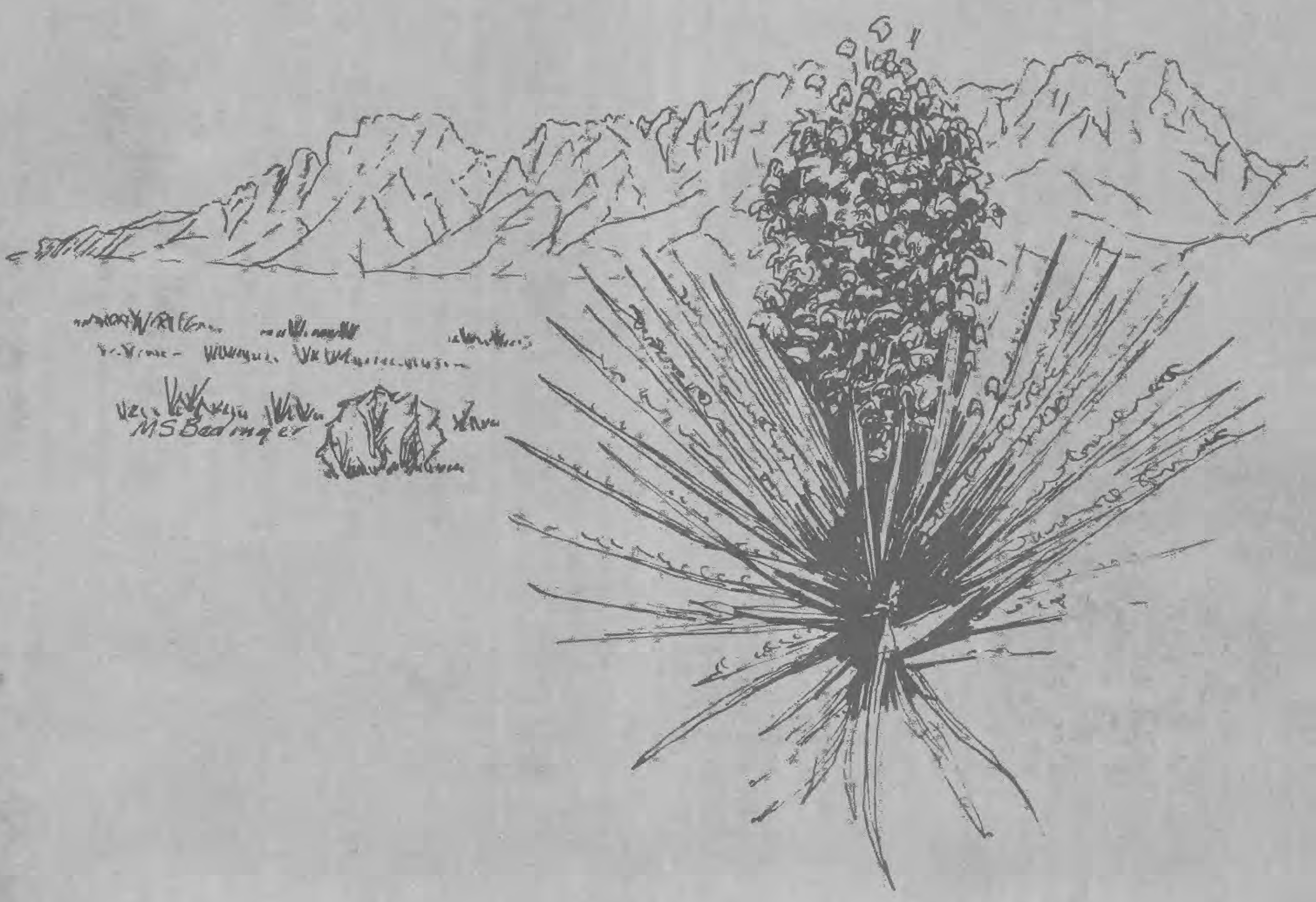
Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, For Isolation of High-Level Radioactive Waste—Characterization of the Rio Grande Region, New Mexico and Texas

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370-C

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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BASIN AND RANGE PROVINCE WORKING GROUP

U.S. Geological Survey Members

Chairman of the Province Working Group:
M.S. Bedinger
U.S. Geological Survey
Denver, CO

Member:
K.A. Sargent
U.S. Geological Survey
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)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
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	
megagram (Mg) or metric ton	1.102	short ton (2,000 lb)
	Temperature	
degree Celsius (°C)	9/5(°C)+32 = °F	degree Fahrenheit (°F)
	Chemical Concentrations	
milligram per liter (mg/L)	About 1	part per million (ppm)

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

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

ABSTRACT

The Rio Grande region, New Mexico and Texas, includes most of the area east of the Rio Grande to the Sacramento Mountains. The region encompasses two large basins, the Jornada del Muerto and Tularosa basins, and the intervening San Andres Mountains. The valley surfaces generally have altitudes from 600 to 1,500 meters, and the mountain ranges generally have altitudes from 1,500 to 2,400 meters. About one-half the area is underlain by basin fill.

