a_{Al(OH)_4^-}) \cdot (a_{H_4SiO_4})^4}. \qquad (7)$$

Formation of clinoptilolite from solution is not a function of pH, but of sodium ion, silicic acid, and aluminate abundance. Regar less of the pH of the system and the ratio of hydrogen ions to alk ions, if its ion product is exceeded, zeolite will form.

One might also conclude that the ratio of alkali ions to hydrog ions is not the variable that controls minerals formed duri diagenesis of volcanic sediment if one considers the form aluminum in clay and zeolite phases and in solution. Montmoril nite consists of silica and aluminum-oxygen tetrahedra that bound to aluminum, iron, and magnesium ions in octahedral co dination. Only if the layers so constructed have a deficiency of po tive charge do either alkali ions or hydrogen ions adhere to the o side of individual crystals and bind adjacent layers together. Dur clay mineral identification procedures, these cations are commo stripped off and replaced by others, without affecting the crystal ity of the layers themselves. Zeolites consist of three-dimensio networks of silica and aluminum-oxygen tetrahedra; because aluminum-oxygen tetrahedra have a net negative charge, posi ions, most commonly alkali or calcium, are attached to framework. The facility with which these cations can be exchan led to use of zeolites as ion-exchange media. In both montmori nite and zeolites, the cations are stuck on the outside of a silic aluminum-oxygen framework; their presence only serves to ance charge. Thus, one should expect that cation ratios are no important controls on the diagenetic process than are silicic and aluminate abundance.

Aluminum in neutral to alkaline solution is present as alumi ion, $Al(OH)_4^-$ (Hem and Roberson, 1967). According Moolenaar and others (1970), aluminate is tetrahedrally co nated. Aluminate readily enters tectosilicate structure from alk solution, substituting for silica. If the abundance of alumina great enough in solution, it will polymerize to form sheets tha proach the composition $Al(OH)_3$ as they grow larger (Hem Roberson, 1967); if silica is present in sufficient quantity, t sheets serve as nuclei for formation of aluminous clays (Gast 1964). Equation (6) shows that with increasing pH, the amou aluminate necessary to form clay becomes much greater. In canic sediment sequences undergoing diagenesis, the pH bec so high that at the prevailing alkali and silicic acid concentr the amount of aluminate necessary to form clay is greater tha required to form zeolites.

The solubility product of clinoptilolite is probably exceede at the downstream end of the ground-water system in volcani iment piles such as the Chambers and Capote Mountain fo tions. As more sediment accumulates, the area of clinopti formation migrates up the system. At this time three diag zones could be present in the sediment accumulation: one of tered glass, one with glass and montmorillonite or opal, an with montmorillonite, opal, and clinoptilolite. The zone of tered glass may be vanishingly small.

Where clinoptilolite forms, the concentration of silicic aluminate, and other constituents is reduced below saturation montmorillonite (Fig. 6). As more glass dissolves, pH rise aluminate ion concentration does not; the solubility prod clinoptilolite is nearly independent of pH.

The ratio of aluminum to silicon in zeolite is controlled ratio of aluminate to silicic acid in solution (Mariner and Su 1970). Because the composition of a solid phase affects energy, the ratio of aluminate to silicic acid of the solution the solubility product of the zeolite. In short, the clinop equilibrium line of Figure 6 may not have exactly zero slope. certainly has one lower than that of montmorillonite equili The slope will be sufficient to allow for the effect of changes ution composition caused by accumulation in solution o stituents of glass not used in the formation of zeolite (W 1972).

In the John Day Formation of Oregon, a zone of dissolv unreplaced shards at the top of the clinoptilolite zone indicat glass shards completely dissolved before precipitation of clin lite (Hay, 1963). Moiola (1970) interpreted the presence of

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Quaternary faulting in Trans-Pecos Texas

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ABSTRACT

Faults that displace Quaternary units can be observed in scarps in Trans-Pecos Texas and are restricted to two north-trending zones in contrast to late Tertiary faults that cover the region and strike north, northwest, and west. The western zone of Quaternary faults, near El Paso, is usually included as the southern part of the Rio Grande rift. The eastern zone of Quaternary faults extends for 300 km from southern New Mexico along the Salt Basin graben through Van Horn, Texas; its probable extensions and subparallel associates extend southward to Presidio, Texas. This belt of faults is parallel to the Rio Grande rift zone and should be considered a southeast extension of that zone.

These fault zones die out southward into the edge of the Chihuahua tectonic belt, a region underlain by a thick Mesozoic carbonate and clastic section that in turn rests on a thick layer of evaporites. The evaporite zone may mask Cenozoic normal faulting and thus may define a zone of no data rather than a southern limit of basin-and-range or Rio Grande graben tectonics.

All Quaternary and most Tertiary faults trend parallel to pre-existing structures. The map pattern of Quaternary scarps suggest a maximum extension oriented about S80°W; however, first-motion studies of the 1931 Valentine, Texas earthquake show a maximum elongation direction of S50° to 55°W. This difference may be unique to this one earthquake or may be due to the pre-existing lines of weakness that control the location of presently active faults.

