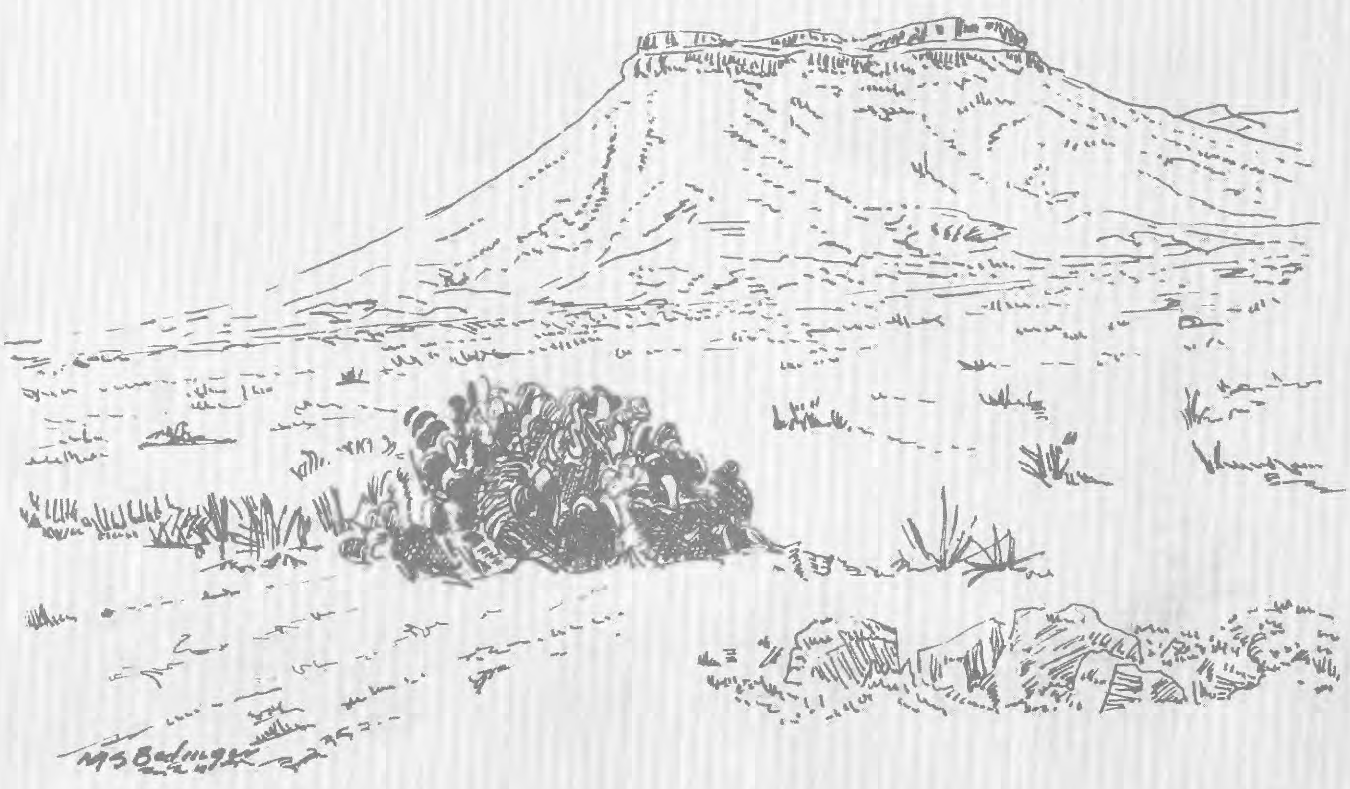
Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, For Isolation of High-Level Radioactive Waste—Characterization of the Trans-Pecos Region, Texas

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370-B

Prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah



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Edited by M.S. BEDINGER, K.A. SARGENT, *and* WILLIAM H. LANGER

STUDIES OF GEOLOGY AND HYDROLOGY FOR ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1989

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., *Secretary*

U. S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Studies of geology and hydrology in the Basin and Range province, southwestern United States, for isolation of high-level radioactive waste—characterization of the Trans-Pecos region, Texas.

(U.S. Geological Survey professional paper ; 1370–B)
"Prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah."
Includes bibliographies.
Supt. of Docs. no.: I 19.16:1370–B
1. Geology—Trans-Pecos Region (Tex. and N.M.) 2. Geology—Texas. 3. Water, Underground—Trans-Pecos Region (Tex. and N.M.) 4. Water, Underground—Texas. 5. Radioactive waste disposal in the ground—Trans-Pecos Region (Tex. and N.M.) 6. Radioactive waste disposal in the ground—Texas. I. Bedinger, M.S. II. Sargent, Kenneth A. III. Langer, William H. IV. Series.
QE168.T7S78 1989 557.64 86–600318

For sale by the Books and Open-File Reports Section, U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

BASIN AND RANGE PROVINCE WORKING GROUP

U.S. Geological Survey Members

Chairman of the Province Working Group:
M.S. Bedinger
Hydrologist
Denver, CO

Member:
K.A. Sargent
Geologist
Denver, CO

State Members and Alternates

ARIZONA

Member:
Larry D. Fellows
State Geologist and Assistant Director
Arizona Bureau of Geology and Mineral Technology
Tucson, AZ

Alternate:
H. Wesley Peirce
Principal Geologist
Arizona Bureau of Geology and Mineral Technology
Tucson, AZ

CALIFORNIA

Member:
Robert Streitz
Geologist
California Division of Mines and Geology
Sacramento, CA

IDAHO

Member:
Frank B. Sherman
Chief, Ground-Water Section
Idaho Department of Water Resources
Boise, ID

Alternate:
Darrel Clapp
Chief, Technical Services Bureau
Idaho Department of Water Resources
Boise, ID

NEVADA

Member:
John Schilling
State Geologist
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Reno, NV

Alternate:
Susan L. Tingley
Deputy to the State Geologist
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Reno, NV

NEW MEXICO

Member:
James M. Hill
Chief, Bureau of Geology
New Mexico Energy and Minerals Department
Santa Fe, NM

Alternate:
Frank E. Kottlowski
Director
New Mexico Bureau of Mines and Mineral Resources
Socorro, NM

TEXAS

Member:
Christopher D. Henry
Geologist
Texas Bureau of Economic Geology
University of Texas at Austin
Austin, TX

Alternate:
Douglas Ratcliff
Associate Director
Texas Bureau of Economic Geology
University of Texas at Austin
Austin, TX

UTAH

Member:
Genevieve Atwood
State Geologist
Utah Geological and Mineral Survey
Salt Lake City, UT

Alternate:
Don R. Mabey
Senior Geologist
Utah Geological and Mineral Survey
Salt Lake City, UT

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For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

Multiply SI unit	*By*	*To obtain U.S. customary unit*
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
liter (L)	0.2642	gallon (gal)
	Flow	
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
meter per day (m/d)	3.281	foot per day (ft/d)
	Mass	
kilogram (kg)	2.205	pound, avoirdupois (lb)
megagram (Mg) or metric ton	1.102	short ton (2,000 lb)
	Temperature	
degree Celsius (°C)	9/5(°C)+32=°F	degree Fahrenheit (°F)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Chemical concentration	
milligrams per liter (mg/L)	About 1	part per million

STUDIES OF GEOLOGY AND HYDROLOGY IN THE BASIN AND RANGE PROVINCE, SOUTHWESTERN UNITED STATES, FOR ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE— CHARACTERIZATION OF THE TRANS-PECOS REGION, TEXAS

Edited by M.S. BEDINGER, K.A. SARGENT, and WILLIAM H. LANGER

ABSTRACT

The Trans-Pecos region of Texas, in the southeasternmost part of the Basin and Range province, is semiarid; precipitation ranges from less than 250 to 450 millimeters and potential evapotranspiration is as great as 2.5 meters annually. Structurally, the region is transitional with the Great Plains to the east; only the northern and western parts of the region have well-developed, northwest-trending basins and ranges. The area has experienced repeated deformation since the Precambrian with igneous activity and basin-and-range extension, and to a lesser extent Laramide structures, dominating the topography. Potential host media for isolation of high-level radioactive waste in the region include: (1) Intrusive rocks occurring as stocks, sills, and laccoliths of several rock types; (2) tuffaceous rocks, which include densely welded ash-flow tuff; (3) basaltic lava flows; and (4) argillaceous rocks. Quaternary tectonism of the region is characterized by: (1) Many small earthquakes and only one damaging earthquake; (2) heat flow that is transitional between that of the craton to the east and the greater heat flow of the Basin and Range; and (3) Quaternary fault scarps, which are more common in the western part of the region. Long-term (late Cenozoic to modern) vertical crustal movement is estimated to be 1 to 2 meters per 10,000 years.

Surface and ground-water drainage in the region is to the Rio Grande and to topographically closed basins. Ground-water recharge in the upland areas and in channels of ephemeral streams probably averages about 10 millimeters or less annually. Relatively long travel paths and traveltimes exist from ground-water divides to natural discharge areas. Ground water generally contains less than 1,000 milligrams per liter of dissolved solids except in the Salt Basin where concentrations exceed 3,000 milligrams per liter.

Mineral production from the Trans-Pecos region has been dominated by silver, fluorspar, and mercury.

Manuscript approved for publication, January 3, 1985.

INTRODUCTION

By M.S. BEDINGER, K.A. SARGENT, and CHRISTOPHER D. HENRY[1]

BACKGROUND AND PURPOSE

A study by the U.S. Geological Survey to evaluate potential hydrogeologic environments for isolation of high-level radioactive waste in the Basin and Range physiographic province of the southwestern United States was begun in May 1981, with the introduction of the study to the Governors of eight Basin and Range States including Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, and Utah—and to respective Indian tribes in those States. Accordingly, these States were invited to participate in the study by designating an earth scientist to serve on a Province Working Group with the U.S. Geological Survey—membership of the working group is shown following the title page. State representatives have provided consultation in selecting guidelines, assembling geologic and hydrologic data, and assessing such information to identify environments that meet the guidelines for further study.

The guidelines for evaluation of the regions and the rationale for their study as well as the basis for hydrogeologic characterization of the regions are given in Chapter A of this Professional Paper (Bedinger, Sargent, Langer, and others, 1989). The evaluation of the regions is given in Chapter H (Bedinger, Sargent, and Langer, 1989). The titles of chapters in this series are as follows:

A Basis of characterization and evaluation
B Characterization of the Trans-Pecos region, Texas
C Characterization of the Rio Grande region, New Mexico and Texas
D Characterization of the Sonoran region, Arizona
E Characterization of the Sonoran region, California
F Characterization of the Death Valley region, Nevada and California
G Characterization of the Bonneville region, Utah and Nevada
H Evaluation of the regions.

These chapters are closely integrated and contain a minimum of repetition. The reader needs to consult Chapters A and H and the appropriate regional Chapters B through G in order to achieve a complete understanding of the characterization and evaluation of an individual region.

Additional background information on this study is given in reports on the province phase of characterization and evaluation by Bedinger and others (1984), Sargent and Bedinger (1985), and Bedinger and others (1985).

This report, Characterization of the Trans-Pecos region, Texas, Chapter B, is one of six reports characterizing the geology and hydrology of the regions of study in the Basin and Range province. Chapter B is divided into six separately authored sections: (1) Introduction, (2) Geology, (3) Potential host media, (4) Quaternary tectonism, (5) Ground-water hydrology, and (6) Mineral and energy resources. Although the report was prepared under the general guidelines set by the Province Working Group, the scope of individual sections was established by their respective authors.

This chapter provides the geologic and hydrologic framework necessary to evaluate the Trans-Pecos region for relative potential for isolation of high-level radioactive waste. Because of the limited and specific goals of the project, emphasis is placed on the characteristics of the region that relate to waste isolation.

The results of this study are not based on original data; no new field work was conducted specifically for this project. It is not intended to be a definitive report on the geologic and hydrologic aspects of the region, but it provides a general summary of the published and unpublished data that are available.

GEOGRAPHIC SETTING

The Trans-Pecos region, as defined in this report, mostly consists of the southern part of the Basin and Range province of Trans-Pecos Texas (pl. 1). It includes the area approximately from Van Horn on the northwest to the Big Bend area on the south, excluding an area along the Rio Grande west of the Sierra Vieja. The eastern boundary is approximately the eastern edge of Brewster County. An irregular northern boundary trends southeast through the Davis Mountains and extends east through the Glass Mountains. It should be noted that this area is not the same as Trans-Pecos Texas, which includes all of Texas west of the Pecos River.

The Trans-Pecos region is in the southeasternmost part of the Basin and Range province at the edge of the Great Plains. Only the northern and western parts of the region have well-developed northwest-trending basins and ranges, which have as much as 1,500 m of relief. The Big Bend area in the southern part experienced extensive basin-and-range-style faulting but large basins were not developed. The easternmost part of the

[1]Texas Bureau of Economic Geology.

area experienced minor faulting and some Laramide deformation, but is geologically transitional to the Great Plains.

ACKNOWLEDGMENTS

This chapter and the other chapter reports in this series were prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah. Each of these States was represented by members of the Basin and Range Province Working Group. The cooperating agencies in each State and members and alternates of the Province Working Group are listed following the title page. The following individuals provided continued advice and assistance to the Basin and Range Province Working Group and in overall planning and execution of the work in preparation of this series of reports: John W. Hawley and William J. Stone of the New Mexico Bureau of Mines and Mineral Resources; Robert B. Scarborough of the Arizona Bureau of Geology and Mineral Technology; T.L.T. Grose of the Nevada Bureau of Mines and Geology and the Colorado School of Mines; and George Dinwiddie and George I. Smith of the U.S. Geological Survey.

Assistance in preparation of the stratigraphy and structure sections of this report was provided by W.R. Muehlberger, F.W. McDowell, and D.S. Barker of The University of Texas at Austin, Department of Geological Sciences.

Assistance in compilation and synthesis of ground-water information for this report was given by Donald E. White, U.S. Geological Survey, and John Mikels, formerly with the U.S. Geological Survey. Ernest T. Baker and Joseph S. Gates, U.S. Geological Survey, contributed to the presentation and interpretation of the ground-water information presented in this report.

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GEOLOGY

By CHRISTOPHER D. HENRY and JONATHAN G. PRICE[2]

STRATIGRAPHY

PRECAMBRIAN ROCKS

The characteristics of the Precambrian rocks in the Trans-Pecos region are interpreted from outcrops in the Van Horn area (King and Flawn, 1953). Precambrian rocks have been penetrated in deep drill holes northwest of Van Horn outside the Trans-Pecos region (fig. 1). Two major sequences of Precambrian rocks are separated by the Streeruwitz thrust fault west of Van Horn (pl. 2): the Carrizo Mountain Group to the south and the Allamoore and Hazel Formations to the north. Although the Allamoore and Hazel Formations do not crop out in the Trans-Pecos region as defined here, they probably occur beneath the overthrusted Carrizo Mountain Group which does crop out in this region. The stratigraphic section in the region is shown in table 1.

The Carrizo Mountain Group consists of quartzite, meta-arkose, slate, muscovite schist, biotite schist, metarhyolite, metabasalt (greenstone and amphibolite), pegmatite, and some granodiorite and carbonate rocks. The basalts probably occur as sills (King and Flawn, 1953), and the rhyolites are dominantly ash-flow tuffs (Rudnick, 1983). Total thickness of the sequency of metasedimentary and metaigneous rocks is about 5,800 m (King and Flawn, 1953). Condie (1982) and Rudnick (1983) suggested that the rocks were deposited in a back-arc basin along the continental margin. Denison (1980), using whole-rock Rb/Sr isochrons, interpreted the age of deposition to be between 1,200 and 1,300 m.y. ago.

North of the Streeruwitz fault, the oldest exposed unit is the Allamoore Formation, which is composed of cherty limestone and dolomite, talcose phyllite, tuff, and basalt flows and sills (King and Flawn, 1953). The Carrizo Mountain Group is thrust over the Allamoore Formation. Although geologic relations do not permit determination of relative ages for these two units, most workers have assumed that the Allamoore is younger.

In normal stratigraphic sequence, the Allamoore Formation is overlain by conglomerates, sandstones, and siltstones of the Hazel Formation. Reid (1974) determined that the Hazel red beds were derived dominantly from the Allamoore Formation, transported northward, and deposited in alluvial fans. Thickness is difficult to determine because deformation is intense in the Allamoore Formation and marker beds are absent in the Hazel Formation. Unpublished seismic data from the western part of the Sierra Diablo area indicate a sequence of greater than 3,000 m of nearly horizontal rocks in the Allamoore and Hazel Formations (fig. 2). Condie (1982) suggested that the Allamoore and Hazel Formations, like the Carrizo Mountain Group, were deposited in a back-arc basin.

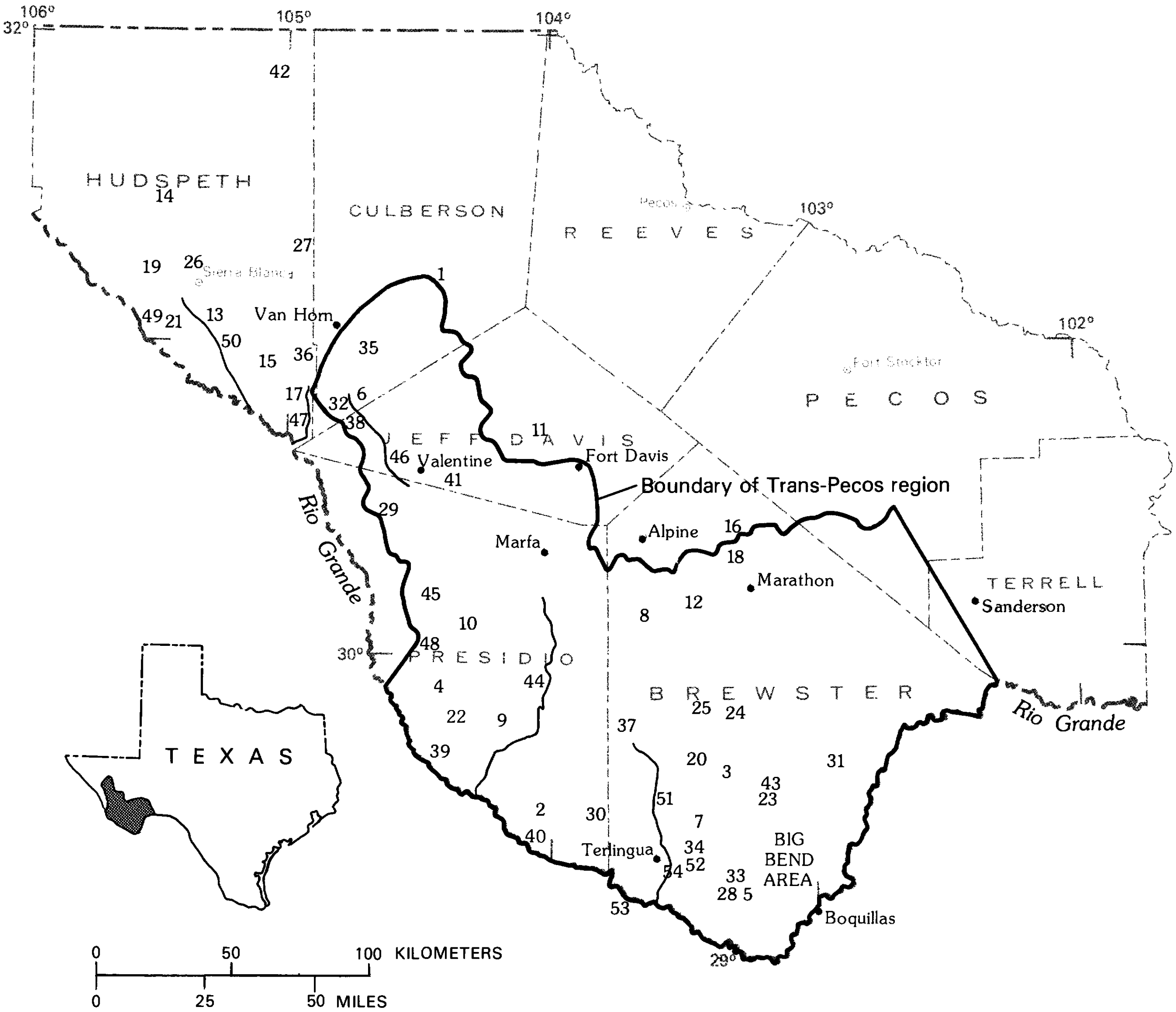
PALEOZOIC ROCKS

Outcrops of Paleozoic rocks are distributed throughout the Trans-Pecos region. Two broad geographic subdivisions can be made: (1) The northern part of the region, including exposures in the Van Horn, Chinati, Glass, and Eagle Mountains and the Sierra Diablo and consisting of autochthonous sedimentary rocks; and (2) the Ouachita-Marathon fold and thrust belt (fig. 3) exposed in the Marathon and Solitario areas and consisting of allochthonous sedimentary rocks. In general, the Middle Cambrian to Upper Permian autochthonous rocks were deposited in shallow cratonic seas; limestone, dolomite, and sandstone dominate the sequence. The allochthonous rocks, which range in age from Cambrian to Pennsylvanian and which underwent thrusting during Pennsylvanian and Early Permian time, are dominated by flysch deposits of sandstone and shale (King, 1980). Authochthonous sedimentary rocks beneath the allochthonous rocks have been penetrated locally in exploration drilling for oil and gas in the eastern Marathon basin (King, 1980).