Sedimentary rocks that crop out in the Rio Grande region range in age from Precambrian to Holocene. The oldest Precambrian rocks are metamorphosed and intruded by plutons. Paleozoic rocks are primarily carbonates, with argillaceous beds in the older Paleozoic units. Clastic and gypsum are in greater abundance in younger Paleozoic units of Pennsylvanian and Permian age. The Mesozoic rocks primarily are clastic rocks with some limestone. Cenozoic rocks consist of sequences of conglomerate, sandstone, mudstone, and siltstone, derived from adjacent mountain masses, interbedded with basalt and andesite flows and silicic tuffs. Early to middle Tertiary volcanic and tectonic processes resulted in the implacement of plutonic bodies; volcanic activity continued into the Quaternary.

Media considered to have potential for isolation of high-level radioactive waste include intrusive rocks, ash-flow tuff, and basaltic lava flows. Laharic and mudflow breccia and argillaceous beds also may be potential host rocks. These and other rocks may be potential media in areas where the unsaturated zone is thick.

Quaternary faults are more common in the southern one-half of the region than in the northern one-half. Range-bounding faults with evidence of Quaternary movement extend northward into the central part of the region. Volcanic activity in the northern part of the region includes basalt flows of Quaternary age. Historical crustal uplift and seismicity have occurred in the vicinity of Socorro, New Mexico. The region is bordered on the west by an area with heat flow greater than 2.5 heat-flow units, and a few measurements of this magnitude have been made within the region.

Recharge to ground water in the Rio Grande region occurs in the higher altitudes where precipitation is greater, that is, in the San Andres and Sacramento Mountains and on the Chupadera Mesa. Ground-water flows from units west of the San Andres Mountains discharge to the Rio Grande. The ground-water flow unit of the Tularosa basin ultimately discharges to the Rio Grande or to wells in the vicinity of El Paso. Intermediate discharge points in the Tularosa basin include seepage to streams and springs and evaporation to playas in the central part of the basin. Dissolved-solids concentrations in ground water in the region generally are more than 1,000 milligrams per liter, although the dissolved-solids concentrations in ground water in the recharge areas generally are less than 1,000 milligrams per liter. Dissolved-solids concentrations ranging from 3,000 to 25,000 milligrams per liter are found in the ground water underlying the playa area in the central part of the Tularosa basin.

More than 40 mining districts occur in the region; they contain base metals and, to a lesser extent, precious metals, in vein and replacement deposits. Four coal fields are located in the region. There has been no significant production of oil, gas, carbon dioxide, or helium in the region.

Manuscript approved for publication, January 10, 1985.

INTRODUCTION

By M.S. Bedinger, K.A. Sargent, and William D. Johnson, Jr.

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 was begun in May 1981, with the introduction of the study to the Governors of the eight Basin and Range States—Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, and Utah—and to 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 the 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 regions

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

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

The results of this study are not based on original data; no 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 published and unpublished data that are available. In parts of the region, inadequate data exist to characterize the area. In these places it was necessary to discuss the geologic or hydrologic characteristics in the vicinity of the region, and then project that data into the region.

This report, Chapter C, is one of six reports characterizing the geology and hydrology of the regions of study in the Basin and Range province. Chapter C 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 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.

GEOGRAPHIC SETTING

The Rio Grande region, as defined in this report (pl. 1), consists of a large area in the south-central New Mexico and the adjacent part of western Texas. This region includes the extensive Jornada del Muerto basin (fig. 1); the Tularosa Valley (fig. 2) and its southern extension, the Hueco Bolson of Texas, and the enclosing mountain ranges. The Malpais, an area of a Quaternary lava flow, occupies about 330 km^2 in the north-central part of the Tularosa Valley (fig. 3). The Rio Grande defines most of the western boundary of the region, but north of Las Cruces, N. Mex., the boundary extends southeastward from the river across the southern end of the Jornada del Muerto to the southern San Andres Mountains, and from there southward through the Organ and Franklin Mountains to rejoin the Rio Grande at El Paso, Tex. Southeastward from El Paso, the river forms the western boundary to the terminus of the region at the junction of the river valley and the southern end of the Quitman Mountains. The eastern boundary of the Rio Grande region extends northward from the Rio Grande valley generally along the crest of the Quitman and Malone Mountains, along the western flank of the Finlay Mountains, and through the Hueco Mountains into New Mexico. In New Mexico the eastern boundary