INTRODUCTION

Late Tertiary faults in Trans-Pecos Texas (Fig. 1) form a pattern of north- and northwest-trending segments that occupy a 100 km-wide band roughly parallel to the southeast-flowing Rio Grande from El Paso into Mexico. Quaternary fault scarps in the Trans-Pecos area form a similar pattern of north- and northwest-trending segments but are found in more restricted belts that trend northerly within the band of late Tertiary faults.

All faults that cut Cenozoic units, as shown on existing geologic maps, and photolinears recognized by us were field checked to see whether Quaternary units were displaced and whether fault scarps were present. Some of these scarps are newly recognized. Quaternary fault scarps are confined primarily to the north-trending, 300 km-long Salt Basin graben and to the northern end of the Presidio basin (Fig. 2), where the fault scarps appear to be the southern extension of the Salt Basin structures. The only other fault scarps formed on Quaternary strata are those associated with the Tularosa-Hueco basin near El Paso (Fig. 1). These are the north-trending major scarps that mark the eastern side of the Franklin Mountains at El Paso and continue northward into New Mexico for more than 100 km and the discontinuous scarps along the eastern margin of the Hueco bolson. On the Mexican side of the Rio Grande, 50 km downstream from El Paso, a major Quaternary fault scarp extends southeastward for 50 to 60 km, forming the southern margin of the Hueco graben.

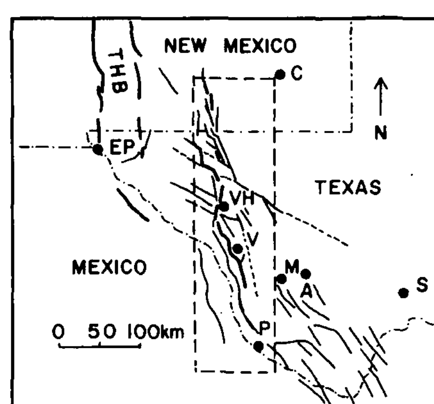

Figure 1. Map showing location of faults that cut Quaternary units (heavy lines) and faults that have been active during late Cenozoic time in Trans-Pecos Texas and adjacent Mexico and New Mexico. Abbreviations, from north to south: C-Carlsbad, EP-El Paso, VH-Van Horn, V-Valentine, THB-Tularosa-Hueco basin, M-Marfa, A-Alpine, S-Sanderson, P-Presidio. Dashed line outlines area of Figure 2, Salt Basin graben and related structures. Modified from King, 1969.

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In Trans-Pecos Texas, Tertiary fault trends are parallel to older fault trends. The north-trending fault segments are parallel to late Paleozoic, Mesozoic and/or Laramide faults; the northwest and west trends are parallel to late Paleozoic and Precambrian faults (King and Flawn, 1953; Kottlowski, 1971; Wiley and Muehlberger, 1971; Kelley, 1971; Black, 1975; and many others). As a result, the Salt Basin graben of late Tertiary age (Fig. 2), northward from Van Horn, consists of north-trending segments that step to the west along older northwest- or west-trending cross structures. South of Van Horn the graben splits with the Wylie Mountains as a horst block between the branches. The western branch contains all Quaternary fault scarps in the graben including the 80 km-long Mayfield fault (the longest continuous scarp in Salt Basin graben), whereas the eastern branch apparently does not contain fault scarps.

Why the distribution of Quaternary faults differs from the late Tertiary basin-and-range fault pattern is as yet unanswered. All scarps mapped and described are younger than the Pliocene-Pleistocene integration of Rio Grande drainage between El Paso and Presidio (see recent summaries in Strain, 1971; Hawley, 1975; Hawley and others, 1976). The scarps are generally steep and if Wallace's (1977) criteria are applicable in this region, then they are Holocene; however, the steepness (and therefore the apparent youthful appearance of the scarps) may be because they are composed of bouldery fanglomerates in the southern region, which are derived from the early Tertiary volcanic sequence (Fig. 3), and of fine-grained calichified Salt Basin fill of the northern region, which is derived from carbonate and fine-grained clastic rocks.

DESCRIPTION OF SCARPS IN SALT BASIN GRABEN

The majority of Quaternary fault scarps in this region trend north or northwest and occur singly or in en echelon patterns (Fig. 2). Northeast- and west-trending scarps are rare and occur: (1) along the east base of the Baylor Mountains, (2) north of Babb flexure, and (3) along the north segment of the Mayfield fault south of Van Horn.

Quaternary fault scarps are short and widely scattered along the eastern side of the graben but are more continuous along the west side and exhibit increasingly larger displacements southward (1 to 3 m, Goetz, 1977). This suggests that the western border of the graben is actively subsiding. Evidence supporting this is the fact that most playa lakes are located along the western edge. Some of the lakes have linear margins (some of the photolinears of Fig. 2 between Dell City and Victorio Peak) that might have originated as fault scarps.