Thicknesses of allochthonous Paleozoic strata vary systematically throughout the region (table 1), in part due to later erosion and in part due to varying rates of deposition in basins and on platforms (Galley, 1958; LeMone and others, 1983).

The Diablo platform, which approximately coincides with the Diablo Plateau, was generally a high area throughout the Paleozoic Era. The thickest Paleozoic units on the Diablo platform are shelf carbonate rocks including reefs, but in the basin areas, sandstone and shale dominate. A section of Permian rocks about 2,500 m thick in the Chinati Mountains area was deposited in the Marfa basin and is dominated by shale and sandstone (Rix, 1953). Permian deposits show thickness variations comparable to those of earlier Paleozoic rocks: as much as 1,500 m in the Sierra Diablo area (King, 1965) and about 6,000 m in the center of the Delaware basin (Galley, 1958) in the subsurface to the east beyond the Basin and Range province.

[2]Texas Bureau of Economic Geology.



EXPLANATION

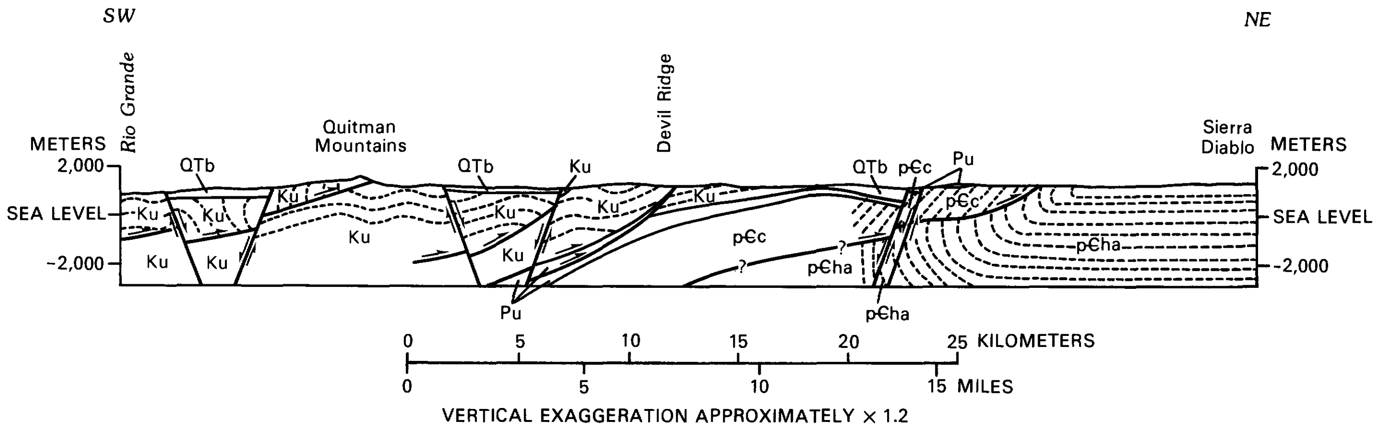
1 --APACHE MOUNTAINS
2 --BOFECILLOS MOUNTAINS
3 --CHALK MOUNTAINS
4 --CHINATI MOUNTAINS
5 --CHISOS MOUNTAINS
6 --CHISPA MOUNTAINS
7 --CHRISTMAS MOUNTAINS
8 --CIENEGA MOUNTAIN
9 --CIENEGA MOUNTAINS
10 --CUESTA DEL BURRO MOUNTAINS
11 --DAVIS MOUNTAINS
12 --DEL NORTE MOUNTAINS
13 --DEVIL RIDGE
14 --DIABLO PLATEAU
15 --EAGLE MOUNTAINS
16 --GLASS MOUNTAINS
17 --INDIO MOUNTAINS
18 --IRON MOUNTAIN
19 --MALONE MOUNTAINS
20 --NINE POINT MESA
21 --QUITMAN MOUNTAINS
22 --RED HILL
23 --ROSILLOS MOUNTAINS
24 --SANTIAGO MOUNTAINS
25 --SANTIAGO PEAK
26 --SIERRA BLANCA
27 --SIERRA DIABLO
28 --SIERRA QUEMADA
29 --SIERRA VIEJA
30 --SOLITARIO
31 --STILLWELL MOUNTAIN
32 --VAN HORN MOUNTAINS
33 --WARD MOUNTAIN
34 --WILDHORSE MOUNTAIN
35 --WYLIE MOUNTAINS
36 --EAGLE FLAT
37 --GREEN VALLEY
38 --LOBO VALLEY
39 --PRESIDIO BOLSON
40 --REDFORD BOLSON
41 --RYAN FLAT
42 --SALT BASIN
43 --TORNILLO FLAT
44 --ALAMITO CREEK
45 --CAPOTE DRAW
46 --CHISPA CREEK
47 --GREEN RIVER
48 --PINTO CANYON
49 --QUITMAN ARROYO
50 --RED LIGHT DRAW
51 --TERLINGUA CREEK
52 --DOGIE MOUNTAIN
53 --SANTA ELENA CANYON
54 --STUDY BUTTE

FIGURE 1.—Geographic index of the Trans-Pecos region and vicinity.

TABLE 1.—*List of Paleozoic and Precambrian stratigraphic units in the Trans-Pecos region and vicinity*

[Only general correlation of units in different geographic areas is implied. Location of geographic areas shown on figure 1. Thickness in meters (m). Shaded areas, strata absent]

System	Series	Sierra Diablo area (King, 1965)	Van Horn and Wylie Mountains (Twiss, 1959; Hay-Roe, 1957)	Chinati Mountains (Rix, 1953)	Marathon region and Glass Mountains (King, 1937; Barnes, 1982; Cooper and Grant, 1971)
PERMIAN	Ochoan				Tessey Limestone 300 m
	Guadalupian	Goat Seep Limestone 60+ m Cherry Canyon Formation 46-60 m	Seven Rivers Limestone 49 m	Mina Grande Formation of Rix (1953) As much as 122 m Ross Mine Formation of Rix (1953) 222 m	Capitan Limestone As much as 550 m Word Formation As much as 470 m
	Leonardian	Cutoff Shale 84 m Victoria Peak Limestone 270-460 m Bone Spring Limestone 274-396 m	Victoria Peak Formation 0-500 m	Cibolo Formation 442 m	Cathedral Mountain Formation 490 m
	Wolfcampian	Hueco Limestone 0-425 m Powwow Member 0-76 m	Hueco Limestone 0-378 m Powwow Conglomerate 0-76 m	Alta Formation 1,700+ m	Skinner Ranch Formation 69-490 m Hess Limestone 490-700 m Lenox Hills Formation 9-206 m Neal Ranch Formation 91 m
PENN-SYLVANIAN		Unnamed beds Thickness un- determined		Cienequita Formation 600+ m	Gaptank Formation 550 m Haymond Formation 910+ m Dimple Limestone 91-300 m Tesnus Formation 91-2,100 m
MISSIS-SIPPIAN		Barnett Shale 41+ m			Caballos Novaculite 61-180
DEVO-NIAN		Unnamed beds 38 m			
SILURIAN		Fusselman Dolomite 90-137 m			
ORDOVICIAN	Upper Ordovician	Montoya Dolomite 70-137 m			Maravillas Chert 30-120 m
	Middle Ordovician	Beds of Middle(?) Ordovician age 18-24 m			Woods Hollow Shale 91-120 m Fort Peña Formation 38-61 m
	Lower Ordovician	El Paso Limestone 350 m Bliss Sandstone 30-49 m			Alsate Shale 7-44 m Marathon Limestone 110-300 m
CAMBRIAN	Upper Cambrian				Dagger Flat Sandstone 91+ m
PRE-CAMBRIAN(?)		Van Horn Sandstone 0-215 m			
PRECAMBRIAN		Hazel Formation 1,525? m Allamoore Formation 760? m Carrizo Mountain Group 5,800 m	Carrizo Mountain Group 730+ m		



EXPLANATION

QTb — QUATERNARY AND UPPER TERTIARY BASIN FILL

Ku — LOWER CRETACEOUS SEDIMENTARY ROCKS--Massive limestone and sandstone

Pu — PERMIAN SEDIMENTARY ROCKS--Massive limestone and sandstone

p€ ha / c — PRECAMBRIAN METAMORPHIC AND GRANITIC ROCKS--p€ha, Hazel and Allamore Formations; p€c, Corrizo Mountain Group

——?—— CONTACT--Queried where doubtful

FAULT--Arrows show direction of movement

------ FORM LINE WITHIN GEOLOGICAL UNITS

FIGURE 2.—**Generalized geologic section from Rio Grande to Sierra Diablo showing Laramide folding and thrusting at Quitman Mountains and Devil Ridge and Precambrian thrusting at Sierra Diablo.**

Thick sequences of evaporite were deposited in the Permian basins. Exposures occur in the northernmost Trans-Pecos region in the Apache Mountains and are limited to gypsum deposited to the southwest of the Delaware basin. In addition, thick sequences of argillaceous rocks occur in the region. In the northern part of Brewster County in the vicinity of Marathon, outcrops of the Word Formation of Early Permian (Guadalupian) age occur. This formation, which is as thick as 460 m, consists mostly of siliceous shale and clay with thin units of fossiliferous limestone, sandstone, and conglomerate. The Word is overlain and underlain by Permian units consisting largely of limestone.

The allochthonous rocks of the Marathon region were interpreted by Thomson and McBride (1978) to belong to several geosynclinal facies, including: (1) Sandstone, conglomerate, shale, limestone, and chert of the Dagger Flat Sandstone, Marathon Limestone, Alsate Shale, Fort Peña Formation, Woods Hollow Shale, and Maravillas Chert (table 1) representing part of the platform and transition facies; (2) the Caballos Novaculite representing a leptogeosynclinal or starved-basin facies; (3) sandstone, shale, and limestone of the Tesnus Formation, Dimple Limestone, and Haymond Formation, which are relatively deep water flysch deposits; and (4) bioclastic limestone, shale, sandstone, and conglomerate of the Gaptank Formation, which are shallower water, molasse-facies rocks. Terrigenous detritus in the Marathon region came dominantly from the southeast or east, and marine, carbonate detritus came from the northwest (McBride, 1978).

MESOZOIC ROCKS

The Bissett Conglomerate is the only rock in the Trans-Pecos region that may possibly be of Triassic age (King, 1937). The conglomerate, which crops out in the western Glass Mountains, consists of rounded dolomite fragments in a calcareous matrix and is as thick as 225 m.

The Chihuahua trough, a deep sedimentary basin was formed in the Jurassic along the southwestern edge of the Trans-Pecos region (Muehlberger, 1980). Other than

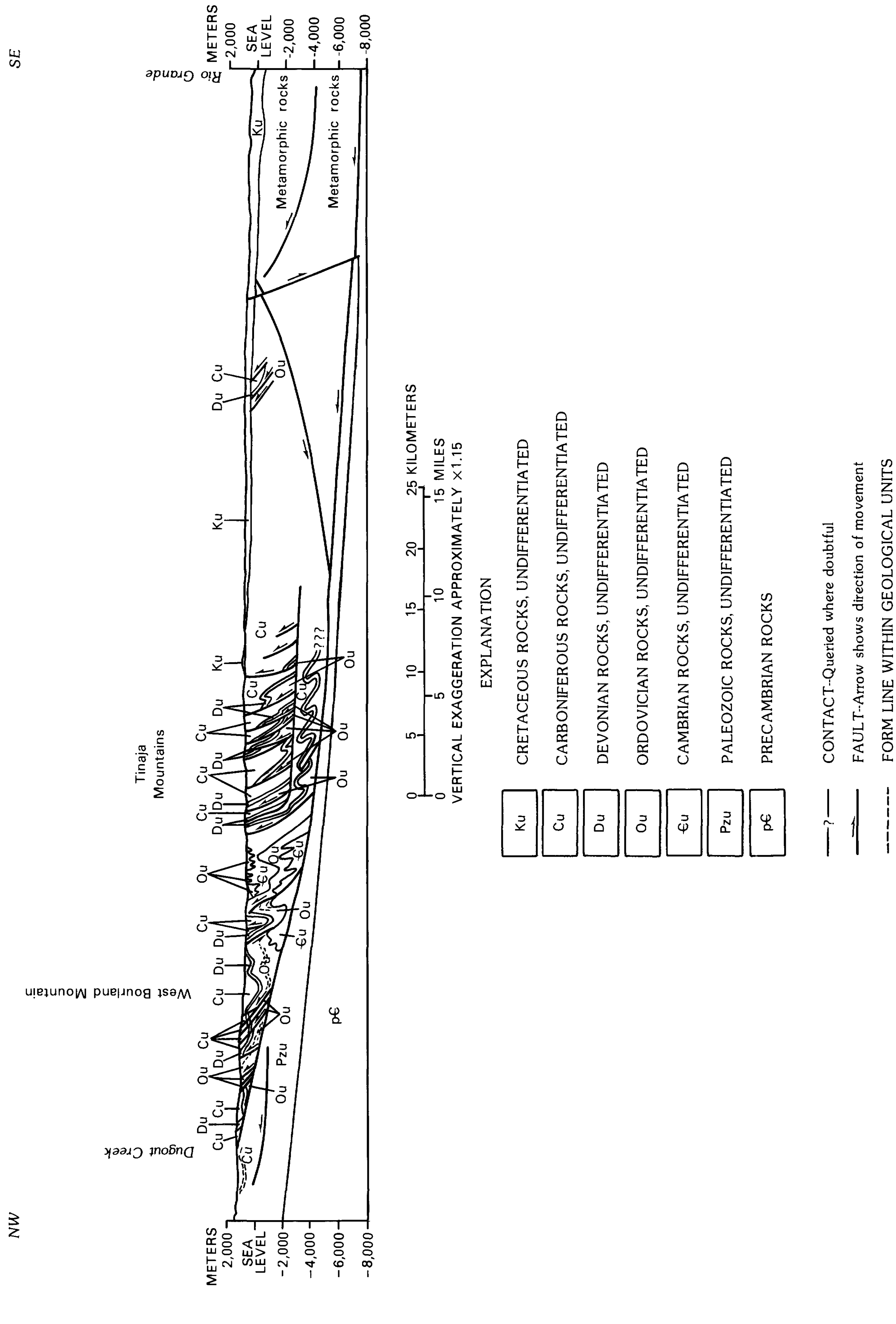


FIGURE 3.—Generalized geologic section of Marathon region showing deformation associated with Ouachita-Marathon orogeny. Modified from W.R. Muehlberger (University of Texas, Austin, Texas, written commun., 1983).

a reentrant extending into the Big Bend area from the south, the Diablo platform occupied the rest of Trans-Pecos region. The geometry of the basin and platform controlled subsequent Mesozoic sedimentation. In Mexico, as much as 2,300 m of salt and gypsum have been penetrated by wells in the Chihuahua trough, and in Texas, Upper Jurassic evaporites have been penetrated in wells along the margins of the trough. These evaporites formed decollement zones for Laramide thrusting. The closest outcrops of Jurassic rocks are in the Malone Mountains about 75 km to the northwest of the Trans-Pecos region (Albritton and Smith, 1965).

Cretaceous rocks are widespread in the Trans-Pecos region and thicken greatly from the Diablo platform to the basin. Lower Cretaceous rocks thicken from 300 to 600 m on the platform to as much as 3,500 m in the southern Quitman Mountains (Jones and Reaser, 1970) along the Rio Grande west of the study area. Figure 2 illustrates the southwestward thickening of the Cretaceous rocks and shows the structures produced by Laramide deformation. A similar depositional thickening occurs in the Chinati Mountains area; the Cretaceous section in Texas is 805 m thick (Amsbury, 1958). Twenty-five kilometers to the southwest, in the Chihuahua trough, the equivalent section is 3,800 m thick (Gries and Haenggi, 1971). The names and correlation of the major Upper Jurassic and Cretaceous formations are shown in table 2.

Lower Cretaceous rocks in the northern Trans-Pecos region consist of sandstone and thin-bedded to massive limestone with marl and shale interbeds and shale (Scott and Kidson, 1977). The rocks record repeated transgressive and regressive deposition along the margin of the Chihuahua trough. The base of the section rises onto the Diablo platform. Typically, the Yucca Formation and parts of the Bluff Mesa Limestone (Bluff Limestone of some authors as shown on table 2), Yearwood Formation (Twiss, 1959) (not in table 2 but equivalent to Bluff Mesa in age), and Benevides Formation, and the Cox and Eagle Mountains Sandstones are sandstone or conglomerate (table 2). Limestones include parts of the Bluff Mesa Limestone and the Yearwood and Benevides Formations, and the Finlay, Loma Plata, and Buda Limestones (table 2). However, lateral variations occur, especially towards the deeper basin. For example, the Cox Sandstone includes thick-bedded limestone in the southern Quitman Mountains (Jones and Reaser, 1970). In addition, the Yucca Formation, the basal formation near the Chihuahua trough, thins and pinches out eastward from more than 1,500 m in the southern Quitman Mountains to 600 m in the Eagle Mountains to 80 m or less in the Van Horn Mountains. The Cox Sandstone is the basal Cretaceous unit in the Wylie Mountains, and the Campagrande Formation is the basal unit throughout most of the Diablo Plateau.

The Lower Cretaceous section in the Big Bend area is predominately limestone which commonly is marly with shale interbeds. The section includes thick shale and sandstone units. The rocks record the transgression of the Cretaceous sea northward onto the platform. The total thickness of Lower Cretaceous rocks increases toward the south and west from about 300 m in the Alpine area to more than 1,200 m in the Solitario uplift west of the Big Bend area to more than 1,850 m in adjacent Chihuahua, Mexico. The basal unit in the Big Bend area, the Glen Rose Formation, has a lower sandstone and conglomerate deposited in a nearshore environment (Maxwell and others, 1967) overlain by massive limestone deposited on a carbonate shelf (Scott and Kidson, 1977). The Glen Rose pinches out around the Marathon basin where it is dominantly clastic. The Maxon Sandstone is a similar nearshore clastic unit; the Del Carmen and Santa Elena Limestones (Maxwell and others, 1967) are massive, fine- to medium-crystalline, cherty limestone deposited on a platform/shelf margin (Scott and Kidson, 1977); the Telephone Canyon and Sue Peaks Formations (Maxwell and others, 1967) and Del Rio Clay are mainly shale and thin limestone deposited in a shelf basin. The Cretaceous section exposed at Santa Elena Canyon is shown in figure 4. It consists of, from bottom to top, the Del Carmen Limestone, Sue Peaks Formation, and Santa Elena Limestone (Maxwell and others, 1967).

Between the Lower and Upper Cretaceous, there is a major change in rock type, which McFarlan (1977) attributes to a worldwide decline in sea level. Upper Cretaceous rocks have similar lithology and thickness in both the northern and the southern areas (table 2); these rocks are thick shale and thin-bedded, marly limestone. Upper Cretaceous rocks are abundant in and west of the Big Bend area and in the Sierra Vieja. Total preserved thickness is about 1,100 m in the Big Bend area and 950 m in the Sierra Vieja. Elsewhere, they are thin or absent due to erosion.

The uppermost unit of Cretaceous age is the nonmarine Javelina Formation (Maxwell and others, 1967), composed largely of bentonitic clay with some lenticular masses of crossbedded channel sandstone, both deposited in nearshore swamps (fig. 5). The Javelina generally ranges in thickness from 75 to 285 m but locally may be as thin as 15 m.

Underlying the Javelina are the continental and marine beds of the Aguja Formation that Wilson (1971) ascribes to a change in environment from rivers and estuaries to tidal flats, lagoons, and beaches. The upper 270 m of the Aguja is an irregular alternation of nonmarine sandstone and clay and some limestone and thin lignitic seams, that is gradational upward into the

TABLE 2.—*Correlation of exposed Upper Jurassic and Cretaceous formations, Trans-Pecos region and vicinity*
[General location of stratigraphic columns shown on figure 1. Thickness in meters (m). Shaded areas, strata absent]

System	Series	Diablo Plateau (Barnes, 1983)	Malone Mountains, Sierra Blanca, and Quitman Mountains (Albritton and Smith, 1965; Jones and Reaser, 1970)	Eagle Mountains (Underwood, 1963)	Van Horn Mountains (Twiss, 1959)	Wylie Mountains (Hay-Roe, 1957)	Sierra Vieja (Barnes, 1979b)	Chinati Mountains (Amsbury, 1958)	Big Bend National Park and Bofecillos Mountains (Maxwell and others, 1967; McKnight, 1970)	Alpine area (Barnes, 1982)
CRETACEOUS	Upper Cretaceous						El Picacho Formation 250 m		Javelina Formation 150-260 m	
							San Carlos Sandstone 425 m		Aguja Formation 0-400 m	
							Ojinaga Formation 255 m		Pen Formation 67-215 m	
									Boquillas Formation 245-305 m	
			Ojinaga Formation 0-610 m	Chispa Summit Formation 490-610 m	Chispa Summit Formation 260 m					Boquillas Formation 0-30 m
			Buda Limestone 0-60 m	Buda Limestone 65-76 m	Buda Limestone 70 m	Buda Limestone 10-45 m		Buda Limestone 2 m	Buda Limestone 20-30 m	Buda Limestone 30-45 m
	?		Eagle Mountains Sandstone 0-60 m	Eagle Mountains Sandstone 25-40 m	Eagle Mountains Sandstone 10 m	Boracho Limestone 55-70 m		Grayson Shale 25 m	Del Rio Clay 1-40 m	Del Rio Clay 3-10 m
	Lower Cretaceous		Espy Limestone 320 m	Espy Limestone 670 m	Loma Plata Limestone 210 m			Loma Plata Limestone 220 m	Santa Elena Limestone 225-260 m	"Washita" rocks 65-80 m
			Benevides Formation 165-240 m	Benevides Formation 20-40 m	Benevides Formation 50 m			Benevides Formation 40-45 m	Sue Peaks Formation 23 m	"Fredericksburg" rocks 40-60
		Finlay Limestone 18-110 m	Finlay Limestone 50-150 m	Finlay Limestone 120-245 m	Finlay Limestone 55 m	Finlay Limestone 35-50 m		Finlay Limestone 90 m	Del Carmen Limestone 105-140 m	
									Telephone Canyon Formation 10-40 m	
		Cox Sandstone 150 m	Cox Sandstone 135-520 m	Cox Sandstone 300-530 m	Cox Sandstone 270-370 m	Cox Sandstone 60-160 m		Cox Sandstone 135 m	Maxon Sandstone 0-3 m	Maxon Sandstone 0-15 m
		Campagrande Formation 8-60 m	Bluff Mesa Limestone[1] 100-600 m	Bluff Mesa Limestone[1] 130-460 m	Bluff Mesa Limestone[1] 0-180 m			Bluff Mesa Limestone[1] 200 m	Glen Rose Formation 185 m	Glen Rose Formation 185 m
			Yucca Formation 1400-1650 m	Yucca Formation 180-615 m	Yucca Formation 0-80 m			Yucca Formation 150-200 m		
			Torcer Formation 120 m							
JURASSIC	Upper Jurassic		Malone Formation 120-300 m							

[1]Designated Bluff Limestone by some authors.

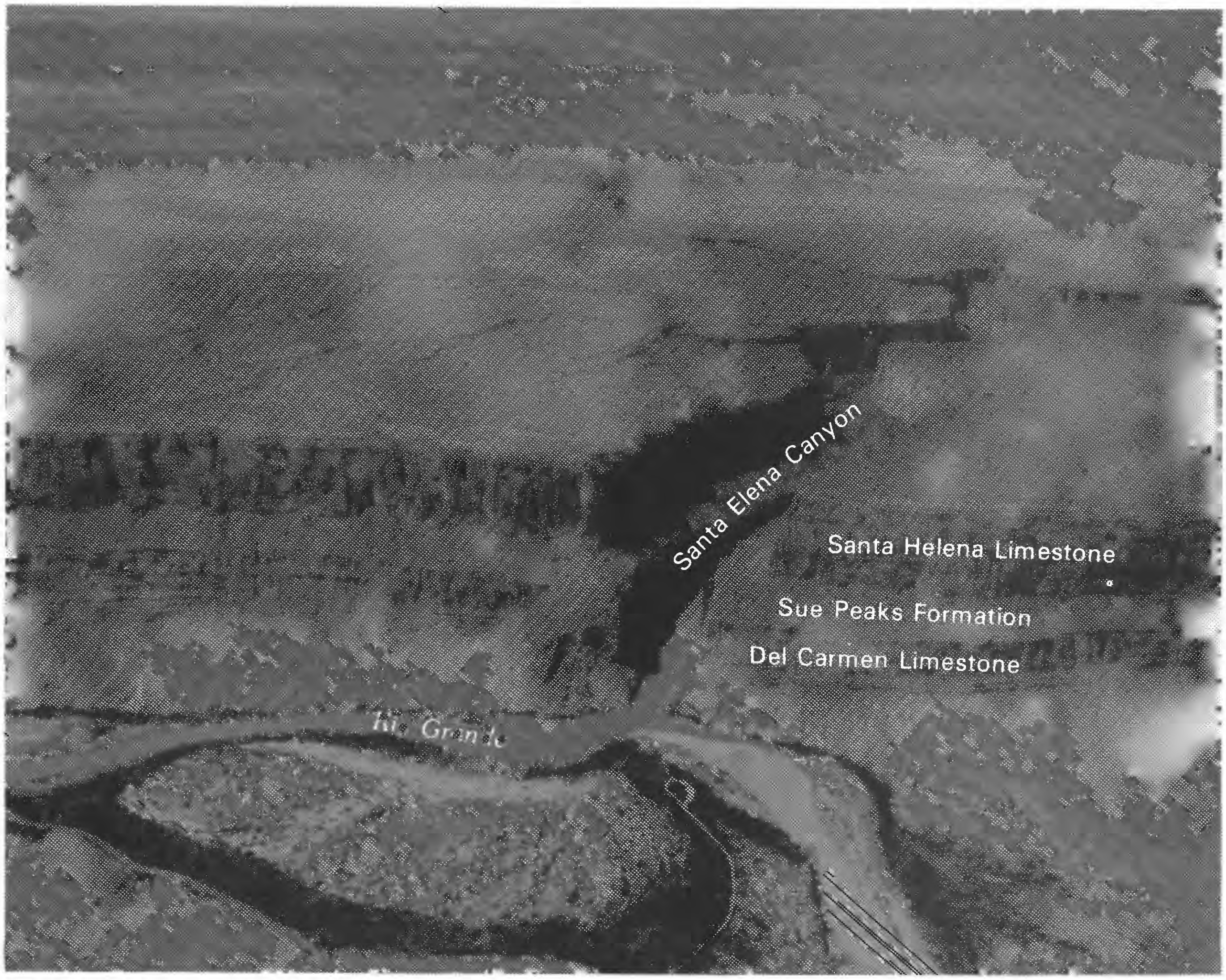


FIGURE 4.—View from Texas into Mexico showing the Cretaceous formations exposed where the Rio Grande emerges from Santa Elena Canyon. Photograph by M.S. Bedinger, 1984.

Javelina Formation. The middle part (55 m to more than 150 m thick) of the Aguja is marine silty to sandy clay containing generally thin sandstone lenses, although locally the basal 60 m of the middle unit is mostly sandstone. The basal unit of the Aguja Formation, which is 2–11 m thick, is thin-bedded sandstone (Maxwell and others, 1967).

Beneath the Aguja Formation is the marine clay of the Pen Formation (Maxwell and others, 1967). The basal part contains very thin chalk beds, and beds of sandstone as thick as 2 m occur locally. The Pen is about 70–210 m thick within the Big Bend area and as much as 300 m thick in the southwestern corner of Brewster County. An outcrop of the Pen Formation in the Study Butte area is shown in figure 6.

The Ojinaga Formation (Barnes, 1979a) or the equivalent Chispa Summit Formation (Twiss, 1959) of Late Cretaceous age crops out in southern Hudspeth County on the eastern flank of the Eagle Mountains and at the southern end of the Quitman Mountains, in westernmost Jeff Davis County on the eastern flank of the Van Horn Mountains, and to the south in Presidio County along the Sierra Vieja. The formation is primarily black to brown fissile calcareous shale with a few beds of

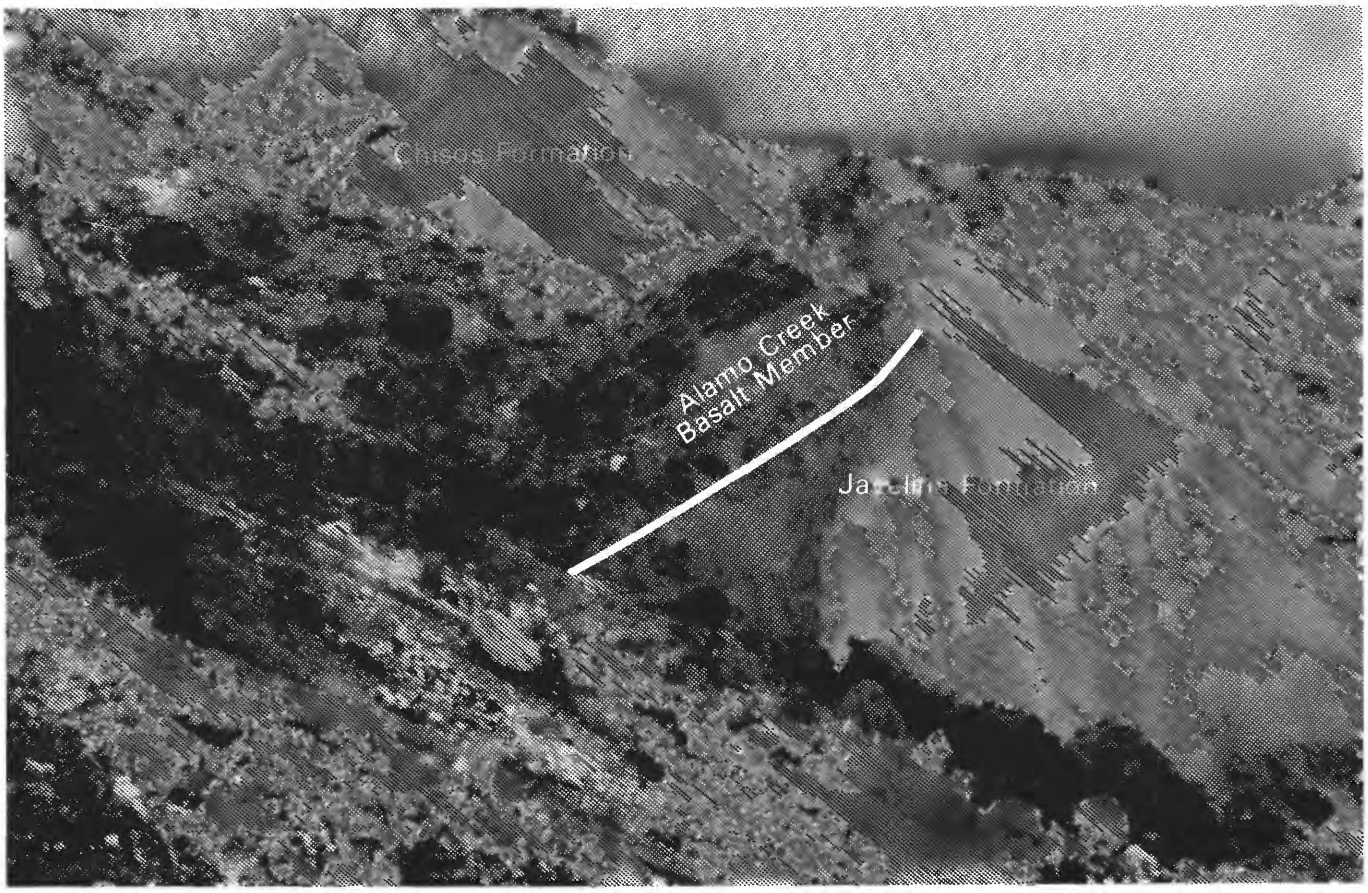


FIGURE 5.—Montmorillonitic and bentonitic tuffs of the Javelina Formation (Upper Cretaceous) overlain by montmorillonitic and zeolitic tuffaceous sediments of the Chisos Formation (Eocene) at Dogie Mountain. Alamo Creek Basalt Member (Eocene) occurs at base of Chisos Formation. Units from Maxwell and others (1967).

sandstone. In the Van Horn Mountains a 45-m-thick limestone unit occurs near the base of the formation. The Ojinaga ranges from 260 m to more than 600 m in thickness; it was deposited in a shallow marine environment. The overlying San Carlos Sandstone and El Picacho Formation (Barnes, 1979a) are continental. The San Carlos is dominantly sandstone with claystone, and the El Picacho is dominantly claystone with sandstone; both contain coal or lignite.

Volcanic material, such as bentonite or andesitic rock fragments, first appears in the San Carlos Sandstone and Aguja Formation and increases in volume in Cenozoic rocks. Volcanoes to the west in Mexico were the probable source.

CENOZOIC ROCKS

The oldest Cenozoic rocks of the Trans-Pecos region, of Paleocene to middle Eocene age, are preserved only in the Big Bend area. They are similar to the underlying Cretaceous rocks, even though a considerable hiatus exists between the highest Cretaceous and lowest Paleocene beds (Wilson, 1971). For example, the Black Peaks Formation (Maxwell and others, 1967), consisting of 75 m to more than 260 m of interbedded clay, siltstone, and sandstone, is similar to the nonmarine part of the Aguja Formation. The lower Eocene Hannold Hill Formation (Maxwell and others, 1967) is nonvolcanic, nonmarine, with thin layers of channel clay sandstone and conglomerate. The Hannold Hill is as much as 260 m thick, and is confined to a small area on the northern flank of the Chisos Mountains.

The late Eocene and Oligocene was a time of major volcanism in the Trans-Pecos. Numerous calderas (pl. 2) mark the areas of thick ash-flow and bedded tuffs, lava flows, and intrusions. Numerous lava flows and small intrusions, unrelated to calderas, both preceded and followed the caldera-related volcanism. A change from compression to extension occurred about 30 m.y. (Price and Henry, 1984); minor late Oligocene to Miocene volcanism occurred during Basin and Range extension.

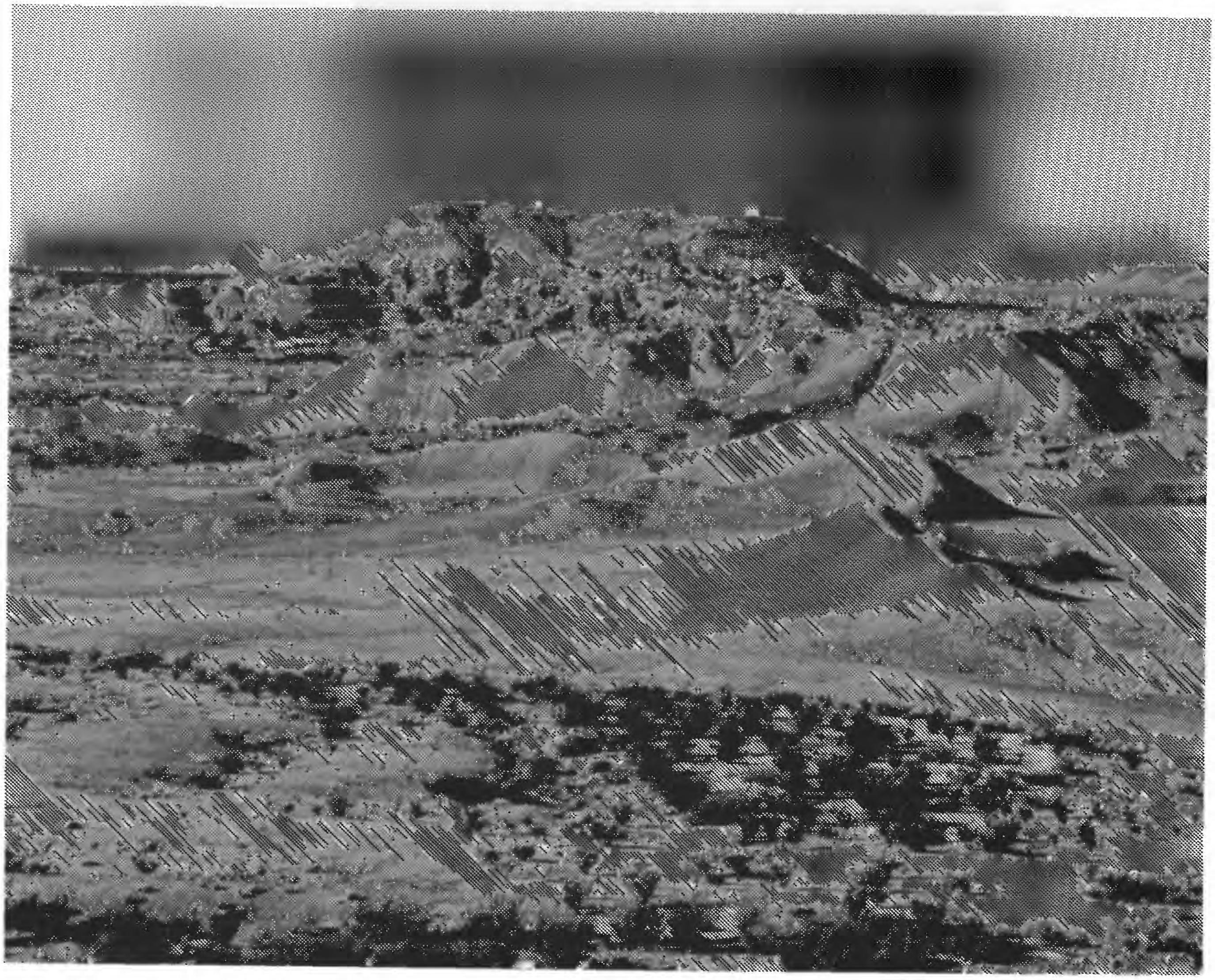
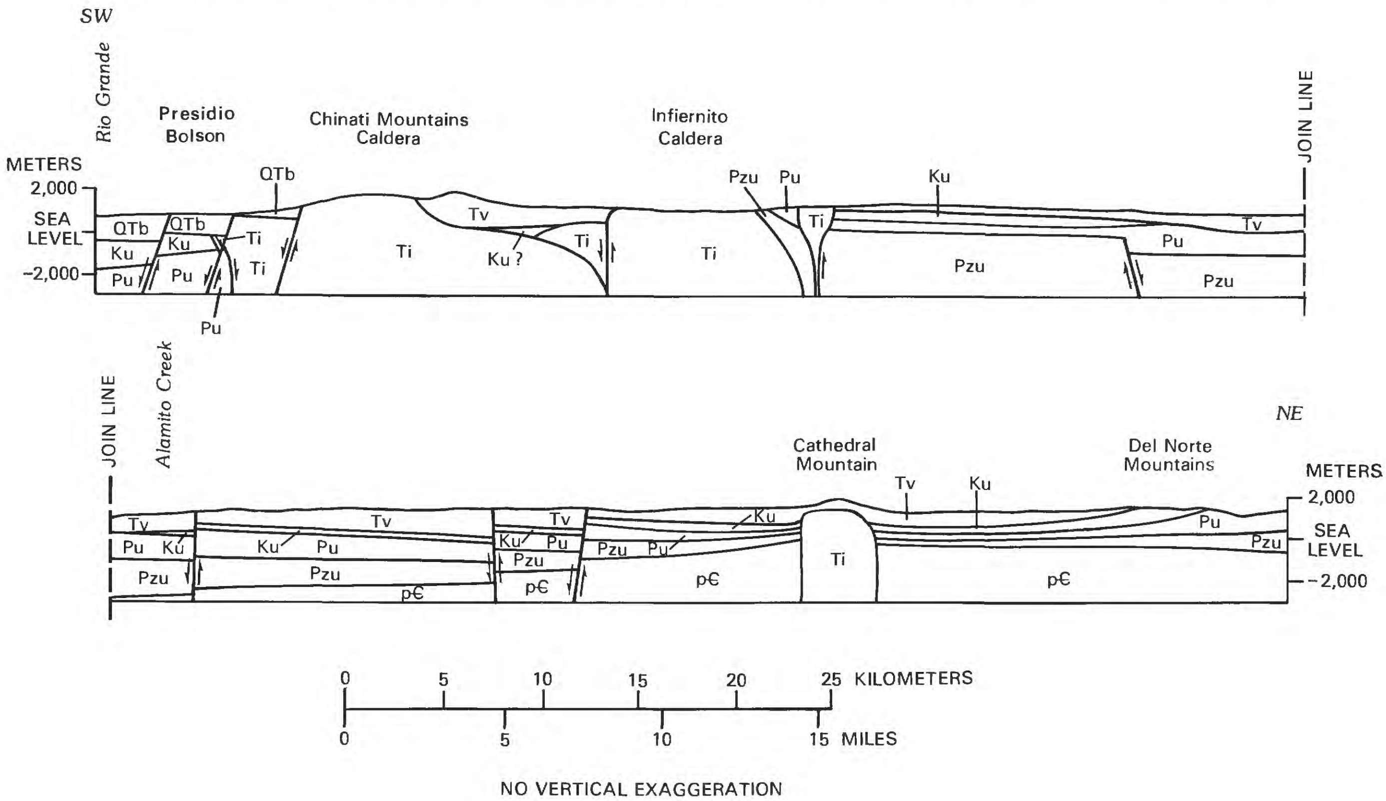


FIGURE 6.—Upper Cretaceous Pen Formation of Maxwell and others (1967) in the Study Butte area.