Only two fault scarps in Quaternary alluvium were found in the New Mexico portion of Salt Basin graben, and these are located along the eastern margin of the graben. The northernmost scarp, 50 km above the Texas border, was mapped northwest of the Brokeoff Mountains by Kelley (1971). A second scarp, 10 km south, was mapped in Crow Flat during our study. A cluster of faults, in the vicinity of Bitterwell Mountain, part of which was mapped by P. B. King (1948, 1965), constitutes the main area of scarps on the east side of the graben. Only two other fault scarps on the east side of the graben definitely can be shown to cut the youngest basin fill; one is at the western base of the southernmost Delaware Mountains, the other is located south of the Apache Mountains.

Fault scarps on the western side extend from a locality 8 km south of Dell City and continue southeastward to U.S. Highway 180 and form an en echelon pattern. From this point the scarps trend southward, and the number of scarps decreases, but individual fault scarps become longer and higher toward Babb flexture, a west-northwest–trending structure that is reflected by the change in strike of the scarps. Discontinuous scarps are found in the Baylor Mountains segment of the graben. King (1965) mapped a fault in the basin fill west of Baylor Mountains, but the fault trace was not found in this study, as the area has been plowed and seeded with grass within the last few years.

The fault scarp south of the Baylor Mountains parallels the trend of the faults east of the Baylor Mountains and corresponds with the trend of a sharp change in the slope of the basement, as indicated by the resistivity work of D. E. White, J. J. Gates, M. T. Smith, and B. J. Fry (1978, in prep.).

Discontinuous, eroded fault scarps located north, west, and southwest of Van Horn show a maximum of 6 m relief and continue southward to the north end of the Van Horn Mountains.

MAYFIELD FAULT

The longest continuous fault scarp, the Mayfield fault south of Van Horn, extends along the east side of the Van Horn Moun-

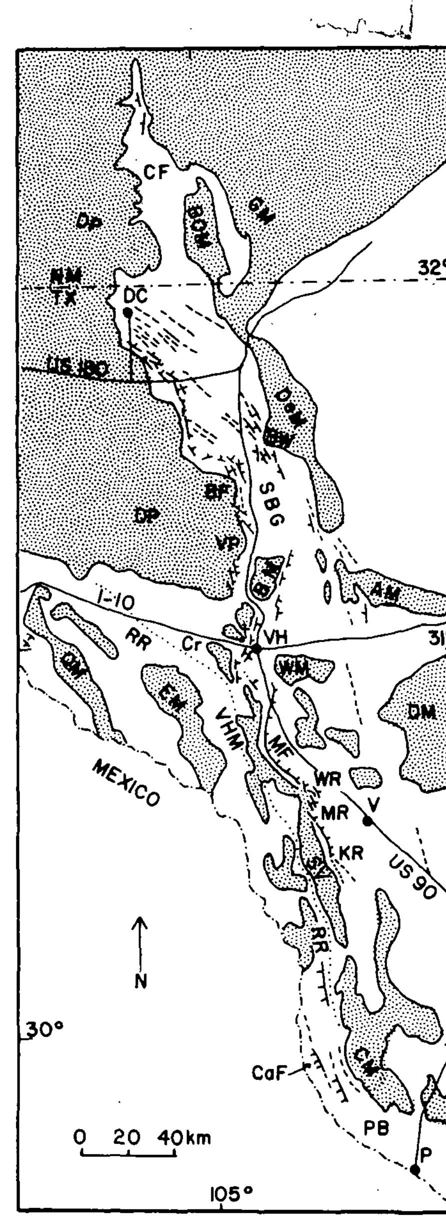

Figure 2. Quaternary fault scarps (barb on downthrown side) and photolinears (dashed lines; no topographic scarp found during field check) of Salt Basin graben (SBG; including Crow Flat-CF), Presidio Basin (PB), and related structures. This area contains all Quaternary fault scarps in Trans-Pecos Texas except for those near El Paso. Mayfield fault (MF) has longest continuous fault scarp and two periods of displacement can be demonstrated for the reach west of Valentine. Major highways labeled with route number, Cities: DC-Dell City, P-Presidio, V-Valentine, VH-Van Horn. Highlands (stippled): AM-Apache Mountains, BM-Baylor mountains, BOM-Brokeoff Mountains, BW-Bitterwell Mountain, DM-Davis Mountains, DeM-Delaware Mountains, DP-Diablio Plateau, EM-Eagle Mountains, GM-Guadalupe Mountains, QM-Quitman Mountains, SV-Sierra Vieja, VHM-Van Horn Mountains, VP-Victorio Peak, WM-Wylie Mountains. Structures: BF-Babb flexure, CaF-Candelaria fault, MF-Mayfield fault, RR-Rim Rock fault (shown by dots). Ranches: KR-King Ranch, MR-Miller Ranch, WR-White Ranch.

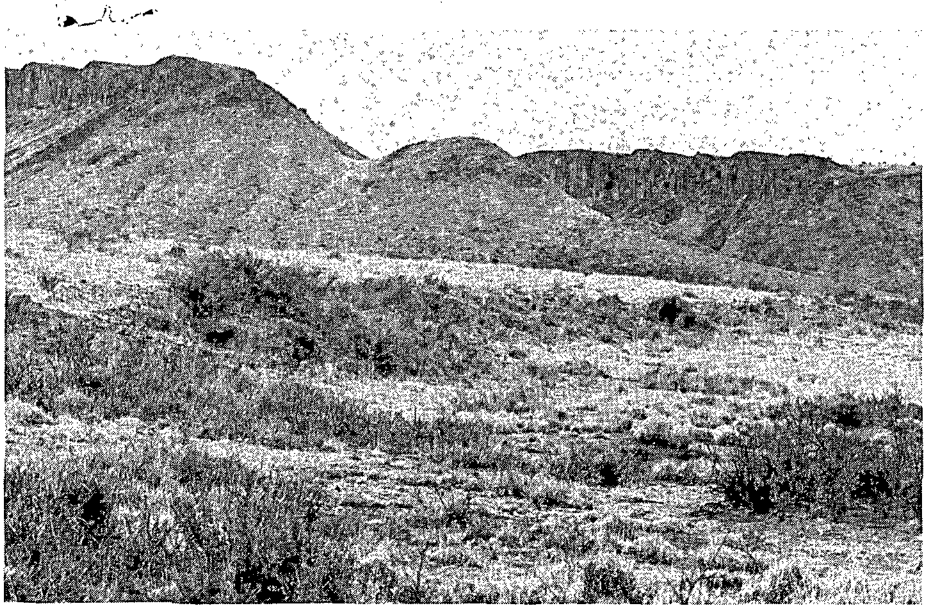

Figure 3. View northwest along Miller Ranch segment of Mayfield fault, in mid-foreground. Approximate displacement: 1.5 m. Present slope angle about 27°. Locality is about 20 km west of Valentine, Texas.

tains and the Sierra Vieja for more than 80 km. In its northern portion, the fault (Neal fault of Twiss, 1959) trends approximately N10°E and terminates north of U.S. Highway 90 by splaying into three subparallel fault segments. Each of these fault segments is down to the east, and each exhibits a throw of 1 m. South of U.S. Highway 90, the Mayfield fault has a throw of approximately 2 m and is preserved as a single fault scarp for 35 km to the vicinity of the White Ranch. From here to its southern termination on the King Ranch, the Mayfield fault is represented by a series of en echelon fault scarps. Individual scarps show displacements ranging from 1 to 7 m, and the Miller Ranch segment has experienced recurrent movement. At the King Ranch the fault scarps terminate, but photolinears continue southward for another 10 km.

In Trans-Pecos Texas recurrent movement can only be demonstrated on the Miller Ranch segment of the Mayfield fault (Fig. 2), west-southwest of Valentine. Present are several surfaces whose formation appears to have been initiated by two separate episodes of fault movement. The oldest surface has been displaced approximately 2 m and is eroded back from the fault trace. The resulting surface, in turn, has been broken by two en echelon faults with displacements of approximately 1.5 m and 7 m (Fig. 3). Modern arroyo-cutting is now forming a new surface by truncating the two older surfaces. Dorman (1976, written commun.) reports an earthquake on 1 August 1975 that was felt in Valentine with an epicenter close to the Miller Ranch segment of the Mayfield fault.

In 1931, a major earthquake (Sellards, 1932) occurred in this region, and the major damage was in Valentine, Texas. Instrumental data for this period are poor and the epicentral locations have large circles of confidence. Thus, this seismic event cannot be assigned to a specific structure. Sanford and Toppozada (1974), using Byerly's data, obtained a fault-plane solution with a N40°W strike and 74°SW dip, not too different from the N35°W, down-to-west, near-vertical, fault-plane solution of Byerly (1934). The isoseismal map of Sellards (1932) shows intensity contours that are elongated in a N50°W direction, whereas Sanford and Toppozada's interpretation lies closer to N30°W. Each of these strikes is essentially that of long segments of the Mayfield fault, but the Mayfield fault dips steeply east, suggesting that it was not responsible for the Valentine earthquake; however, no geologist searched this region for fault displacements after the Valentine quake (Sellards, 1932), and none were reported by local inhabitants.

Hay-Roe (1957) mapped an east-dipping fault extending southward along the east side of the Wylie Mountains to just north of Valentine. This fault has no scarp in the alluvium and is shown as a photolinear on Figure 2.

RIM ROCK FAULT

The Rim Rock fault is a major late Tertiary fault that also is the boundary between the Mesozoic Chihuahua tectonic belt of Mexico and the Diablo platform of Texas (DeFord, 1969; Wiley, 1970). The main part of the fault, however, is in Tertiary rocks along the length of the Van Horn Mountains and the Sierra Vieja (Fig. 2), where Quaternary displacements are not observable. It is also a region of high relief and difficult access. It essentially parallels major segments of the Mayfield fault; the mountain block between the two faults is a horst along the structural province boundary.