The oldest igneous rocks other than those of Precambrian age in the Trans-Pecos region are in the Big Bend area and in adjacent areas to the north. In the Tornillo Flat area of Big Bend, the middle Eocene Canoe Formation (Maxwell and others, 1967), composed of sandstone, conglomerate, clay, tuff, and basalt, contains the oldest basalt and the oldest tuff in the Trans-Pecos region (Wilson, 1980). Isotopic ages of tuffaceous sediment in the Middle Tertiary Devils Graveyard Formation (Stevens and others, 1984) in Green Valley, tuffaceous sediments and basalts in the Chisos Formation (which overlies the Canoe Formation) in the Big Bend area, and gabbroic intrusions in the Christmas Mountains range in age from 40–50 m.y. However, only the mafic intrusions and flows were locally derived. The tuffaceous rocks were derived from volcanoes to the west in Mexico; no sources of tuff were active in Texas at that time. Elsewhere in the Trans-Pecos region, the Tertiary Jeff Conglomerate (McKnight, 1970) is the basal Tertiary deposit. It preceded most volcanism and is of irregular thickness, filling valleys and veneering the surface produced by erosion after Laramide deformation.

Beginning 38 m.y., the first of the 12 calderas in and near the Trans-Pecos region became active (fig. 7, table 3). These calderas dominated volcanism until about 30 m.y. ago. The volcanic rocks can be divided into two northwest-trending belts based on the composition of produced rocks: a western alkali-calcic or metaluminous belt and an eastern alkalic belt (Barker, 1977; Henry and Price, 1984). Both belts became active at about the same time with the initiation of volcanism at the



EXPLANATION

QTb	QUATERNARY AND UPPER TERTIARY BASIN FILL
Tv	OLIGOCENE AND EOCENE VOLCANIC AND VOLCANICLASTIC ROCKS--Ash-flow tuff, lava flows, and tuffaceous sediments
Ti	OLIGOCENE AND EOCENE INTRUSIVE ROCKS--Generally silicic
Ku	LOWER CRETACEOUS SEDIMENTARY ROCKS--Massive limestone and sandstone
Pu	PERMIAN SEDIMENTARY ROCKS--Massive limestone and sandstone
Pzu	PALEOZOIC (OLDER) SEDIMENTARY ROCKS
pЄ	PRECAMBRIAN METAMORPHIC AND GRANITIC ROCKS
	CONTACT
	FAULT--Arrows show direction of movement

FIGURE 7.—Generalized geologic section from Rio Grande to Del Norte Mountains. Section shows Chinati Mountains and Infiernito calderas and Basin and Range structure of Presidio Bolson. Faults in the area surrounding Alamito Creek were active when upper Paleozoic and Permian rocks were being deposited, thereby accounting for the differences in thickness.

Infiernito caldera in the west and the Buckhorn caldera in the Davis Mountains in the east. The northern parts of both belts were active until about 35 m.y. ago. Subsequent caldera formation occurred in the Big Bend area between 34 and 32 m.y. ago and in the Chinati Mountains (fig. 8) (the largest caldera in the Trans-Pecos

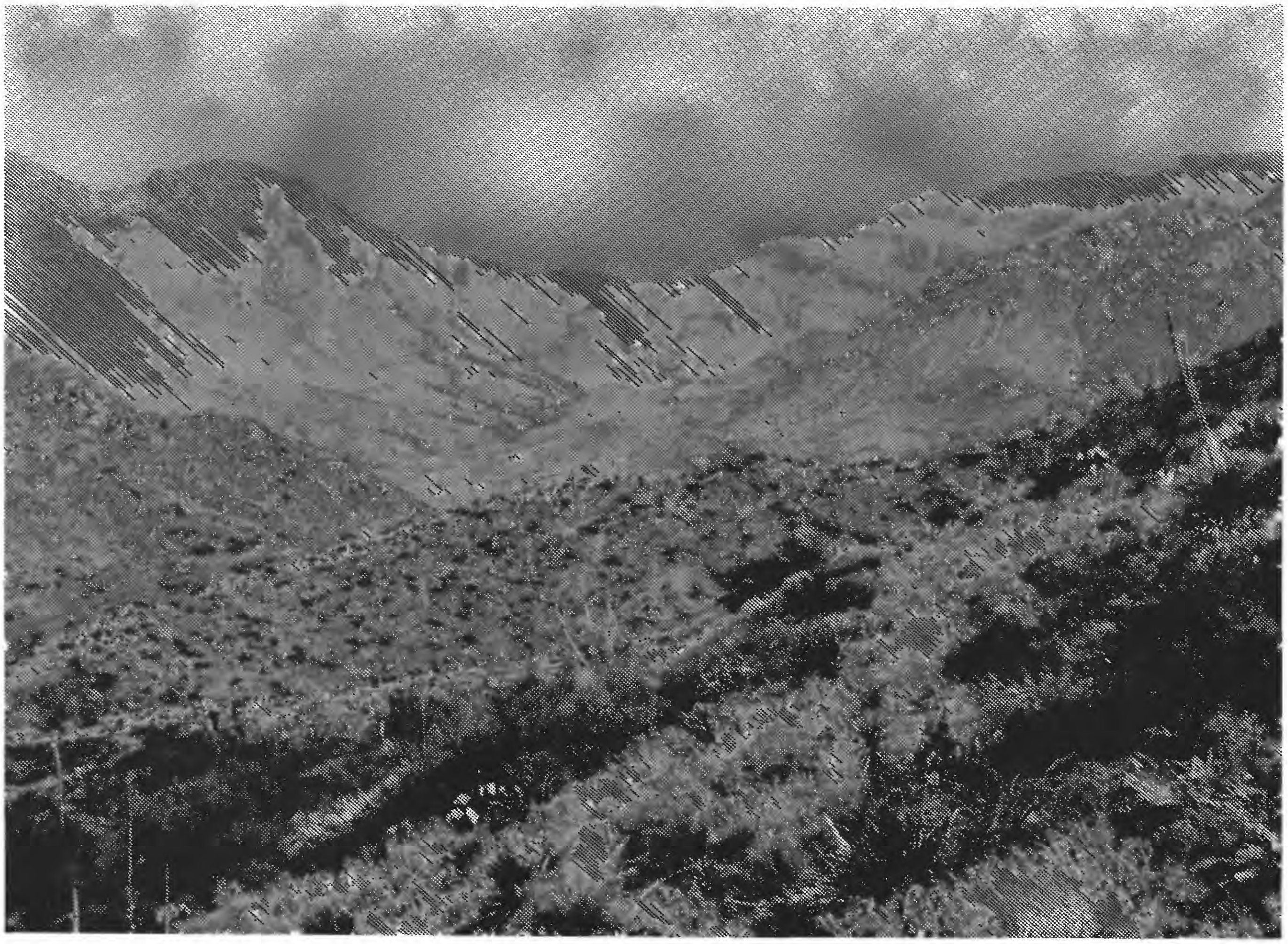


FIGURE 8.—View within Chinati Mountains caldera looking northeast from San Antonio Canyon. West Chinati stock, in left background and right middle ground, intrudes lava flows of the Chinati Mountain Group of Amsbury (1958) seen in right background.

region) about 32 m.y. ago. The last caldera-forming eruptions were in adjacent Chihuahua, Mexico, 30 and 28 m.y. ago; ash-flow tuff from these calderas spread into the southern part of Trans-Pecos region. Tilted fault blocks of zeolitic tuffaceous sediments and resistant lava flows and ash-flow tuff of the Sierra Vieja are shown in figure 9.

Each of the calderas produced at least one major ash-flow tuff; the extent and volume of these tuffs varied considerably (table 3). Intracaldera tuffs are as thick as 800 m, but outside the calderas the tuffs are much thinner, commonly less than 100 m thick. Following ash-flow eruption, calderas were filled with sequences as thick as 1 km of rhyolitic to basaltic lava flows, volcaniclastic sediments, and tuff. Major intrusions in the form of resurgent domes and ring-fracture stocks are associated with the calderas. Thick sequences of zeolitic, tuffaceous sediments accumulated as alluvial fans in sedimentary aprons between calderas. Only a few, relatively thin, ash-flow tuffs and lava flows are interbedded with the sediments. Tuffaceous sediment sequences include the Hogeye Tuff, Vieja Group, Tascotal Formation, and Fresno Formation in the western belt and the Huelster Tuff, Pruett Formation, Duff Tuff, and Chisos Formation in the eastern belt, all of Tertiary age (Barnes, 1979a,b). These sediment sequences are as thick as 1,000 m.

Volcanism and intrusion unrelated to calderas continued during caldera formation. Extensive rhyolitic, trachytic, and basaltic lava flows occur in both belts. Numerous, but volumetrically minor, silicic to mafic intrusions occur throughout the Trans-Pecos region as stocks, laccoliths, and sills. Major areas include the Cienega Mountains in the western belt and the southern Davis Mountains, Christmas Mountains–Solitario area, and Big Bend area in the eastern belt. The Wax Factory

FIGURE 9.—View to the north showing tilted blocks of white zeolitic tuffaceous sediments of the Sierra Vieja and overlying, resistant lava flows and ash-flow tuffs.

laccolith (fig. 10) is one of many large intrusive bodies in the Terlingua area.

Basin and range extension began about 30 m.y. ago (Price and Henry, 1984), but basin formation did not occur until several million years later. Isotopic ages of basalts intruded into early basin fill and paleontologic ages of the fill show that basins were well developed by early Miocene time (Dasch and others, 1969; Stevens, 1969; McDowell, 1979). Igneous activity associated with Basin and Range development includes the late Oligocene and Miocene(?) Bofecillos volcano, which erupted alkalic basaltic rocks 28–26 m.y. ago (McDowell, 1979), before faulting had begun. Miocene alkali basalts are widespread but volumetrically minor in the Trans-Pecos region. They occur as flows, dikes, and sills at several locations immediately west and east of the Big Bend area and in the Sierra Vieja in the northwestern part of the region.

Sedimentation in the basins began in Miocene time and has probably continued uninterrupted to the present. Dates for geologic deposits in the basins include Miocene isotopic and paleontologic ages (Dasch and others, 1969; Stevens, 1969) and Pleistocene ages on fossils and ash beds in the upper parts of basin fill (Strain, 1980). Most sedimentation was in closed basins. Integration of the closed basins in the upper Rio Grande with the lower Rio Grande did not occur until Pleistocene time (Strain, 1971). Salt Basin and Lobo Valley are still closed basins.

Basin fill commonly grades from coarse gravel and sand near the margins to muds and evaporites in the central parts of the basins (Groat, 1972). Sources of the material are almost entirely the adjacent mountain ranges, but minor fluvial material in some basins may have been brought in by overflow from adjacent basins before the present state of integration and some material is windblown. Alluvial-fan and playa deposition are still occurring in the closed basins. Thickness of basin fill, known from a few wells and geophysical data, varies considerably within and between basins. Maximum thicknesses of basin fill in the Trans-Pecos region include: (1) Salt Basin, as much as 700 m; (2) Lobo Valley, a maximum of about 300 m; (3) Eagle Flat, about 600 m; (4) Red Light Draw, as much as 900 m; (5) Green

TABLE 3.—*Calderas in the Trans-Pecos region and vicinity*
[n.d., not determined; <, less than; ~, approximately]

Caldera	Diameter (kilometers)	Ash-flow tuff	Volume (cubic kilometers)	Age (m.y.)	Comments
Infiernito	12	Unnamed caldera fill.	40–69	n.d.	Oldest caldera of western belt.
		Buckshot Ignimbrite (Barnes, 1979a).	30–40	37–38	Buckshot Ignimbrite is equivalent outflow tuff.
Van Horn Mountains.	4	Lower marker horizon of Chambers Tuff (Barnes, 1979a).	<30	38	High Lonesome Tuff formerly known as Pantera Trachyte (Barnes, 1979a).
		High Lonesome Tuff (Henry and Price, 1985).	4–15	38	
Wylie Mountains.	6–8	n.d.	n.d.	38	Possible caldera.
Eagle Mountains.	9–11	Upper rhyolite (caldera fill).	10–30	36–37	Relative ages of Eagle and Quitman Mountains calderas unknown.
		Various unnamed tuffs outside caldera.	30–100	36–37	
Quitman Mountains.	6–7	Parts of Square Peak Volcanics (caldera fill).	<20	36	No equivalent outflow tuff known.
Chinati Mountains.	30–20	Mitchell Mesa Rhyolite (Goldich and Elms, 1949).	~1,000 (outside caldera) 100–400 (inside caldera)	32–33	Largest caldera and ash-flow tuff in Trans-Pecos region.
		Various local tuffs.	<100 total	32–34	
San Carlos	25–32	Tuff of San Carlos Formation.	50–150	30	Chihuahua, Mexico; entirely caldera fill.
Santana	25–32	Santana Tuff (Barnes, 1979b).	60–150	28	Chihuahua, Mexico.
Buckhorn	24–16	Gomez Tuff (Barnes, 1979)	220	37	Oldest known caldera of eastern belt.
		Barrel Springs Formation (Barnes, 1979a).	675	36	Barrel Springs and Wild Cherry are composite units; unidentified caldera source in Davis Mountains.
		Wild Cherry Formation (Barnes, 1979a).	n.d.	n.d.	
Paisano Pass.	5	Members of Decie Formation (Parker, 1983).	150 for total Decie Formation	36	Summit caldera of trachytic shield volcano.
Sierra Quemada.	6	Mule Ear Springs	10–30	[1,2]34	Association with Mule Ear Springs Tuff is speculative.
Pine Canyon.	6–7	South Rim Formation.	10–20	[1]33	South Rim Formation includes several ash-flow tuffs and lava flows.

[1]McDowell (1979 and unpublished data).
[2]Gregory (1982).

River valley, about 700 m; and (6) Presidio Bolson, about 1,500 m (Gates and others, 178). Figure 7 illustrates basin and range structure and the thickness of basin fill in Presidio Bolson.

STRUCTURE

Structures of basin and range extension, and to a lesser extent Laramide structures, dominate the

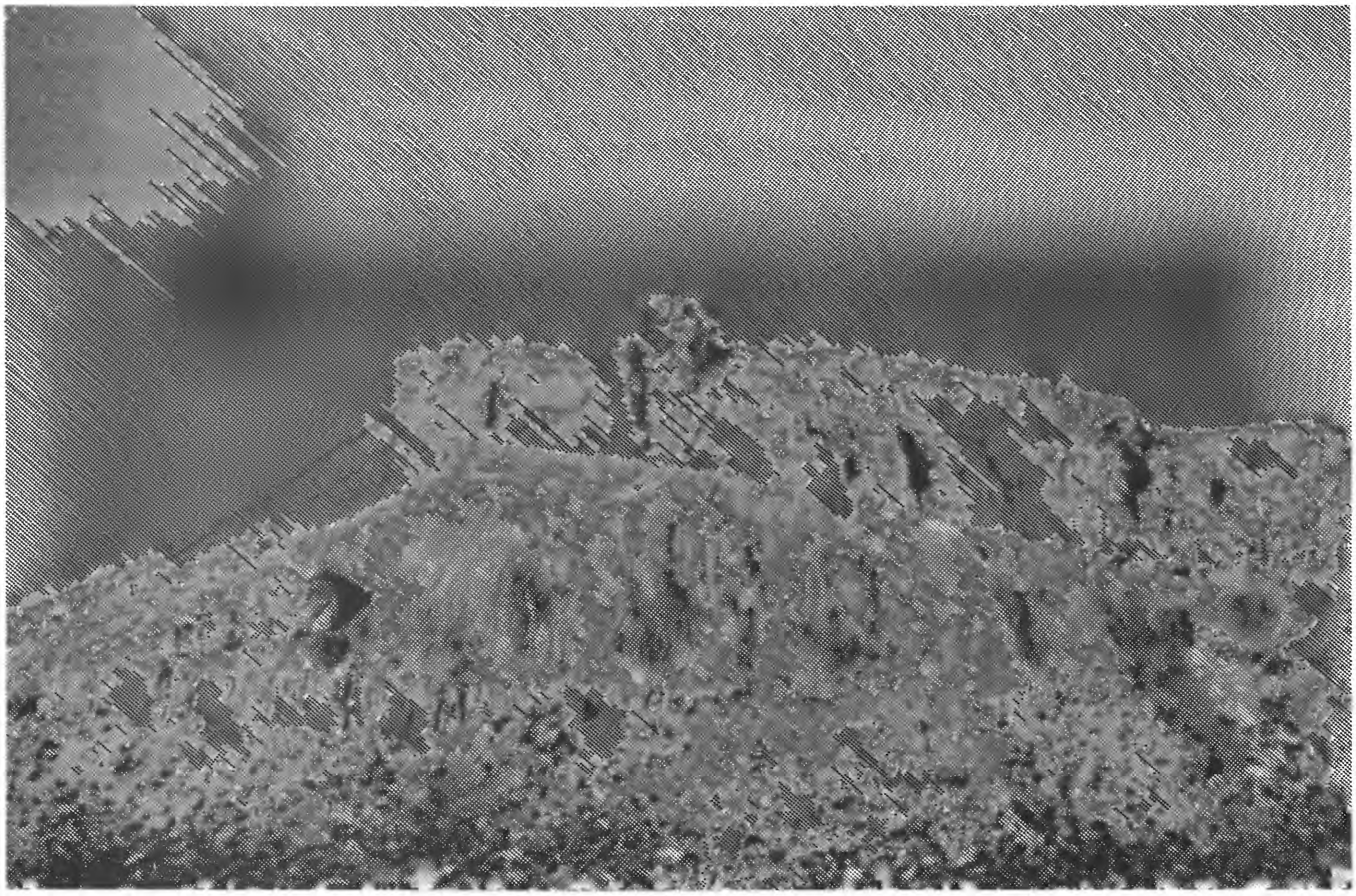


FIGURE 10.—The dissected Tertiary Wax Factory laccolith intruded into the Upper Cretaceous Boquillas Formation in the Terlingua area. Photograph by R.G. Yates, circa 1959.

topography of the Trans-Pecos region. However, the area has experienced repeated deformation since the Precambrian. Major tectonic events occurred in the Precambrian, late Paleozoic, early to middle Mesozoic, late Mesozoic to early Cenozoic, and late Cenozoic. Structures and trends established during earlier events repeatedly affected later events, thus the structure of the Trans-Pecos region is complex and subsurface structural relationships are poorly known.

PRECAMBRIAN

Several episodes of Precambrian deformation affected the Trans-Pecos region. Two or more periods of structural activity produced northeast-trending folds and south-southeast- and southeast-dipping foliation in the 1,200–1,300-m.y.-old Carrizo Mountain Group. The following major tectonic events may have been more or less coincident at about 1,000 m.y. before present: (1) Metamorphism of the Carrizo Mountain Group, (2) northward thrusting of the Carrizo Mountain Group over the Allamoore Formation (fig. 3) and locally of the Allamoore Formation over the Hazel Formation, (3) folding and low-grade metamorphism of the Allamoore and Hazel Formations, and (4) eruption of rhyolite ash-flow tuffs and intrusion of granites to the northwest of the Van Horn area (Thomann, 1981; Denison, 1980).

The intensity of regional metamorphism in the Carrizo Mountain Group increases from greenschist facies in the north to amphibolite facies in the south. Using K/Ar dates from metamorphic minerals, Denison (180) estimated the time of metamorphism to be 1,000 ± 25 m.y. ago. Folding and thrusting of the Allamoore and Hazel Formations into dominantly east-trending folds probably accompanied northward thrusting of the Carrizo Mountain Group along the Streeruwitz fault (King and Flawn, 153). Deformation and metamorphism of the Allamoore and Hazel Formations are most intense near the Streeruwitz fault.

Relatively minor tectonic events occurred near the close of the Precambrian. King and Flawn (1953) and King (1965) demonstrated that left-lateral, strike-slip displacement of the folded Hazel Formation occurred along a west-northwest-striking fault.