At its southern termination at the north end of the Presidio bolson, the Candelaria fault, parallel to the Rim Rock fault, cuts old Quaternary terrace deposits and, in turn, is truncated by young terrace deposits.

A fault scarp along the west side of the Chinati Mountains has a height of 5 m and is down to the west (Amsbury, 1958; Christopher Henry, 1977, oral commun.). Amsbury (1958) and Dietrich (1965) show many faults cutting Quaternary-Tertiary bolson fill in the area surrounding Presidio, but field checks have revealed that most of the mapped faults are photolinears rather than fault scarps.

OTHER FAULT SCARPS IN TRANS-PECOS TEXAS

Major fault scarps (5 to 7 m high) in Quaternary deposits are found along the east side fo the Franklin Mountains and the northeast side of the Sierra de la Amargosa in Mexico (Fig. 1). Both of these scarps indicate movement down to the east. Smaller, discontinuous fault scarps extend north toward New Mexico along the east edge of the Hueco graben, 40 km east of El Paso.

Along the west side of the north end of the Quitman Mountains, a few small discontinuous fault scarps are found. They exhibit displacements that are down to the west and appear to be unrelated to any major structural feature.

No other scarps formed on Quaternary units were found in the remainder of Trans-Pecos Texas.

DISCUSSION

Field evidence shows that there are two main belts of fault scarps in Trans-Pecos Texas; both are elongated in a north-south direction. The western belt, only briefly mentioned in this paper, is the line through El Paso that is usually defined as the southern continuation (termination?) of structures related to the Rio Grande rift (Chapin, 1971; Decker and Smithson, 1975; Ramberg and Smithson, 1975; Woodward and others, 1975; Ramberg and others, 1978). This paper has emphasized another line of fault scarps that lies, for the most part, along the western margin of the Salt Basin graben and that effectively defines the present eastern margin of Quaternary faulting in this region. Because it is presently active, lies parallel to the presently active segments of the Rio Grande rift that straddle the Rio Grande in southern New Mexico, and is a graben of a size comparable to those to the west (Ramberg and others, 1978), we believe that the Salt Basin graben and its possible continuation southward to Presidio, Texas, should be considered an eastern offset of the Rio Grande rift zone.

Whether the Rio Grande rift zone extends into Mexico is as yet unknown. The prominent fault scarps visible in satellite imagery in the Quaternary fill of southern New Mexico turn southeastward in northern Mexico and fade away (Woodward and others, 1975). Gries (1977) has suggested that if basin-and-range or Rio Grande rift structures do extend into northern Mexico, then the evidence for normal faulting would be lost in the ductile flow of the evaporite zone that underlies the Chihuahua tectonic belt.

Because all Quaternary fault scarps in Trans-Pecos Texas lie nearly parallel to pre-existing structural trends, the pattern of stress fields in this area is not uniquely defined. The fact that the fault scarps that cut Quaternary units do not include all of Trans-Pecos Texas that is broken by basin-and-range faulting may be either a result of our studying too narrow a slice of geologic time or of a change in the stress field.

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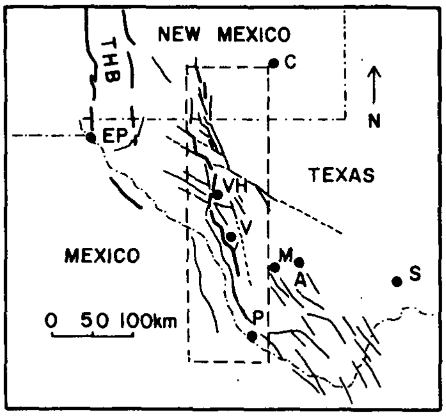

Figure 1. Map showing location of faults that cut Quaternary units (heavy lines) and faults that have been active during late Cenozoic time in Trans-Pecos Texas and adjacent Mexico and New Mexico. Abbreviations, from north to south: C-Carlsbad, EP-El Paso, VH-Van Horn, V-Valentine, THB-Tularosa-Hueco basin, M-Marfa, A-Alpine, S-Sanderson, P-Presidio. Dashed line outlines area of Figure 2, Salt Basin graben and related structures. Modified from King, 1969.

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Discontinuous, eroded fault scarps located north, west, and southwest of Van Horn show a maximum of 6 m relief and continue southward to the north end of the Van Horn Mountains.

MAYFIELD FAULT

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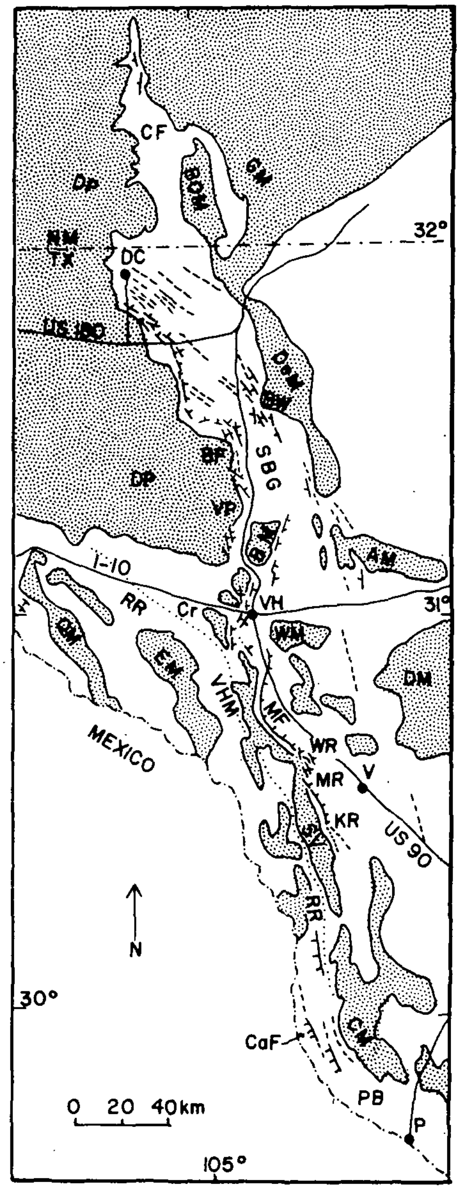

Figure 2. Quaternary fault scarps (barb on downthrown side) and photolinears (dashed lines; no topographic scarp found during field check) of Salt Basin graben (SBG; including Crow Flat-CF), Presidio Basin (PB), and related structures. This area contains all Quaternary fault scarps in Trans-Pecos Texas except for those near El Paso. Mayfield fault (MF) has longest continuous fault scarp and two period of displacement can be demonstrated for the reach west of Valentine. Major highways label with route number, Cities: DC-Dell City, P-Presidio, V-Valentine, VH-Van Horn. Highla (stippled): AM-Apache Mountains, BM-Bayl mountains, BOM-Brokeoff Mountains, BW-Bitterwell Mountain, DM-Davis Mountains, DeM-Delaware Mountains, DP-Diablio Plat EM-Eagle Mountains, GM-Guadalupe Mour QM-Quitman Mountains, SV-Sierra Vieja, Van Horn Mountains, VP-Victorio Peak, Wylie Mountains. Structures: BF-Babb fl CaF-Candelaria fault, MF-Mayfield fault Rim Rock fault (shown by dots). Ranch KR-King Ranch, MR-Miller Ranch, WR-Ranch.

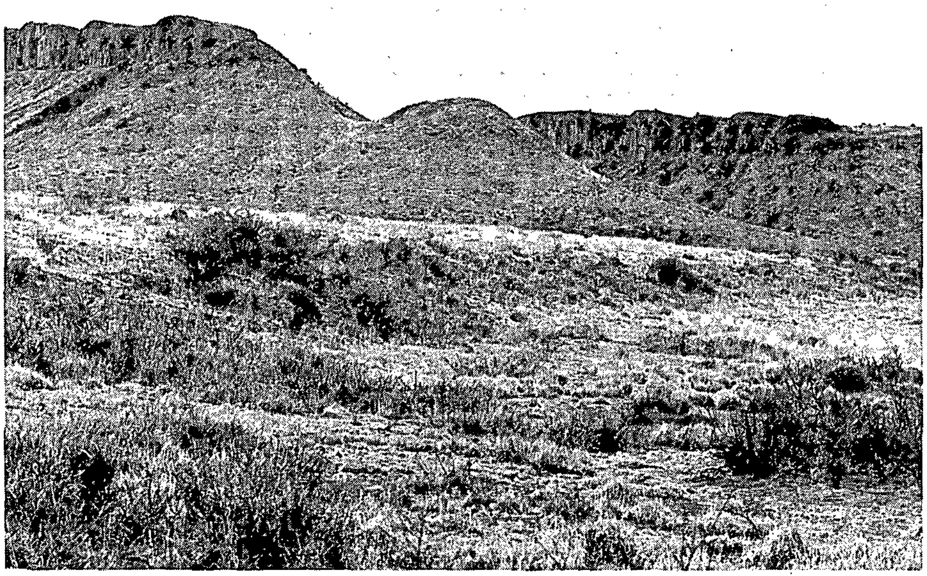

Figure 3. View northwest along Miller Ranch segment of Mayfield fault, in mid-foreground. Approximate displacement: 1.5 m. Present slope angle about 27°. Locality is about 20 km west of Valentine, Texas.

tains and the Sierra Vieja for more than 80 km. In its northern portion, the fault (Neal fault of Twiss, 1959) trends approximately N10°E and terminates north of U.S. Highway 90 by splaying into three subparallel fault segments. Each of these fault segments is down to the east, and each exhibits a throw of 1 m. South of U.S. Highway 90, the Mayfield fault has a throw of approximately 2 m and is preserved as a single fault scarp for 35 km to the vicinity of the White Ranch. From here to its southern termination on the King Ranch, the Mayfield fault is represented by a series of en echelon fault scarps. Individual scarps show displacements ranging from 1 to 7 m, and the Miller Ranch segment has experienced recurrent movement. At the King Ranch the fault scarps terminate, but photolinears continue southward for another 10 km.