PALEOZOIC

Several unconformities with little or no angular discordance attest to mild deformation episodes during early Paleozoic time. Muehlberger (1980) suggested that these deformations may have been epeirogenic in nature. Variations in thicknesses of the Cambrian through Devonian rocks (Galley, 1958; LeMone and others, 1983) indicate that certain structural elements that became prominent features during late Paleozoic time had precursors during early Paleozoic time. Examples include the Tobosa basin (Galley, 1958); the forerunner of the Delaware basin, the center of which lies east of the Basin and Range province; and the Diablo platform which forms the southwestern margin of the Tobosa and Delaware basins.

Major Paleozoic deformation is associated with the Ouachita-Marathon fold and thrust belt, which is exposed in the Marathon and Solitario areas. Deformation probably began with uplift in Mississippian time (King, 1937; Galley, 1958) and culminated with thrusting, folding, and uplift in Late Pennsylvanian and Early Permian time. Folds in the Marathon area trend dominantly east-northeast to northeast, and the direction of thrusting was from the southeast to the northwest (fig. 3) (King, 1937). Ouachita rocks are allochthonous, and the total distance of tectonic transport is unknown (Muehlberger, 1980). The youngest rocks involved in thrusting are Early Permian (early Wolfcampian) in age (King, 1980).

Uplift and erosion accompanied the Ouachita-Marathon deformation. Early Permian (Wolfcampian) rocks, commonly conglomeratic at the base, rest in angular unconformity on rocks ranging in age from Pennsylvanian to Precambrian in the Sierra Diablo area, on the oldest Precambrian rocks of the region in the Van Horn and Wylie Mountains, and on Pennsylvanian rocks in the Marathon region (table 1). In the Chinati Mountains area, no angular unconformity is recognized between Pennsylvanian and Permian rocks or between Permian and Cretaceous rocks (Rix, 1953).

Evidence for post-Wolfcampian deformation of probable Permian age was presented by King (1965) in the Sierra Diablo area. North-northwest-trending flexures and faults with down-to-the-north displacements of as much as 518 m probably controlled the location of limestone reefs in this area during Leonardian time (King, 1965). Northward tilting of Permian rocks in the Glass Mountains occurred before deposition of the more flat lying Lower Cretaceous sedimentary rocks (King, 1980). Subsidence in the Delaware basin to the northeast of the Diablo platform and in the Marfa basin to the southwest (King, 1965) resulted in thick accumulations of Permian sediments. Development of these and other Permian basins and intervening uplifts or platforms is an integral but poorly understood part of the plate collision that produced the Ouachita-Marathon fold and thrust belt.

MESOZOIC

Development of the Chihuahua trough (pl. 2) began in Jurassic time. The margin of the trough probably consists of a series of large-displacement, down-to-the-west normal faults (Muehlberger, 1980). These faults approximately parallel the Rio Grande from El Paso to the southwestern edge of the Big Bend area in a zone extending from near the Texas-Mexico boundary to about 25 km onto the Texas side. Muehlberger postulates a reentrant into the Big Bend area because Laramide structures there are similar to those along the margin of the Chihuahua trough. Several west-northwest-trending monoclines in the Diablo plateau were active at the same time and probably are related to the formation of the trough. The structures along the margin of the trough were subsequently buried by the thick Cretaceous sequence, but they are important in determining the geometry of the sedimentary basin and the location of Laramide deformation.

CENOZOIC

Laramide Deformation

Laramide deformation produced north- and northwest-trending thrust faults, folds, and monoclines along the eastern margin of the Chihuahua trough (fig. 2) and in the reentrant into the Big Bend area. In addition, high-angle reverse faults, some strike-slip faults, and monoclines extend out into more cratonic parts of the Trans-Pecos region. Otherwise the Diablo platform was undisturbed. Laramide deformation in this area may in part be related to uplift of the Chihuahua trough and sliding of the Cretaceous sandstones and limestones over the underlying evaporites. The sedimentary rocks piled up against the stable Diablo platform so that the most intense deformation, which resulted in low-angle thrusts and overturned folds, is along the boundary between the platform and the trough. Where exposed, the Laramide stuctures generally are well mapped. However, they are buried in many places beneath Tertiary volcanic rocks and basin fill. Our knowledge of these buried areas comes from extrapolation from adjacent exposed areas and from sparse well and seismic data. Figure 2 shows one of the better studied areas, but even there, buried structures, especially folds, are only partly known.

The major episode of Laramide folding must have occurred in the late Paleocene in the Big Bend area (Wilson, 1971) and probably at that time throughout the Trans-Pecos region. Maxwell and others (1967) postulated several episodes of deformation with the primary one between Late Cretaceous and Tertiary time, that is, between deposition of their Javelina Formation and deposition of their Black Peaks Formation. However, Wilson (1971) showed that, because the Black Peaks Formation was lithologically similar to Cretaceous formations, significant deformation could not have occurred before or during its deposition. Coarse pebbles of Lower Cretaceous limestone in rocks of early Eocene age are the first evidence of major folding and erosion. Regional uplift without significant folding probably occurred at the end of the Early Cretaceous and several times in the Late Cretaceous so that erosional surfaces developed on the older rocks (Maxwell and others, 1967).

Geologic mapping in the Malone Mountains (Berge, 1981) and in the Indio Mountains (Price and others, 1985) has established two separate episodes of Laramide compression. The first compression was oriented northeast and produced northwest-trending folds, thrusts, and related fractures. A later compression was oriented east-northeast and produced north-northwest-trending folds that refolded earlier thrusts. The absolute timing of these events and their relationship to the paleontologically dated events in the Big Bend area is unknown.

The east-northeast direction of compression continued during the middle Tertiary episode of volcanism (Price and Henry, 1984). Space-filling veins in homogeneous, virtually isotropic, resurgent intrusions of several calderas as young as 32 m.y. trend consistently east-northeast, as do veins in other rocks and most dikes. This trend requires a least principal stress oriented north-northwest, which is not consistent with any direction of Basin and Range extension in the Trans-Pecos region but is consistent with east-northeast compression. Other evidence that supports compression during volcanism includes: (1) East-northeast-trending strike-slip faults that transect volcanic rocks, (2) minor folding of volcanic rocks, and (3) the occurrence as sills of many of the intrusive rocks.

Middle Tertiary Volcanism

Caldera collapse during middle-Tertiary volcanism produced approximately circular fault systems (pl. 2). Calderas of the western belt are located along the margin of the Chihuahua trough where rising magma bodies probably followed established zones of weakness. In a few places caldera boundaries even followed Laramide faults. Later, the buttressing effect of the large batholiths in part determined the distribution of Basin and Range faults. Numerous intrusions caused local doming and faulting of the intruded rocks throughout the Trans-Pecos region.

Basin and Range Extension

A transition from compression remaining from Laramide deformation to tension at the beginning of Basin and Range extension occurred between about 32 and 30 m.y. ago (Price and Henry, 1984). However, normal faulting probably began several million years later. Basaltic dikes, intruded along range-bounding faults into basin fill at 23 m.y. ago, show that faulting and basin formation were by then well developed (Dasch and others, 1969; Henry and others, 1983). Similarly, Stevens (1969) found early Miocene vertebrate remains in clastic sediments composing the lowest basin fill in grabens in the Big Bend area.

Early extension was oriented east-northeast (Henry and others, 1983) similar to the early stress regime in the rest of the Basin and Range province (Zoback and others, 1981). The resulting normal faults were oriented north and northwest, but in part, these directions were the result of Laramide trends. Contemporaneous east-northeast- and northeast-trending fractures document the change to northwest-oriented extension (Price, 1983). The timing of this change in stress orientation has not been established, but a similar change occurred in the northern Rio Grande rift and in the rest of the Basin and Range province about 10 m.y. ago (Golombek, 1982; Zoback and others, 1981). First-motion studies of the 1931 Valentine earthquake indicate a further change in stress orientation to N. 74° E. extension (Dumas and others, 1980). Although most displacment is normal, several studies show a strike-slip component. W.R. Muehlberger (University of Texas at Austin, oral commun., 1983) attributes this overall pattern to northwest-oriented extension along the Texas lineament. The north- to northwest-trending basins and ranges of the Trans-Pecos region may have formed continuously during the entire late Tertiary episode of extension.

Range boundaries are either single faults or a series of parallel faults. Total displacment may be as much as several kilometers, but the thickest basin fill is about 1,500 m. Strata can be matched across the faults to document displacment only for some of the lesser faults; even these, however, have as much as 1,300 m displacement. In the Salt Basin, Presidio Bolson, and the graben in the Big Bend area, parallel faults are abundant well into the middle of the basin. However, the displacements of the faults within the basin are considerably less than that of the boundary fault or fault zone. Faults within the ranges are at most minor, and in some ranges, none have been mapped. All identified calderas occupy the centers of ranges, and faults within the ranges generally disappear into calderas. The underlying magma chamber apparently resisted extension so that the faults largely went around them.

Major boundary faults dip from 50 to 90°; most are steeper than 70°. However, some evidence exists for listric faulting. Downthrown blocks generally dip gently toward the faults except at the scarp where drag has produced the opposite dip; for example, Tertiary volcanic rocks in the Sierra Vieja dip eastward as much as 10°. Basin fill in Presidio Bolson dips 3-5° toward the margin on both sides; however, the central "anticline" is not exposed. Fill in most other basins is not sufficiently exposed to determine its attitude.

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POTENTIAL HOST MEDIA FOR RADIOACTIVE WASTE

By K.A. SARGENT

Potential host media for a mined repository for isolation of radioactive waste in the Trans-Pecos region, Texas, include intrusive rocks such as granite; ash-flow tuff, especially where densely welded and having a thickness greater than 100 m; and basalt and basaltic andesite lava flows where thicker than 100 m. Other, less abundant rock types that occur in the region may have potential as host media. These include certain shallow intrusive bodies, such as domes and laccoliths, and certain argillaceous beds if thick enough and relatively undisturbed. In addition, basin-fill deposits and possibly other rock types have potential as host media in the unsaturated zone. The outcrop areas of potential host rocks and areas believed to have thick unsaturated zones in the Trans-Pecos region are shown in plate 3.

INTRUSIVE ROCKS

Intrusive rocks in the Trans-Pecos region occur as stocks, laccoliths, sills, and dikes, nearly all of Tertiary age. Rock types include granite, syenite, quartz monzonite, gabbro, trachyte, latite, rhyolite, and intrusive basalt. Henry and Fisher (1984a) have summarized these intrusive rocks. Numerous stocks and other large intrusive bodies may be prospective host sites; however, most of the laccoliths, sills, and dikes need additional evaluation. Descriptions of the thickness and extent of nearly all the laccoliths and smaller intrusive bodies are not available; because their thicknesses commonly are not great enough and their subsurface extents are not known, only a few are considered to be potential host rocks.

Several of the large stocks in the Trans-Pecos region may be potential host rocks. Syenite and quartz monzonite stocks are widespread and vary in size throughout the region; a few are mentioned here. Several of the stocks are in the western part of ground-water unit TP-02. The Chinati Mountains, for example, contain a large quartz monzonite stock intruded into Tertiary volcanic rocks. About 10 km to the northeast of the Chinati Mountains, a stock of similar composition intrudes Pennsylvanian and Permian sedimentary rocks and Tertiary lavas. Scattered outcrops of a late Oligocene syenite stock occur in the southern part of ground-water unit TP-02, about 20 km west of the Solitario. In the northwestern part of ground-water unit TP-01, at Cienega Mountain, a large syenite stock intrudes Mesozoic sandstone and limestone and Tertiary volcanic rocks. A smaller syenite stock occurs at Iron Mountain north of Marathon in ground-water unit TP-01. A large quartz monzonite stock occurs south of the Wylie Mountains in the northern part of ground-water unit TP-03. A smaller syenite stock occurs about 20 km north of Valentine in ground-water unit TP-03. A group of stocks or laccoliths of granite occur in the Davis Mountains in the northeastern part of ground-water unit TP-03. Numerous additional intrusive rocks, many of which are probably stocks, occur in the Big Bend area, but most need special study to evaluate their extent.

Large exposures of fine-grained, silicic- to intermediate-composition intrusive rocks also are common in the Trans-Pecos region. A stock or laccolith of Oligocene peralkaline rhyolite occurs in the Cienega Mountains (fig. 1; pl. 3). Three stocks (two rhyolite, one trachyte) in the Van Horn Mountains in the northwestern part of ground-water unit TP-03 are relatively close to the discharge area. In the Big Bend area in the southern part of ground-water unit TP-01, most of the numerous intrusions are finely crystalline sills, laccoliths, and dikes. Large intrusions occur in the Rosillos Mountains, Nine Point Mesa, Christmas Mountains, Ward Mountain, Sierra Quemada, Wildhorse Mountain, and many other areas. The lateral and vertical extent of most of these intrusions is uncertain and would need additional work if other favorable factors justify their further consideration.

TUFFACEOUS ROCKS

The thickest, most densely welded ash-flow tuffs occur as intracaldera flows. In the Chisos Mountains (fig. 1; pl. 3), the Pine Canyon caldera (pl. 2) extruded welded tuff that is more than 300 m thick within the caldera collapse zone (southern part of ground-water unit TP-01). This tuff unit, the Oligocene South Rim Formation, is about 32 m.y. old (Maxwell and others, 1967).

Densely welded Oligocene ash-flow tuffs are 800 m thick in the Cuesta del Burro Mountains inside the Infiernito caldera (pl. 2) and 180 m thick in the Chinati Mountains caldera (pl. 2). Both the Cuesta del Burro and Chinati Mountains occurrences have thick unsaturated zones. The High Lonesome Tuff (Henry and Price, 1984b) is a 10-m-thick Oligocene ash flow which crops out in the Van Horn Mountains in the northwestern part of ground-water unit TP-03. In the Buckhorn caldera located in the Davis Mountains in the northeastern part of ground-water unit TP-03, the Gomez Tuff (Barnes,

1979) is as much as 300 m thick and occurs in a thick unsaturated zone.

Elsewhere in the Trans-Pecos region, extracaldera equivalents of the above tuffs occur but rarely exceed 100 m in thickness and, therefore, are of little interest as host rocks. A summary of the ash-flow tuffs of the Trans-Pecos region was given by Henry and Fisher (1984b).

BASALTIC ROCKS

Basaltic and other mafic extrusive rocks are widespread, but generally thin (less than 100 m) throughout most of the Trans-Pecos region. A few areas that have sections thick enough for further study were summarized by Henry and Fisher (1984c).

In the Stillwell Mountain area in ground-water unit TP-01, basaltic rocks as thick as 130 m crop out in a thick unsaturated zone. The Bofecillos Mountains in the southern part of ground-water unit TP-02 is a complex stratovolcano consisting of mafic to intermediate lava flows that are 22–28 m.y. old. The main unit, the Rawls Formation (Barnes, 1979), is late Oligocene to early Miocene and has a total aggregate thickness of 375 m. The upper part of much of the volcanic section is unsaturated in the Bofecillos Mountains.

Basaltic and trachytic rocks occur in the Chispa Mountains and appear in scattered outcrops to the southeast for 60 km into the southern Davis Mountains. As thick as 200 m on the north, these rocks thin to less than 20 m to the southeast.

A few kilometers south of Alpine, near Cienega Mountain, basaltic rocks crop out throughout a large area. Several flows are as much as 140 m in aggregate thickness. In the southeastern Chinati Mountains, the Morita Ranch Formation (Barnes, 1979) contains numerous mafic flows, most of which are too thin for further consideration.

ARGILLACEOUS ROCKS

In the Big Bend area of Brewster County, Tex. (ground-water unit TP-01), several thick Cretaceous shale units, a locally thick clay of Eocene age, and a sandstone and clay unit of Paleocene age crop out in a generally circular pattern around the Chisos Mountains. Many of the outcrops are faulted and transected by numerous Tertiary intrusions. The youngest unit, the Hannold Hill Formation (Maxwell and others, 1967) of Eocene age, is largely nonvolcanic, nonmarine clay with thin layers of channel sandstone and conglomerate. The Hannold Hill is as thick as 260 m and is confined to a small area on the northern flank of the Chisos Mountains.

Underlying the Hannold Hill is the basal Paleocene Blacks Peak Formation of interbedded sandstone and clay from 74 to 264 m thick. Its outcrop area is similar to the Hannold Hill (Maxwell and others, 1967).

The uppermost unit of Cretaceous age is the nonmarine Javelina Formation, which is largely composed of bentonitic clay with some lenticular masses of cross-bedded channel sandstone. The Javelina generally ranges in thickness from 75–285 m but locally may be as thin as 15 m (Maxwell and others, 1967).

Underlying the Javelina Formation are the continental and marine beds of the Aguja Formation. The upper 270 m of the Aguja is an irregular alternation of nonmarine sandstone and clay and some limestone and thin liguite seams. The middle part (53 m to more than 150 m thick) of the Aguja is marine silty to sandy clay containing generally thin sandstone lenses, but locally the basal 60 m of the middle unit is mostly sandstone. The basal 1.5- to 10.5-m-thick unit of the Aguja is thin-bedded sandstone.

Unconformably underlying the Aguja Formation is the marine clay of the Pen Formation (Maxwell and others, 1967). The basal part of the Pen contains very thin chalk beds, and beds of sandstone as thick as 1.5 m occur locally. The Pen is about 70–210 m thick within the Big Bend area and as much as 300 m thick in the southwestern corner of Brewster County.

In the northern part of Brewster County in the vicinity of Marathon, outcrops of the Word Formation of Early Permian (Guadalupian) age are mostly siliceous shale and clay with thin units of fossiliferous limestone, sandstone, and conglomerate. The formation is as thick as 450 m. The Word is overlain and underlain by Permian units consisting predominantly of limestone.

UNSATURATED ZONE

Outcrops of intrusive rocks in the Chalk Mountains, Santiago Peak in the Santiago Mountains, and a few small intrusions in the Christmas Mountains all occur in thick unsaturated areas in ground-water unit TP-01. Basaltic rocks in the Stillwell Mountain area (ground-water unit TP-01) crop out in a thick unsaturated zone.

Ash-flow tuffs, basaltic rocks, and granites in the Chinati Mountains (ground-water units TP-02 and TP-03) and tuffs near the boundary of ground-water units TP-01 and TP-02 border crop out in thick unsaturated zones. In ground-water unit TP-03, intrusions and tuffs in the Cuesta del Burro Mountains and tuffs in the southern Davis Mountains all occur in thick unsaturated zones.

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QUATERNARY TECTONISM

By CHRISTOPHER D. HENRY[3], JONATHAN G. PRICE[3], and K.A. SARGENT

Quaternary tectonism in the Trans-Pecos region is described relative to seismicity, heat flow, Quaternary faulting, and vertical movement of the region. Seismic strain release, earthquakes of Richter magnitudes 5 or greater, and Quaternary faults in the region are shown in figure 11. There are no Upper Cenozoic volcanic rocks in the Trans-Pecos region, and long-term vertical movement is at a rate of about 1-2 m/10^4 yr.

SEISMICITY

Three recent compilations show differing degrees of seismicity in the Trans-Pecos region. A compilation of the entire Basin and Range province from 1803 to 1977 by Askew and Algermissen (1983) shows six epicenters in the region including two with Richter magnitudes (surface waves) 5-6 (fig. 11). Sanford and Toppozada's (1974) study of southeastern New Mexico and western Texas listed 11 felt earthquakes prior to 1961 and 6 instrumentally detected earthquakes between 1961 and 1972. In a study of part of the Trans-Pecos region and part of Chihuahua, Mexico, using a local seismic network of 5 stations, Dumas (1980) detected or located about 300 earthquakes between 1976 and 1980, all with magnitudes less than 3.7 (Richter scale). Dumas (1980) shows 30-50 epicenters in two clusters, one 10-20 km west of Van Horn and one 20-30 km northwest of Valentine in Lobo Valley. The discrepancy in the number of epicenters reported is due to the differences in location of seismic stations.

The area near Valentine is the most active seismic zone in Texas and was the epicenter of the 1931 Valentine earthquake (magnitude 6.4, Richter scale), which was the strongest reported earthquake in Texas (Dumas and others, 1980). The area has a diffuse, northwest-striking zone that Dumas (1980) stated indicated an active fault system. The fault system is along the eastern side of Lobo Valley; however, Quaternary fault scarps are located exclusively along the western side (Muehlberger and others, 1978). The largest magnitude earthquake detected between 1976 and 1980 was only 2.6 (Richter scale), but a moderately strong earthquake in 1955 was also in this zone (Sanford and Toppozada, 1974). Ni and others (1981) believed vertical crustal movements, determined from releveling in the Valentine area, were related to this fault zone.

The area near Van Horn also had extensive seismic activity, but the presence of blasting associated with talc mining makes identification of natural earthquakes difficult. Dumas (1980) stated that at least some of the events were earthquakes. They occur near the Rim Rock fault, a major Basin and Range normal fault.