In Trans-Pecos Texas recurrent movement can only be demonstrated on the Miller Ranch segment of the Mayfield fault (Fig. 2), west-southwest of Valentine. Present are several surfaces whose formation appears to have been initiated by two separate episodes of fault movement. The oldest surface has been displaced approximately 2 m and is eroded back from the fault trace. The resulting surface, in turn, has been broken by two en echelon faults with displacements of approximately 1.5 m and 7 m (Fig. 3). Modern arroyo-cutting is now forming a new surface by truncating the two older surfaces. Dorman (1976, written commun.) reports an earthquake on 1 August 1975 that was felt in Valentine with an epicenter close to the Miller Ranch segment of the Mayfield fault.

In 1931, a major earthquake (Sellards, 1932) occurred in this region, and the major damage was in Valentine, Texas. Instrumental data for this period are poor and the epicentral locations have large circles of confidence. Thus, this seismic event cannot be assigned to a specific structure. Sanford and Toppozada (1974), using Byerly's data, obtained a fault-plane solution with a N40°W strike and 74°SW dip, not too different from the N35°W, down-to-west, near-vertical, fault-plane solution of Byerly (1934). The isoseismal map of Sellards (1932) shows intensity contours that are elongated in a N50°W direction, whereas Sanford and Toppozada's interpretation lies closer to N30°W. Each of these strikes is essentially that of long segments of the Mayfield fault, but the Mayfield fault dips steeply east, suggesting that it was not responsible for the Valentine earthquake; however, no geologist searched this region for fault displacements after the Valentine quake (Sellards, 1932), and none were reported by local inhabitants.

Hay-Roe (1957) mapped an east-dipping fault extending southward along the east side of the Wylie Mountains to just north of Valentine. This fault has no scarp in the alluvium and is shown as a photolinear on Figure 2.

RIM ROCK FAULT

The Rim Rock fault is a major late Tertiary fault that also is the boundary between the Mesozoic Chihuahua tectonic belt of Mexico and the Diablo platform of Texas (DeFord, 1969; Wiley, 1970). The main part of the fault, however, is in Tertiary rocks along the length of the Van Horn Mountains and the Sierra Vieja (Fig. 2), where Quaternary displacements are not observable. It is also a region of high relief and difficult access. It essentially parallels major segments of the Mayfield fault; the mountain block between the two faults is a horst along the structural province boundary.

At its southern termination at the north end of the Presidio bolson, the Candelaria fault, parallel to the Rim Rock fault, cuts old Quaternary terrace deposits and, in turn, is truncated by young terrace deposits.

A fault scarp along the west side of the Chinati Mountains has a height of 5 m and is down to the west (Amsbury, 1958; Christopher Henry, 1977, oral commun.). Amsbury (1958) and Dietrich (1965) show many faults cutting Quaternary-Tertiary bolson fill in the area surrounding Presidio, but field checks have revealed that most of the mapped faults are photolinears rather than fault scarps.

OTHER FAULT SCARPS IN TRANS-PECOS TEXAS

Major fault scarps (5 to 7 m high) in Quaternary deposits are found along the east side fo the Franklin Mountains and the northeast side of the Sierra de la Amargosa in Mexico (Fig. 1). Both of these scarps indicate movement down to the east. Smaller, discontinuous fault scarps extend north toward New Mexico along the east edge of the Hueco graben, 40 km east of El Paso.

Along the west side of the north end of the Quitman Mountains, a few small discontinuous fault scarps are found. They exhibit displacements that are down to the west and appear to be unrelated to any major structural feature.

No other scarps formed on Quaternary units were found in the remainder of Trans-Pecos Texas.

DISCUSSION

Field evidence shows that there are two main belts of fault scarps in Trans-Pecos Texas; both are elongated in a north-south direction. The western belt, only briefly mentioned in this paper, is the line through El Paso that is usually defined as the southern continuation (termination?) of structures related to the Rio Grande rift (Chapin, 1971; Decker and Smithson, 1975; Ramberg and Smithson, 1975; Woodward and others, 1975; Ramberg and others, 1978). This paper has emphasized another line of fault scarps that lies, for the most part, along the western margin of the Salt Basin graben and that effectively defines the present eastern margin of Quaternary faulting in this region. Because it is presently active, lies parallel to the presently active segments of the Rio Grande rift that straddle the Rio Grande in southern New Mexico, and is a graben of a size comparable to those to the west (Ramberg and others, 1978), we believe that the Salt Basin graben and its possible continuation southward to Presidio, Texas, should be considered an eastern offset of the Rio Grande rift zone.