Dumas (1980) identified several other areas of seismicity in the Trans-Pecos region but outside his seismic network. One seismically active area is along the eastern margin of the Salt Basin where Quaternary fault scarps are abundant (Muehlberger and others, 1978). Another is near the northern edge of Presidio Bolson, also an area of Quaternary scarps. Two other areas are east of the Big Bend area and in the Davis Mountains.

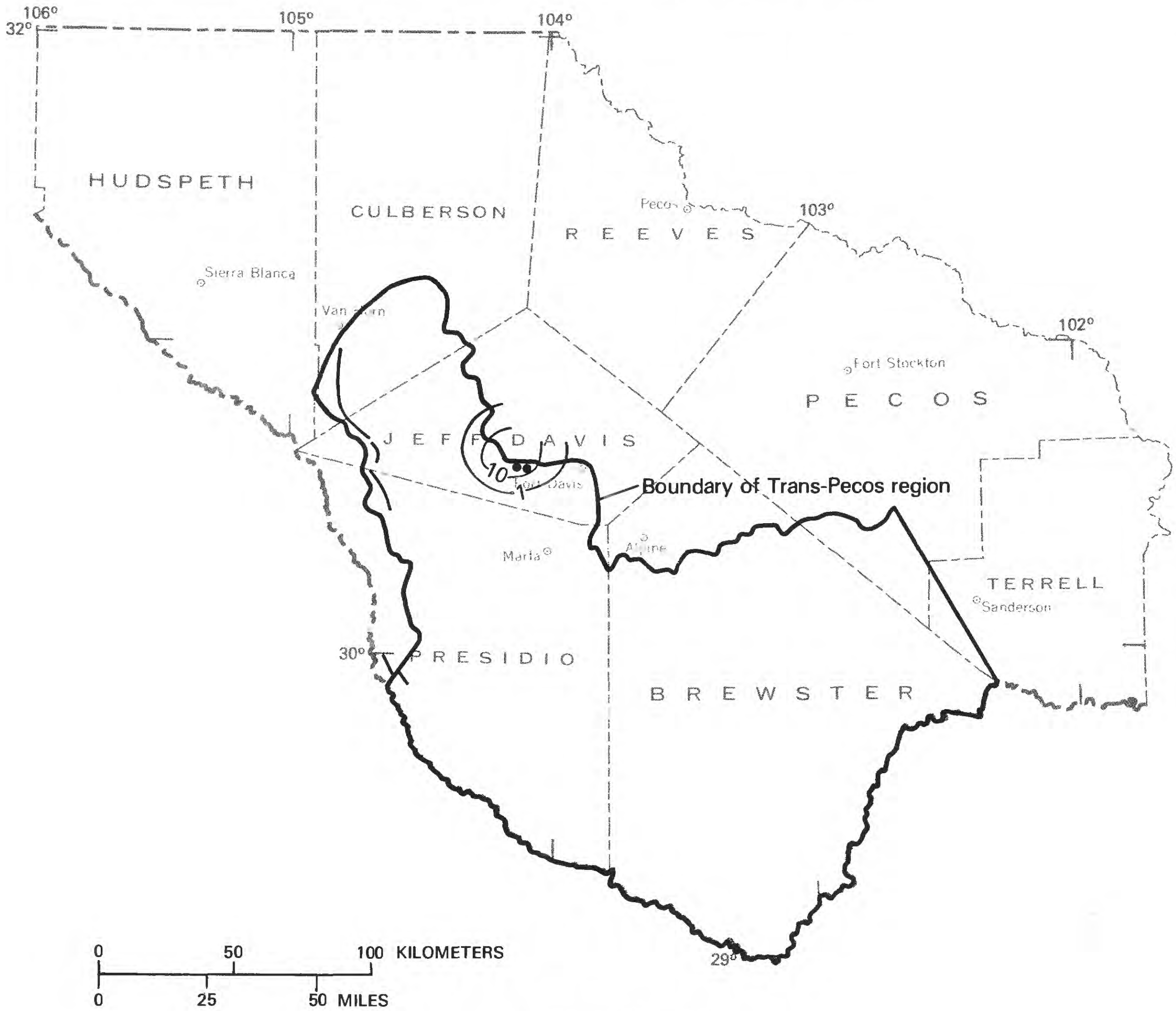
In summary, detailed study of the Trans-Pecos region shows many small earthquakes. However, only the Valentine area has experienced historical, damaging earthquakes.

HEAT FLOW

The Trans-Pecos region is an area of transition between lesser heat flow characteristic of the craton to the east and greater heat flow characteristic of the Basin and Range province to the west (Henry and others, 1983). There are few heat-flow measurements, but thermal gradients from deep petroleum exploration wells and distribution and temperatures of hot springs and wells give some information on the distribution of heat flow. Heat-flow values in the Trans-Pecos region (pl. 4) range from 1.2 to 1.5 HFU (heat-flow units). Values of 1.5 HFU in Coahuila just south of the Rio Grande and 1.8 HFU at Van Horn just north of the region have virtually identical values as those measured within the Trans-Pecos region. Thermal gradients in deep exploration wells having depths of 1,500-6,000 m range from 21-29 °C/km. Hot springs in this region along the Rio Grande in the Big Bend area have maximum measured temperatures of 40 °C; geothermometry calculations indicate that maximum subsurface ground-water temperatures are not much higher (Henry, 1979). The hot springs in the Big Bend area and others in Texas and adjacent Mexico result from deep circulation of meteoric ground water (Henry, 1979; Henry and Gluck, 1981).

In the Presidio Bolson area, the geothermal gradient in two wells is 38-41 °C/km. Northward along the Rio Grande to the Van Horn Mountains (just outside the Trans-Pecos region), geothermal gradients in four deep wells range from 36-43 °C/km. Four hot springs in these

[3]Texas Bureau of Economic Geology.



EXPLANATION

—1— LINE OF EQUAL STRAIN RELEASE, IN EQUIVALENT MAGNITUDE 4 EARTHQUAKES (RICHTER SCALE) PER 823 SQUARE KILOMETERS

• EPICENTER OF MAGNITUDE 5-6 (SURFACE WAVES) EARTHQUAKE (RICHTER SCALE) AS DEFINED BY ASKEW AND ALGERMISSEN (1983)

——— QUATERNARY FAULT

FIGURE 11.—Strain release, earthquakes of magnitude 5 or greater (Richter scale), and Quaternary faults.

areas have temperatures of 31–45 °C, and a nearby spring in Chihuahua, Mexico, has a temperature of 90 °C (pl. 4). Temperatures from geothermometry are as much as 160 °C, but most are in the range of 60–120 °C. The only heat-flow value near these areas is 1.5 HFU in the Presidio Bolson area as reported by Decker and Smithson (1975) (pl. 4); however, their data indicate significant changes in thermal gradient and heat flow with depth, which in turn indicate vertical ground-water movement. For the deepest interval, 620–880 m, in the Presidio Bolson area, the heat flow is 1.5 HFU. For the depth range of 180–560 m, which is considerably deeper than any of the wells investigated by Decker and Smithson (1975) in the Rio Grande rift in New Mexico, the heat flow is 2.1 HFU. The thermal gradient and hot springs reflect the heat-flow convection by ground water and may indicate greater heat flow in the area from Presidio Bolson northward along the Rio Grande to the Van Horn Mountains than in other parts of the Trans-Pecos region.

These data indicate that near the Rio Grande, the Trans-Pecos region has thermal characteristics intermediate between those of the craton to the east and the average for the Basin and Range province, especially the Rio Grande rift, to the west. The adjacent craton is characterized by heat-flow values about 1.1 HFU (Herrin and Clark, 1956; Sargent and Bedinger, 1985). J.H. Sass (in Sargent and Bedinger, 1985) determined that the Rio Grande rift in southern New Mexico has a heat flow greater than 2.5 HFU. The intermediate area in the Trans-Pecos region, which includes the major grabens of Salt Basin, Lobo Valley, and the Big Bend area has a heat flow of 1.2–1.5 HFU, although heat flow in the Presidio Bolson area probably is 2.5 HFU or greater, similar to that found by J.H. Sass in southern New Mexico.

QUATERNARY FAULTING

Quaternary fault scarps occur in a north-trending zone through western Texas (Muehlberger and others, 1978; Henry and others, 1983; Nakata and others, 1982). The zone extends from southern New Mexico 300 km south into the region (pl. 4) along the margins of the basin-and-range grabens. Quaternary faults in the Trans-Pecos region include one in Lobo Valley (Mayfield fault) and two in the Presidio Bolson (Candelaria fault and unnamed fault). The trace of the Mayfield fault on the western side of Lobo Valley near the Van Horn Mountains is shown in figure 12. To the south and east, older Basin and Range faults appear to have no Quaternary movement. However, these faults are almost entirely in Cretaceous or Tertiary rocks, and Quaternary movement may be difficult to detect. The southern limit of Quaternary scarps is in the Chihuahua trough-tectonic belt and, as suggested by Gries (1979), ductile

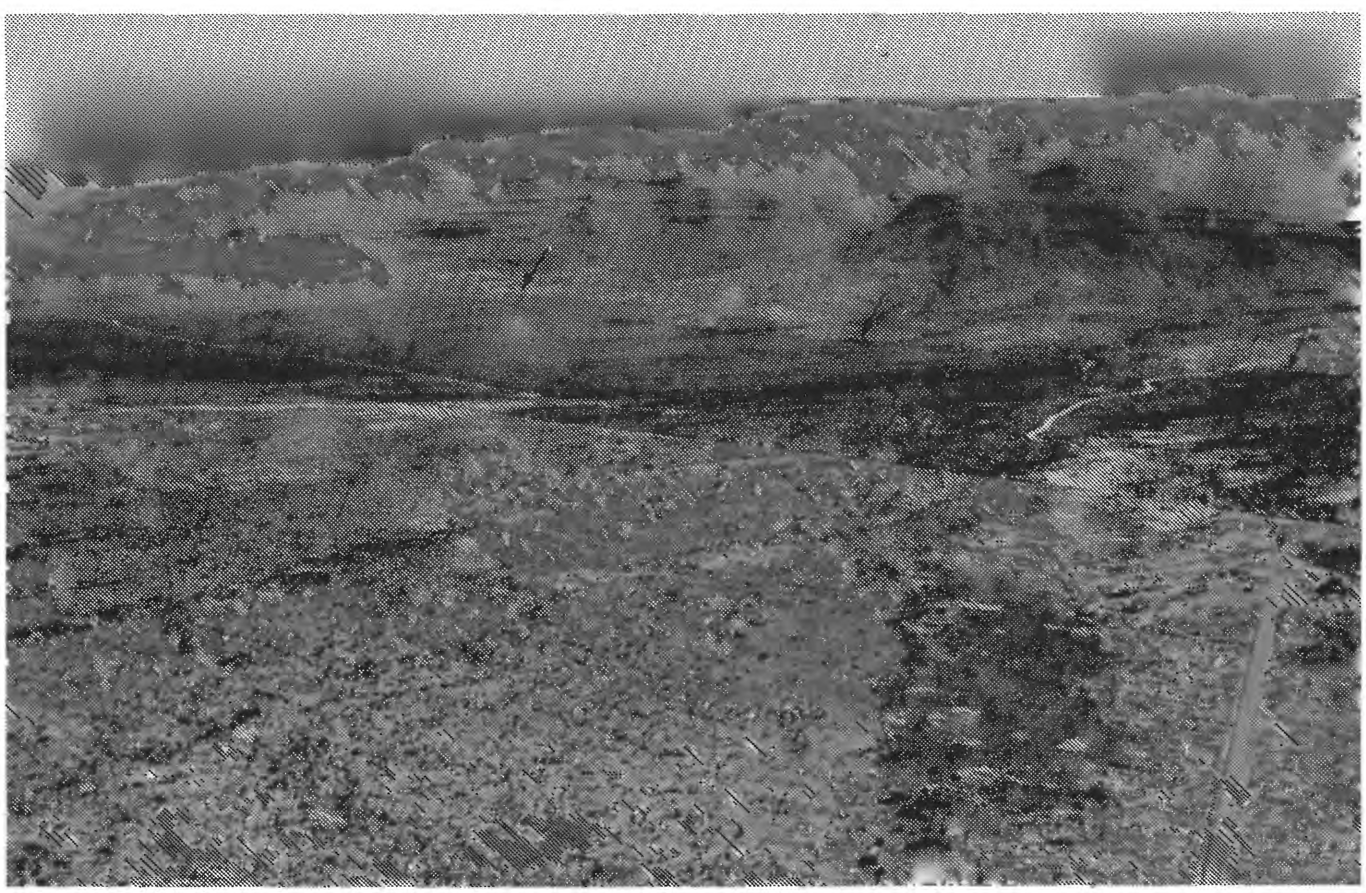


FIGURE 12.—Mayfield fault scarps on the western side of Lobo Valley (arrows). View is toward the southwest across Lobo Valley to the Cretaceous limestone and sandstone of the Van Horn Mountains.

flow in evaporites underlying the area may disguise recent extension.

In the Salt Basin to the north of the Trans-Pecos region, scarps are more abundant and continuous along the western side of the valley; scarps along the eastern side are sparse and discontinuous (Muehlberger and others, 1978). Scarp heights generally are 1-3 m but increase southward to as much as 6 m in the southern part of Salt Basin. Most scarps trend north or northwest and are parallel to the range fronts. However, a zone of faults trends northeast along the base of an isolated mountain block in the Salt Basin and north of Van Horn.

The Mayfield fault along the western side of Lobo Valley is the longest continuous Quaternary fault scarp in the Trans-Pecos region. The fault consists of several segments continuous for more than 80 km along the eastern side of the Van Horn Mountains and Sierra Vieja. As shown by Muehlberger and others (1978), two episodes of movement occurred on the middle segment of this fault. An older period had about 2 m of displacement and a younger episode, represented by two en-echelon faults, has scarps 1.5 and 7 m in height.

Quaternary scarps in Presidio Bolson include the Candelaria fault and an unnamed fault (pl. 4). One scarp, which is continuous for about 4 km and is about 5 m high, transects all but the youngest of six Quaternary alluvial surfaces. Another scarp, along the Candelaria fault in an area of dominantly Tertiary volcanic rocks, displaces a Quaternary gravel surface as much as 50 m. Its lateral continuation to the north or south cannot be determined because of the lack of Quaternary deposits.

VERTICAL CRUSTAL MOVEMENT

To obtain accurate estimates of the rates of vertical crustal movement, one needs to consider both the average rates during a significant part of Basin and Range time, and the short-term, modern rates. Gable and Hatton (1983) estimated 1-2 m/10^4 yr of vertical uplift for the last 10 m.y. in the Trans-Pecos region. An approximate estimate of the average rate of uplift for the Trans-Pecos region can be made from regional topography and the elevation of Cretaceous formations that continue into the region from central Texas. Assuming about 1,100 m of uplift during the last 25 m.y. gives a rate of 0.04 m/10^4 yr. The rate could be considerably greater if much of the uplift occurred during a shorter time.

Short-term rates of vertical movement determined from releveling data within the last 50 yr or so are as much as two orders of magnitude greater than long-term rates of movement. Analysis of releveling data presented by Ni and others (1981) across the Trans-Pecos region from Sierra Blanca through the Valentine area to Sanderson, shows the total unadjusted apparent uplift at Sierra Blanca of about 250 mm, or 6 mm/yr from 1917 to 1957. Ni and others (1981) could not ascertain whether this apparent uplift was due to systematic leveling error or to a regional tectonic effect. Reilinger and others (1980) determined an apparent uplift rate of 4.4 mm/yr from the Sierra Diablo Plateau north of the Rio Grande to near Carlsbad, N. Mex. (just outside map area of figure 1), during 1934-1977; they ascribed this uplift to tectonic activity.

The releveling lines examined by Ni and others (1981) indicated subsidence of 2.8 mm/yr at Valentine, which was concluded to represent movement related to the Valentine earthquake of 1931. Apparent subsidence east of Van Horn, in the Salt Basin, was attributed by Ni and others (1981) to ground-water withdrawal and topography-related survey errors. Apparent subsidence at the Salt Basin on the releveling line examined by Reilinger and others (1980) was related to the regional tectonic uparching, although near-surface, nontectonic effects could not be excluded. Although releveling data have large uncertainties, the similarity of local rates of uplift throughout such a large area of regionally similar geologic setting indicates similar causes. Unfortunately, we do not know how far back to extrapolate these rates. Certainly the rates cannot have been operative long, as uplift at these rates would produce unrealistic relief in even a short time; uplift at a rate of 5 mm/yr for 10,000 yr would be 50 m.

An approximate estimate of the average rate of erosion for ranges can be made from volumes of basin fill, by assuming that all basin fill was derived from adjacent ranges with negligible in or out migration and by comparison of areas of erosion and deposition. Thickness of basin fill ranges from about 300 to 1,500 m. If the filling has taken about 20 m.y., and the areas of basin and ranges are about equal, the rates of filling and erosion are each about 0.015-0.075 mm/yr.

Two types of basins are recognized: (1) Closed basins that are aggrading (Salt Basin and Lobo Valley), and (2) open basins that have been eroded since integration by the Rio Grande in the Pleistocene (Presidio Bolson and Quitman Arroyo-Red Light Draw). Assuming that the floors of the open basins were nearly flat before downcutting began, and by comparing the elevations of the margin (highest part of the basin) and center (lowest part of the basin, along the Rio Grande), one can estimate a maximum rate of downcutting. The differences in elevation are at most 430 m for Presidio Bolson and 380 m for Quitman Arroyo-Red Light Draw. If integration of the Rio Grande took place about 0.7 m.y. ago (Seager and others, 1984), downcutting has occurred at a rate of about 0.57 mm/yr. Because the basins were not completely flat and allowing for uncertainty in the time of integration, a reasonable range of rates may be 0.2–0.8 mm/yr. These rates should be applicable to present-day conditions. Continued downcutting for 10,000 yr at these rates would lower the Rio Grande 2–8 m.

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GROUND-WATER HYDROLOGY

By M.S. Bedinger, William H. Langer, and J.E. Reed

The Trans-Pecos region is semiarid with precipitation ranging from less than 250 to 450 mm and potential evapotranspiration as great as 2.5 m annually. Surface drainage is open to the Rio Grande in ground-water units TP-01 and TP-02; surface drainage in ground-water unit TP-03 is to the topographically closed Salt Basin (fig. 1).

MAJOR HYDROGEOLOGIC UNITS

The stratigraphic units in the region, discussed in the "Geology" section, have been grouped into several hydrogeologic units based on their predominant hydrologic characteristics. The relation between hydrogeologic and stratigraphic units is discussed in the following paragraphs and shown in plate 5. The hydraulic properties of the hydrogeologic units used in areal and cross-sectional models are given in tables 4 and 5, respectively.

Basin fill of the Presidio and Redford Bolsons in the southwestern part of ground-water unit TP-02 is as much as 1,500 m thick as estimated from seismic and electrical resistivity data by Gates and others (1978). The basin fill includes a thick section of fine-grained sediments, most of which probably are lacustrine clay and silt and volcaniclastic rocks. Coarse clastic and volcanic rocks are a major part of the section locally, in the southern part of Presidio Bolson and Redford Bolson.

The bolson deposits in Lobo Valley in ground-water unit TP-03 include sand, gravel, volcaniclastic rocks, and thin lava flows and are overlain by fine-grained alluvial material. Volcaniclastic rocks are predominant in the lower part of the section. Maximum thickness of the bolson deposits is more than 300 m.

Volcanic rocks include lava flows, mostly mafic and some felsic; ash-flow tuff; rhyolite; trachyte; reworked and bedded tuff; and other volcanic material. Flows of trachyte and rhyolite are thin to medium bedded and occur in aggregate thicknesses of as much as 120 m. The basalt flows, of Eocene to Miocene age, are mapped in the Davis Mountains in the northwestern part of ground-water unit TP-01 and the southeast one-quarter of ground-water unit TP-03. Basalt flows yield small to moderate supplies of water locally. Tuffs in the Chinati Mountains and Sierra Vieja (western and southwestern parts of ground-water units TP-02 and TP-03, respectively) attain an aggregate thickness of 1,200 m. Tuffs include fractured to dense ash-flow tuffs and pumiceous and zeolitized bedded and reworked sedimentary tuffs of Eocene to Miocene age. Tuffaceous sedimentary rocks compose the principal aquifer in the Marfa area (Davis, 1961).

Intrusive rocks of Oligocene to Miocene age are sparsely distributed in the western part of the region and densely distributed in the southwestern part of ground-water unit TP-01. These intrusive rocks are predominantly rhyolite and trachyte, but some of the large intrusions are granite, syenite, and quartz monzonite. The intrusive masses occur as stocks, sills, dikes, laccoliths, and ring dikes.