Whether the Rio Grande rift zone extends into Mexico is as yet unknown. The prominent fault scarps visible in satellite imagery in the Quaternary fill of southern New Mexico turn southeastward in northern Mexico and fade away (Woodward and others, 1975). Gries (1977) has suggested that if basin-and-range or Rio Grande rift structures do extend into northern Mexico, then the evidence for normal faulting would be lost in the ductile flow of the evaporite zone that underlies the Chihuahua tectonic belt.

Because all Quaternary fault scarps in Trans-Pecos Texas lie nearly parallel to pre-existing structural trends, the pattern of stress fields in this area is not uniquely defined. The fact that the fault scarps that cut Quaternary units do not include all of Trans-Pecos Texas that is broken by basin-and-range faulting may be either a result of our studying too narrow a slice of geologic time or of a change in the stress field.

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Quaternary faulting in Trans-Pecos Texas

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ABSTRACT

Faults that displace Quaternary units can be observed in scarps in Trans-Pecos Texas and are restricted to two north-trending zones in contrast to late Tertiary faults that cover the region and strike north, northwest, and west. The western zone of Quaternary faults, near El Paso, is usually included as the southern part of the Rio Grande rift. The eastern zone of Quaternary faults extends for 300 km from southern New Mexico along the Salt Basin graben through Van Horn, Texas; its probable extensions and subparallel associates extend southward to Presidio, Texas. This belt of faults is parallel to the Rio Grande rift zone and should be considered a southeast extension of that zone.

These fault zones die out southward into the edge of the Chihuahua tectonic belt, a region underlain by a thick Mesozoic carbonate and clastic section that in turn rests on a thick layer of evaporites. The evaporite zone may mask Cenozoic normal faulting and thus may define a zone of no data rather than a southern limit of basin-and-range or Rio Grande graben tectonics.

All Quaternary and most Tertiary faults trend parallel to pre-existing structures. The map pattern of Quaternary scarps suggest a maximum extension oriented about S80°W; however, first-motion studies of the 1931 Valentine, Texas earthquake show a maximum elongation direction of S50° to 55°W. This difference may be unique to this one earthquake or may be due to the pre-existing lines of weakness that control the location of presently active faults.

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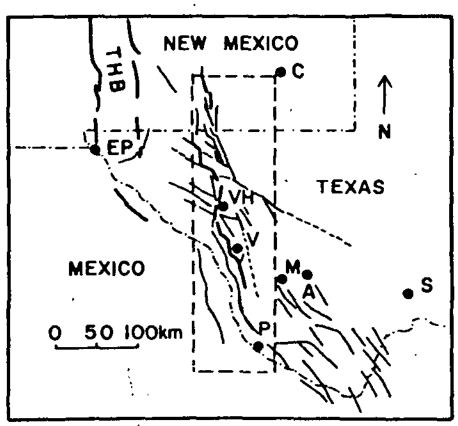

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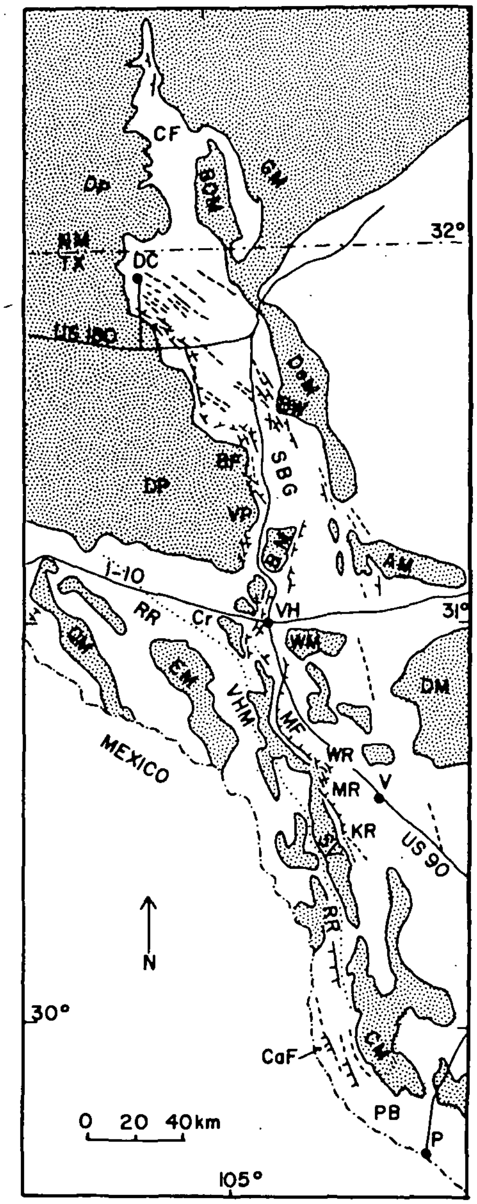

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C. D. Henry

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