The entire region is underlain by Precambrian sedimentary, metasedimentary, and volcanic rocks. In the southern part of the region, these rocks consist of quartzite, meta-arkose, slate, schist, metarhyolite, metabasalt, pegmatite, and some granodiorite and carbonate rocks. In the northern part of the region, these rocks consist of limestone, dolomite, phyllite, tuff, and basalt flows and sills. Permeability, which is primarily fracture permeability, commonly is minimal.

Carbonate rocks of Early and Late Cretaceous and Paleozoic age are widespread in the region. The Cretaceous carbonate rocks are as thick as 1,800 m. The Lower Cretaceous rocks are predominantly limestone with marly, argillaceous limestone and minor shale. Paleozoic carbonates probably exceed 2,000 m in thickness, but their maximum thickness is not known. Rock sequences composed of about 25 percent or more carbonate rocks are mapped as carbonate rock in plate 5. In the Trans-Pecos region, the unit commonly contains more than 75 percent carbonate rock.

Fine-grained clastic rocks of Late Cretaceous and early Tertiary age, including shale and other argillaceous rocks and interbedded with sand, silt, and carbonate rocks, occur primarily in the southwestern part of ground-water unit TP-01 and at 50-300 m thick. Shale of Permian age crops out west of Marathon (northern part of ground-water unit TP-01) and is about 450 m thick.

Mixed sedimentary rocks of the Ouachita-Marathon fold belt of Paleozoic age crop out in the Marathon basin south of Marathon in ground-water unit TP-01 and in the Solitario uplift and underlie adjacent parts of the region. These rocks include well-indurated shale, limestone, and chert. The principal aquifer in rocks of the Marathon basin is the Ordovician Marathon Limestone in the outcrop area near Marathon in ground-water unit TP-01 (DeCook, 1961). Permeability is attributed to fractures and joints as the result of folding and faulting of the strata.

GROUND-WATER FLOW REGIME

Ground-water recharge occurs along the foothills of the mountains and plateaus and along the channels of ephemeral streams, where the sediments are coarse grained and permeable. Although most precipitation falls in the summer when evaporation demand is great, much of the precipitation occurs in torrential rainstorms. Recharge probably occurs from such storms that cause surface flow. Recharge has been estimated by Gates and others (1978) from limited water-budget data for several basins in ground-water units TP-02 and TP-03 to be about 1 percent of the mean annual precipitation, which ranges from less than 250 to about 450 mm/yr. Littleton and Audsley (1957, p. 26) estimated that recharge to ground water in the Alpine area was about 5 percent of precipitation. We have calculated, based on a seepage measurement on the Rio Grande in February 1925, that the recharge to a large part of ground-water unit TP-01 is about 13 mm/yr or about 4 percent of the 320 mm of annual precipitation.

The major discharge of ground water from ground-water unit TP-01 is to the Rio Grande and Terlingua Creek; the major discharge of ground water from ground-water unit TP-02 is to the Rio Grande and Alamito Creek. The greatest withdrawal of ground water in the region is from ground-water unit TP-03 where pumpage averaged about 13.6 hm^3/yr from 1949 through 1972.

Springs having a discharge temperature of 30 °C or greater and springs having a discharge greater than 200 L/min are shown in figure 13. Thermal springs in the Trans-Pecos region are located near the Rio Grande, in ground-water unit TP-01. The largest reported flow of a single spring is 450 L/min. There are numerous small cold seeps and springs in ground-water unit TP-01 but few that discharge more than 200 L/min.

The recharge to Ryan Flat in the southern part of ground-water unit TP-03 was estimated by Gates and others (1978) to be about 7.2 hm^3/yr. They further estimated that the underflow northward toward Lobo Flat is about 2.0 hm^3/yr. The ground-water withdrawal from Ryan Flat is about 1.2 hm^3/yr. Gates and others (1978) postulated that some ground water moves westward and discharges to springs at the western base of the Sierra Vieja in the Rio Grande drainage basin.

Low-flow records of the Rio Grande collected during February 1925 by the U.S. Geological Survey indicate no significant increase in flow of the river from the mouth of Terlingua Creek to Boquillas, Coahuila, a distance of about 100 km along the river. The ground-water tributary area to this reach of the river contains a relatively large outcrop area of argillaceous rocks. Also, topographic maps of the area show many small, cold springs. We tentatively conclude that the recharge is decreased by low permeability surface rock and that local discharge of ground water is facilitated by stratigraphic control of the small springs.

GROUND-WATER FLOW ANALYSIS

AREAL GROUND-WATER FLOW

Ground-water traveltime near the water table was analyzed using the procedure described in Chapter A of this professional paper (Bedinger, Sargent, and others, 1989). The relative velocities in the hydrogeologic units are shown in plate 5. Relative velocities are reported because hydraulic properties of the hydrogeologic units are not known from site-specific data and complete areal coverage of the hydraulic gradient is not available for the region. The estimated values of hydraulic properties of the units and estimated average hydraulic gradient used in estimating relative ground-water velocities are given in table 4.

TABLE 4.—*Hydraulic properties of hydrogeologic units modeled in areal ground-water flow analysis*

[K/ϕ, hydraulic conductivity/effective porosity; n.d., not determined]

Hydrogeologic unit	Map symbol (pl. 5)	K/ϕ	Hydraulic gradient
Basin fill in ground-water unit TP-03.	a	6×10^1	0.003
Basin fill in ground-water unit TP-02.	a	6×10^1	.018
Undifferentiated volcanic rocks.	v	1×10^{-1}	.007
Basaltic lava flows	b	3×10^0	.007
Ash-flow tuff and tuffaceous sedimentary rocks.	t	1×10^{-1}	.007
Intrusive rocks	g	2×10^{-1}	.007
Carbonate rocks (Presidio Bolson).	c	3×10^{-1}	.007
Carbonate rocks (Wylie Mountains and ground-water unit TP-01).	c	1×10^1	.007
Fine-grained clastic rocks.	f	3×10^{-9}	n.d.
Mixed sedimentary rocks of the Marathon basin.	s	2×10^{-1}	.007

The hydraulic gradients for the hydrogeologic units are representative gradients obtained from the water-level contour map of the region (Brady and others, 1984). The ratio of hydraulic conductivity to effective porosity was estimated using the values in Chapter A (Bedinger, Langer, and Reed, 1989) as a guide and was modified from the lithologic and hydrologic description of the units in the Trans-Pecos region. The hydraulic properties were further refined during the iterative process of verification of the cross-sectional models in which the flow along hydrogeologic sections, estimated from precipitation and seepage to the Rio Grande, and water levels were simulated.

Relative ground-water traveltimes, flow paths along which the relative traveltimes were calculated toward major discharge areas (the Rio Grande, Terlingua Creek, and Alamito Creek), and large ground-water withdrawal areas are shown in plate 6. Traveltimes in the shale units were not calculated because of lack of data on hydraulic gradients. Relative ground-water velocity in shale, under a unit hydraulic gradient, is five or more orders of magnitude slower than in the other hydrogeologic units. The traveltime in shale probably exceeds greatly the longest relative traveltime of the other units shown on plate 6.

The longest relative traveltimes shown on plate 6, which are 100–200, are in the northern parts of ground-water unit TP–01, in ground-water unit TP–02, and in the southeastern part of ground-water unit TP–03. Traveltimes are long because of the great distances from the ground-water divides to the major discharge areas and the associated lack of intermediate discharge points.

The relative traveltimes indicated on plate 6 from divide areas to discharge areas are extremely conservative because actual flow paths from recharge areas dip below the water table and are longer than the map distance. As a result, the relative traveltimes are larger than what would be expected based on map distance alone. The relative traveltimes are useful for comparing relative velocities near the water table and for calculating relative traveltimes at shallow depths between nearby points. A more realistic estimate of relative traveltime between widely spaced points, such as from near a water-table divide to a discharge area, is given in the hydrogeologic sections (pl. 7).

CROSS-SECTIONAL MODELS

Cross-sectional models were used to analyze ground-water flow along selected flow paths. The mathematical model used in modeling flow in the sections is given in Chapter A (Reed, 1989) of this Professional Paper. The location of the hydrogeologic sections and the model parameters are shown in plate 7. The values of hydraulic properties of the rock units in the hydrogeologic sections used in analysis of the ground-water flow are given in table 5.

Distributions of rock units, relative traveltimes, and flow paths are shown in the hydrogeologic sections (pl. 7). Relative traveltimes are given in intervals of one order of magnitude from 10^1 and indicate the relative time of travel from points on the line to the discharge area. Flow paths show the directions of ground-water movement and relative quantity of flow in the section below the flow line.

TABLE 5.—*Hydraulic properties of hydrogeologic units used in cross-sectional models*
[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; ---, not determined]

Hydrogeologic unit	Symbol (pl. 7)	Hydrogeologic sections on plate 7							
		A-A'		*B-B'*		*C-C'*		*D-D'*	
		K	ϕ	K	ϕ	K	ϕ	K	ϕ
Ash-flow tuff and tuffaceous sediments.	t	4×10^{-4}	3.5×10^{-1}	---	---	4×10^{-4}	3.5×10^{-1}	4×10^{-4}	3.5×10^{-1}
Carbonate rocks	c	3×10^{-3}	1×10^{-2}	1×10^{-2}	1×10^{-2}	2×10^{-4}	1×10^{-2}	3×10^{-1}	1×10^{-2}
Crystalline rocks, upper part of section.	G	---	---	5×10^{-4}	3×10^{-3}	---	---	---	---
Crystalline rocks, lower part of section.	g	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}
Volcanic rocks, undifferentiated.	v	4×10^{-4}	4×10^{-3}	---	---	4×10^{-4}	4×10^{-3}	---	---
Basin fill	a	1×10^{-1}	1.8×10^{-1}	4×10^{-2}	1.8×10^{-1}	---	---	---	---

The hydrogeologic sections give a more realistic concept of the traveltime between widely spaced points in the region, for example, between the water-table divide areas and the discharge areas. As shown in the sections, the flow paths in the water-table divide areas of the flow system dip steeply into the flow system and take the longest flow paths to the discharge areas. Relative traveltimes from the water-table divide areas to discharge areas are as great as 10^6 to 10^7. Commonly, the longest relative traveltimes from sites are of restricted surface area and restricted cross-sectional area at depth in the section. This situation restricts the target area for the longer flow times. The areas of longer relative traveltime enlarge with depth and would provide more confidence in locating an area of long traveltime at depth beneath the water table than above the water table.

Broad areas of relative traveltime greater than 10^5 exist at the water table in section *B–B'*; broad areas of greater than 10^4 exist at the water table in section *A–A'*; and broad areas of greater than 10^3 exist at the water table in sections *C–C'* and *D–D'*.

Hydrogeologic environments where argillaceous units lie in the flow paths between prospective host rocks and the discharge areas are not identified in the region. Carbonate rocks, which occupy a significant part of each section modeled, are relatively permeable as inferred from model verification tests. Several thick argillaceous units in the southern part of ground water unit TP–01 may provide potential host environments or barriers in the flow system from a potential repository site.

QUALITY OF GROUND WATER

The quality of ground water in the Trans-Pecos region is characterized by the areal distribution of dissolved solids (fig. 13) and predominant chemical constituents in solution (fig. 14). These maps are generalized from that compiled by Thompson and Nuter (1984) from the water-quality files of the U.S. Geological Survey (WATSTORE) and of the Texas Department of Water Resources and from data from published reports. The data mostly are from nongeothermal springs and wells less than 150 m deep completed in alluvial and basin-fill deposits. In areas where data are not available, the water-quality parameters were estimated from the position of the area in the ground-water flow system and the lithology of the local bedrock.

In most of the region, dissolved-solids concentrations are less than 1,000 mg/L (fig. 13). Near the Salt Basin, in the northwestern part of ground-water unit TP–03, the dissolved-solids concentration exceeds 3,000 mg/L. Ground water predominantly is either a calcium magnesium bicarbonate type or a sodium bicarbonate type; each type is distributed throughout about one-half of the region. The calcium magnesium bicarbonate type water is predominant in the eastern and southern parts of the region; other extensive areas of this type of water are south and west of the Davis Mountains in ground-water unit TP–03. Sulfate is the dominant anion in ground water occurring in small areas near Van Horn and along the Rio Grande in ground-water units TP–01 and TP–02. Chloride is the dominant anion in ground water occurring in the northwestern part of ground-water unit TP–03 near the natural discharge area. The areas of greatest dissolved-solids concentrations correspond to areas of sulfate and chloride type waters and to the extensive area of calcium magnesium bicarbonate type water in the eastern part of the region.

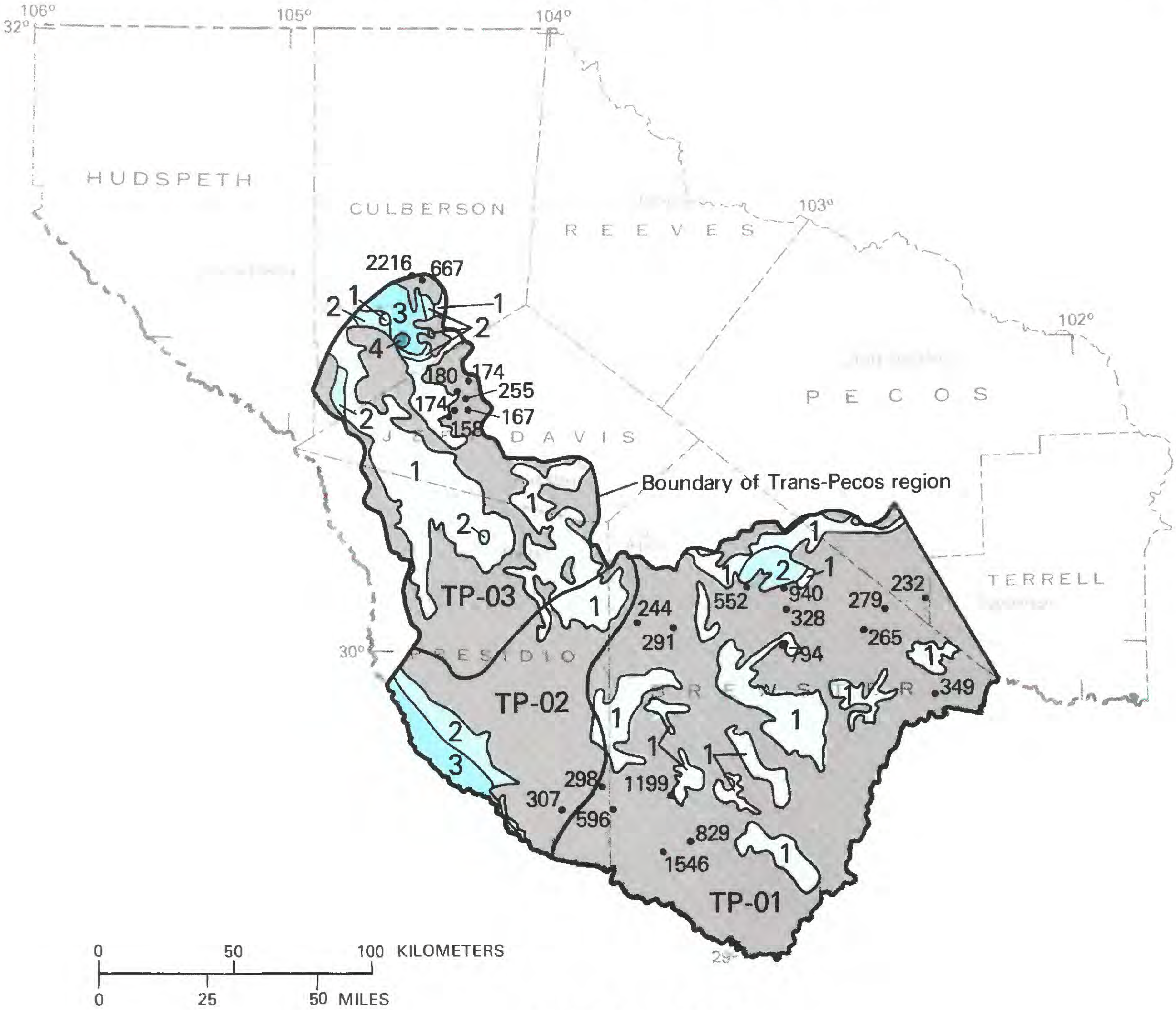
PLEISTOCENE HYDROLOGIC CONDITIONS

Notable differences in Pleistocene hydrologic conditions in the Rio Grande region include: (1) Lower base level (Gulf of Mexico) for the Rio Grande, which borders the southwestern part of the region; and (2) a pluvial climate that probably was characterized by greater annual precipitation and lower mean annual temperature as evidenced by the existence of a Pleistocene lake in the Salt Basin north of the region in Culberson and Hudspeth Counties, Tex., and Otero County, N. Mex.

Estimates of maximum lowering of sea level during the Pleistocene full-glacial intervals range from 80–140 m (Bloom, 1978). The average rate of entrenchment of the Rio Grande in the Trans-Pecos region along about 1,125–1,450 km of the river from the Gulf of Mexico during the Pleistocene Epoch was about 0.8 m/10^4 yr. Entrenchment at 0.8 m/10^4 yr or even at twice this rate would have small effect on the ground-water flow during 100,000 yr.

Various types of full-glacial climate have been estimated for areas north of the region in New Mexico and Texas. Using Pleistocene lake levels in the Estancia basin of east-central New Mexico, Leopold (1951) estimated that during the full-glacial climate, annual precipitation was 50–70 percent greater, annual temperature was 6.6 °C lower, and annual evaporation was 23–50 percent less than at present. From information on Pleistocene lakes of the Llano Estacado of western Texas, Reeves (1966) estimated that during the full-glacial climate, annual precipitation was 89 percent greater, annual temperature was 5 °C lower, and annual evaporation was 27 percent less than at present.

The evidence for the existence of a lake in the Salt Basin during the glacial climate indicates that a similar change in climate existed in the Trans-Pecos region. The Pleistocene lake of the Salt Basin is estimated to have had a maximum area of 960 km^2 and a maximum lake



EXPLANATION

DISSOLVED-SOLIDS CONCENTRATION OF GROUND WATER IN BASIN FILL, IN MILLIGRAMS PER LITER

1 Less than 500

2 501 to 1,000

3 1,001 to 3,000

4 3,001 to 10,000

CONSOLIDATED ROCK

•174 WELL COMPLETED IN CONSOLIDATED ROCK--Number is dissolved-solids concentration in milligrams per liter

BOUNDARY OF GROUND-WATER UNIT

TP-01 DESIGNATION OF GROUND-WATER UNIT

FIGURE 13.—Dissolved-solids concentration in ground water in the Trans-Pecos region, Texas.

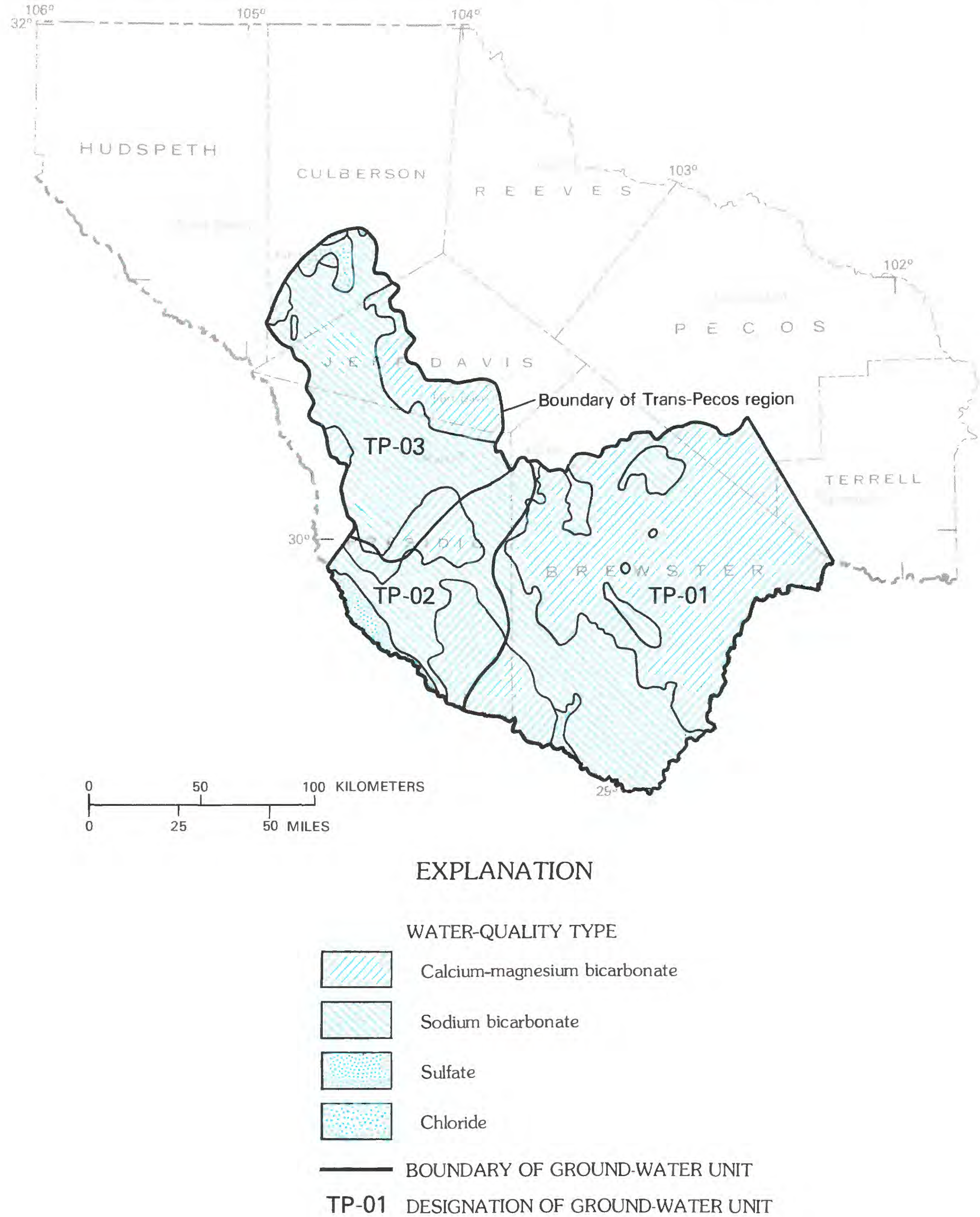


FIGURE 14.—Distribution of chemical types of ground water near the water table in the Trans-Pecos region, Texas.

elevation of 1,115 m, that is, 12 m above the low point of the present land surface (Williams and Bedinger, 1984). The lake had a maximum level about 3 m above the present (1983) ground-water level at the southern margin of the lake.

Recurrence of a lake in the Salt Basin to an elevation of 1,115 m would not extend into the northern part of ground-water unit TP-03 but would raise the phreatic base level by about 3 m. An increase in recharge would further increase the ground-water level. Based on estimates of a full-glacial climate by Leopold (1951) and Reeves (1966), potential recharge could conceivably increase by as much as 2 to 4 or more times the present rate. An increase in recharge could raise the ground-water level to the surface in Chispa Creek (northern part of ground-water unit TP-03). The potential increase in the ground-water level in the divide areas of ground-water units TP-01, TP-02, and TP-03 could be as much as 100 m or more. The rise in ground-water-level elevation would be constrained by the ground-water discharge level of the Rio Grande, Alamito Creek, and Terlingua Creek.

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MINERAL AND ENERGY RESOURCES

By JONATHAN G. PRICE[4], CHRISTOPHER D. HENRY[4], and B.T. BRADY

Mineral production from the Trans-Pecos region has been dominated by silver from the Shafter district, mercury from the Terlingua district, and fluorspar from the Christmas Mountains. There has been limited production of a variety of other mineral commodities. Development of energy resources has been limited to natural gas in the Marathon region and small quantities of Upper Cretaceous coal from several localities. Exploration to date has not revealed significant oil, uranium, or geothermal resources.

Geologic data and production statistics from known mineral deposits in Trans-Pecos Texas were recently compiled by Price and others (1983). Information concerning ownership and location of currently producing mineral operations, including sand and gravel and crushed stone, was tabulated by McBride and Dobbs (1983). These references provide the basis for the following discussion of resources. A summary of the commodities and general characteristics for each resource area in the Trans-Pecos region is contained in table 6. The locations of these mineral resource areas are shown in figure 15.

METALLIC MINERAL RESOURCES

SILVER, LEAD, ZINC, AND COPPER

There are numerous silver deposits in the Trans-Pecos region, but substantial production has come primarily from the Shafter area (Ross, 1943). Mantos, and to a lesser extent veins, mined between 1880 and 1942 yielded 930,000 kg of silver, 3,600,000 kg of lead, and small quantities of zinc and gold. The host rock for most ores is the Permian Mina Grande Formation (Rix, 1953). Many of the intrusions in the vicinity of the Chinati Mountains caldera are hydrothermally altered and locally contain metal deposits. Mineralization probably occurred during Oligocene igneous activity. Caldra-related silver-lead-zinc-quartz veins similar to those at Shafter occur in the quartz-monzodiorite resurgent dome of the Chinati Mountains caldera (McAnulty, 1972) and in the quartz-monzonite resurgent dome of the Infiernito caldera (Price and others, 1983).

Silver-copper-lead ores occur in red-bed sequences (chiefly sandstone) of varying host-rock ages in the Van Horn area. An example of this type of metal deposit is found at the Plata Verde Mine in the northwestern foothills of the Van Horn Mountains immediately west of the region outlined in figure 15. Mineralization at this locality occurs in originally reduced rocks of the clastic Powwow Member of the Hueco Limestone of Permian age. Supergene silver-bearing ores are found principally along small fractures or near surface faults that generally are conformable with the bedding. These deposits are not directly associated with Tertiary igneous rocks of the region and probably formed at low temperatures during Basin and Range extension (Price, 1982). Nearly 8,700 kg of silver was produced from about 14,600 Mg of ore at the Plata Verde Mine between 1934 and 1943 (Price, 1982). Sixteen kilometers north-northwest of Van Horn, a similar deposit in the Precambrian Hazel Formation at the Hazel Mine yielded about 120,000 kg of silver between 1856 and 1947 (King and Flawn, 1953).

MERCURY

A total of 5,170,000 kg of mercury was produced from the Terlingua area, mostly between 1902 and 1943 (Yates and Thompson, 1959). Cinnabar deposits occur dominantly in Cretaceous limestones as: (1) Lodes related to solution collapse along the Santa Elena Limestone–Del Rio Clay contact; (2) calcite veins in the Boquillas Formation and Buda Limestone; (3) solution-collapse breccia pipes in the Santa Elena Limestone, Del Rio Clay, Buda Limestone, and Boquillas Formation; and (4) fracture fillings in Tertiary rhyolitic intrusions. Production from similar deposits outside the Terlingua area, in the Christmas Mountains and in the Mariscal area in the Big Bend area, was minor. Temporal and genetic relationships between the large mercury deposits and the numerous Tertiary intrusions in the southern part of the Trans-Pecos region have not been established.

MOLYBDENUM, TUNGSTEN, AND TIN

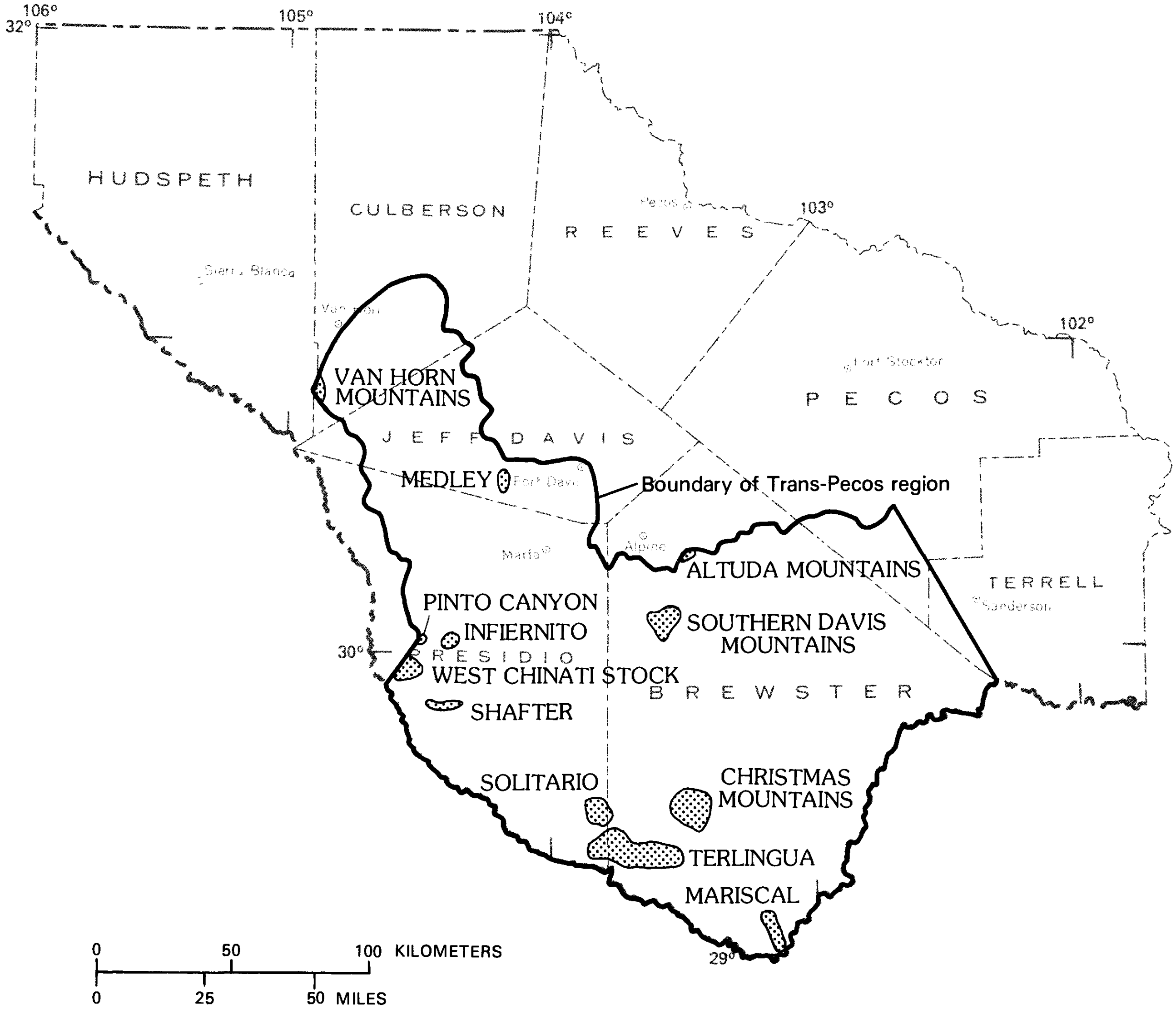
Porphyry-type molybdenum deposits with varying copper, tin, and tungsten contents are associated with isolated middle Tertiary intrusions in the eastern alkalic igneous belt and with calderas in the western alkali-calcic belt in the Trans-Pecos region. Examples include Red Hill in the foothills of the Chinati Mountains at the western end of the Shafter district (Price and Henry, 1982b), a prospect in the Infiernito caldera (Price and Henry, 1982a), and perhaps the Bird Mine in the Altuda Mountains immediately north of the Trans-Pecos region (fig. 15) (Sankaran, 1981). None of the porphyry-type deposits have been exploited.

[4]Texas Bureau of Economic Geology.

TABLE 6.—*Mining areas by county*

[Data from Henry, Price, and Hutchins (1983); Ag, silver; Au, gold; Cu, copper; Hg, mercury; Mo, molybdenum; Pb, lead; U, uranium; and Zn, zinc]

County	Mineral resource areas or districts	Location	Commodities	Description of deposit and host rock	References
Brewster	Altuda Mountains	East of Alpine, south of U.S. Highway 90. About lat 30°21′ N., long 103°31′ W.	Ag, Pb, Mo, Cu, Zn	Replacement bodies in Permian Capitan Formation (limestone) adjacent to breccia pipe-intrusive complex. Deeper porphyry-type mineralization in breccia pipe-intrusive complex.	Garner and others, 1979; Redfield, 1943; Sankaran, 1982.
	Southern Davis Mountains.	South of Alpine along both sides of State Highway 118. About lat 30°04′ N., long 103°33′ W.	U	Mineralization in lignite and reduced lacustrine limestone and tuff of the Tertiary Pruett Formation (Barnes, 1979).	Reeves and others, 1979.
	Christmas Mountains.	North of the Big Bend area, east of State Highway 118. About lat 29°28′ N., long 103°27′ W.	Fluorite, U, Mo, Hg	Replacements and open-space fillings in Cretaceous limestone and shale and in Tertiary rhyolitic intrusions.	Duex and Henry, 1980; Garner and others, 1979; McAnulty, 1972.
	Mariscal	Southernmost part of the Big Bend area. About lat 29°06′ N., long 103°11′ W.	Hg, fluorite	Deposits in caverns and fractured zones in Cretaceous limestone and shale and locally in fractured intrusive rocks.	Bailey, 1962; Sellards and Evans, 1946.
Brewster and Presidio.	Solitario	Southwestern Brewster and southwestern Presidio Counties. About lat 29°26′ N., long 103°47′ W.	Ag, Pb, Zn, Mo	Veins in Cretaceous Santa Elena Limestone (Maxwell and others, 1967) and in Tertiary rhyolites. Minor mineralization in a granitic intrusion underlying the Solitario.	Corry and others, 1977; Maxwell and others, 1967.
	Terlingua	Southwestern Brewster and southwestern Presidio Counties. In the vicinity of lat 29°20′ N., long 103°40′ W.	Hg, fluorite	Mineral deposits in Cretaceous Santa Elena Limestone (Maxwell and others, 1967), intruded by dikes, sills, and laccoliths of basaltic to rhyolitic composition.	Bailey, 1962; Maxwell and others, 1967; Yates and Thompson, 1959.
Culberson	Van Horn Mountains.	The western flank of the Van Horn Mountains along the county boundary. Lat 30°50′ N., long 104°52′ W.	Ag, Cu, feldspar, mica (muscovite, biotite).	Disseminated Ag and Cu deposits along bedding planes in sandstone within Permian Powwow Conglomerate Member of Hueco Limestone; mica and feldspar in Precambrian pegmatites.	Evans, 1975; Garner and others, 1979; Price, 1982; Sellards and Baker, 1934.
Jeff Davis	Medley	Southern Davis Mountains. About lat 30°32′ N., long 104°10′ W.	Kaolin, rutile	Kaolinite and minor pods of rutile in silicified Tertiary volcanic rocks.	Mark, 1963; Sellards and Baker, 1934.
Presidio	Infiernito	Northern Chinati Mountains. About lat 30°02′ N., long 104°21′ W.	Mo, Ag	Veins and stockwork veinlets in Tertiary quartz monzonite porphyry.	Price and Henry, 1982a.
	Pinto Canyon	Northern Chinati Mountains. About lat 30°02′ N., long 103°30′ W.	U	Mineralization in fracture zones in Tertiary rhyolitic intrusions.	Amsbury, 1958.
	Shafter	South edge of Chinati Mountains. About lat 29°49′ N., long 104°20′ W.	Ag, Pb, Zn, Mo, Cu, Au.	Mantos and minor veins in dolomitic limestones of Permian Mina Grande Formation. Porphyry Mo-Cu mineralization in quartz monzonite.	Evans, 1975; McKnight and others, 1962; Price and Henry, 1982b; Ross, 1943.
	West Chinati stock	Northwestern part of Chinati Mountains. About lat 30°29′ N., long 104°34′ W.	Ag, Pb, Zn, fluorite, Cu.	Veins in Tertiary intrusive rocks of the West Chinati stock.	Garner and others, 1979; McAnulty, 1972; Sellards and Evans, 1946.



EXPLANATION

OUTLINE OF MINERAL RESOURCE AREAS OF HENRY, PRICE, AND HUTCHINS (1983) APPROXIMATELY LOCATED--These areas generally enclose productive workings, and do not indicate the limits of mineralized rock, nor do they correspond to legal mining districts. Informal names are used for areas that have no formal name. Areas which contain only natural aggregate, dimension stone, and semi-precious or precious gemstones are not shown

FIGURE 15.—Mineral resource areas.

Some copper-zinc skarn is exposed at Red Hill (Price and Henry, 1982b), and molybdenite-bearing skarn crops out along the contact between the resurgent dome of the Infiernito caldera and Pennsylvanian sedimentary rocks. Molybdenum and uranium are commonly concentrated in fluorspar deposits associated with rhyolite intrusions in the Christmas Mountains (Duex and Henry, 1980).

URANIUM

Uranium occurrences, which are widely distributed throughout the Trans-Pecos region, generally can be related to uraniferous Tertiary volcanic source rocks. None of the occurrences in Brewster, Presidio, or Jeff Davis Counties have proven to be economically developable.

Exploration has been concentrated in and near three known deposits: (1) The Mammoth "mine" in western Presidio County immediately west of the Trans-Pecos region, where uranium occurs in cavities and fractures in the Buckshot Ignimbrite (Henry and others, 1980); (2) the Shely Prospect in Pinto Canyon in southwestern Presidio County, where uranium occurs along a fault in a shallow rhyolite intrusion (Henry and others, 1980); and (3) the Anderson Ranch Prospect in the southern Davis Mountains of northern Brewster County, where mineralization occurs in Tertiary lacustrine limestone, carbonaceous shale, and water-laid tuff (Reeves and others, 1979).

OTHER METALS

Occurrences of other metals in the Trans-Pecos region have not led to significant production. Manganese is widely distributed throughout the region as: (1) Manganese oxides along bedding planes and joints in Paleozoic chert, novaculite, and siliceous shale in the Marathon and Solitario uplifts; (2) veins and fracture fillings in Cretaceous limestone, Tertiary volcanic rocks, and Quaternary-Tertiary bolson fill in Presidio County; and (3) psilomelane plus barite along a Basin and Range normal fault of Miocene to Holocene age at the Mayfield Prospect in Jeff Davis County. Titanium (rutile) is associated with kaolinization and silicification of Tertiary volcanic rocks in the Medley area in the central Davis Mountains.

NONMETALLIC MINERAL RESOURCES

FLUORSPAR

Although fluorite occurrences are widespread throughout the Tertiary volcanic province (McAnulty, 1972), major fluorspar production in the Trans-Pecos region has come only from replacement deposits in Lower Cretaceous limestones near rhyolite intrusions in the Christmas Mountains (Daugherty, 1982). These deposits produced 63,000 Mg of ore (McAnulty, 1974).

MICA

Muscovite schist from the Precambrian Carrizo Mountain Group is being mined in the western Van Horn Mountains immediately west of the region outlined in figure 16. Muscovite and minor biotite are separated from quartz and feldspar. The mica is used as a drilling-fluid additive to prevent loss of circulation. Between 1920 and 1943, small quantities of muscovite were extracted from pegmatite veins in this area.

OTHER NONMETALS

Tertiary rhyolite and Cretaceous limestone are mined for crushed rock at several localities in the Trans-Pecos region. Sand and gravel operations are few because the region is sparsely populated and demand is minimal.

Other commodities that have been mined to a limited extent or that have been the object of detailed exploration include perlite in rhyolite intrusions southwest of Marfa, kaolin in hydrothermally altered rhyolite ash-flow tuffs in the Medley area west of Fort Davis, gem agate from intermediate to mafic flows south of Alpine, and zeolite in tuffaceous sedimentary rocks widely distributed in Presidio and Brewster Counties.

COAL, OIL, AND GAS RESOURCES

Bituminous coal occurs in Upper Cretaceous rocks at several localities in the Trans-Pecos region (Evans, 1974). Coal near Terlingua was mined in the 1930's and 1940's for fuel in mercury production. More recently, some Upper Cretaceous carbonaceous shale and impure coal was mined for agricultural uses as fertilizer and soil conditioner and for additives in oil-field drilling.

There is no current oil and gas production in the Trans-Pecos region. Exploration in Trans-Pecos is focused in two areas: (1) The Laramide overthrust belt of the Chihuahua trough (Pearson, 1980), and (2) the Marathon overthrust region (Pearson, 1978). Paleozoic host rocks that have considerable production immediately to the north of the region continue beneath the deformed Paleozoic rocks of the Marathon fold belt. Extensive drilling has occured recently in both the Marathon area and the Laramide belt; however, almost all data are proprietary.

GEOTHERMAL RESOURCES

Convective geothermal systems in Trans-Pecos Texas are potential resources (Henry, 1979; Henry and Gluck, 1981). The convective systems are characterized by hot springs that discharge along Basin and Range normal faults and by shallow hot wells. Geothermal gradients of about 40 °C/km have been measured in deep oil-test wells along the Rio Grande and in the Marathon region. Most water temperatures from thermal wells and springs are about 40 °C (Henry, Price, and McDowell, 1983); maximum temperatures of 70 and 72 °C have been measured in two wells west of the study area in the western slope of the Sierra Vieja.

The Mobil No. 1 Adams well, a deep well located along the Ouachita thrust belt a few miles southwest of Marathon in north-central Brewster County, had an original bottom-hole temperature of 153 °C at a total depth of 3,231 m (Woodruff and others, 1982). A chloride concentration of 350 mg/L was indicated by a drill-stem test at total depth in the Ordovician Ellenburger Limestone in this well (Woodruff and others, 1982).

None of the temperatures are high enough to generate electricity with present technology. In addition, the highest temperatures occur in areas of extremely sparse population where industrial or space-heating applications are currently (1984) unlikely. Several hot springs are or have been used as resorts, however.

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