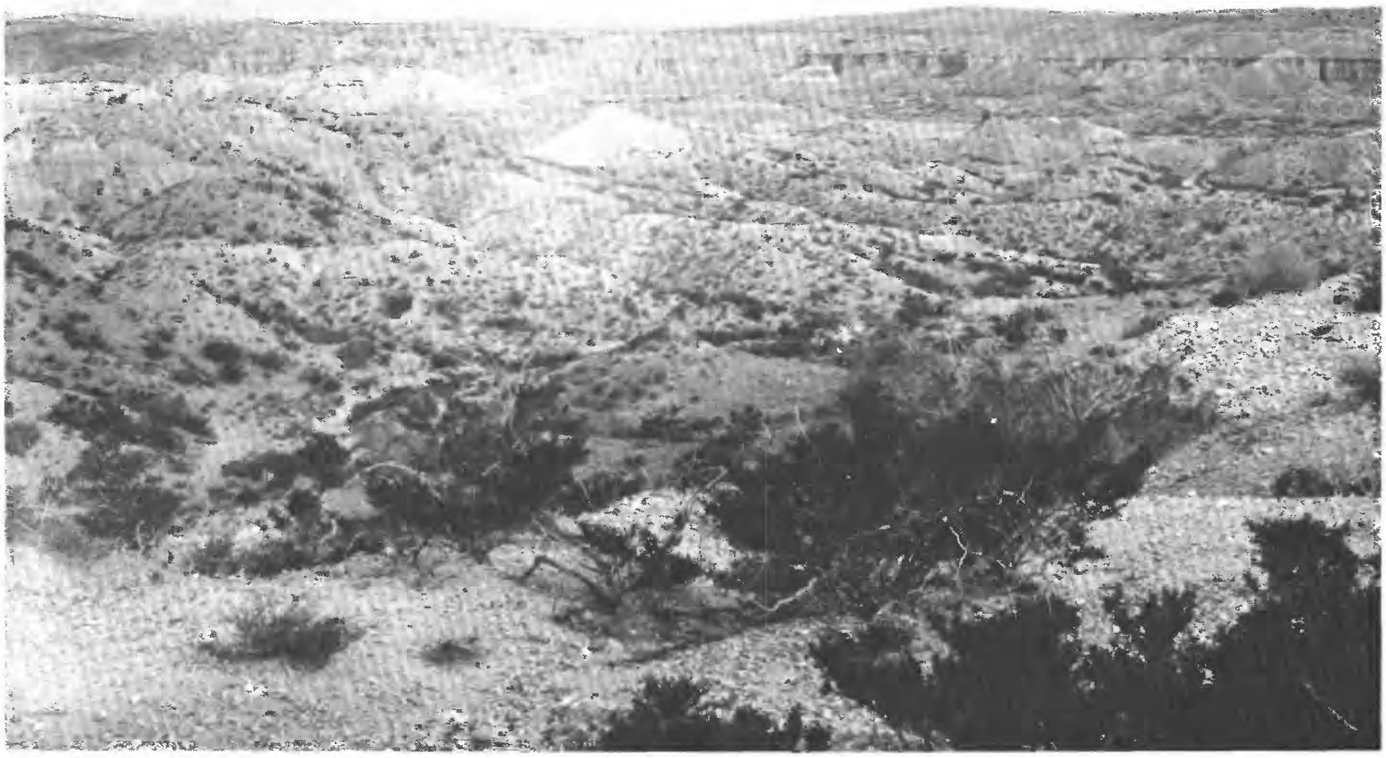

FIGURE 1.—Beds of the Santa Fe Group in the Jornada del Muerto Basin east of Socorro, N. Mex., looking south. Photograph by N.H. Darton, 1915.

is aligned from Otero Mesa on the south through the Sacramento Mountains, Sierra Blanca Peak, and Jicarilla Peak to Gallinas Peak on the north. The northern boundary of the region follows an arcuate line from the Gallinas Peak northwestward across the southern end of the Estancia basin to the southern end of the Manzano Mountains, and from there south-westward to the Rio Grande. Much of the Rio Grande region is divided by the south-trending alignment of Chupadera Mesa and the Oscura, San Andres, Organ, and Franklin Mountains into the Jornada del Muerto on the west and the Tularosa Valley and northern Hueco Bolson on the east. Geographic features are shown in figure 4.

The valley surfaces generally have altitudes from 600 to 1,500 m, and the mountain ranges generally have altitudes from 1,500 to 2,400 m; in places the mountains are higher than 2,900 m. About one-half of the area is underlain by basin fill.

ACKNOWLEDGMENTS

This report and the other 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. Frank E. Kottlowski of New Mexico, alternate member of the Province Group, contributed significantly to the regional phase of the study. 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;

FIGURE 2.—Tularosa Valley from the east showing the white gypsum sand of the playa in the middle distance and San Andres Mountains on the horizon. Photograph by R.T. Hill, circa 1899.

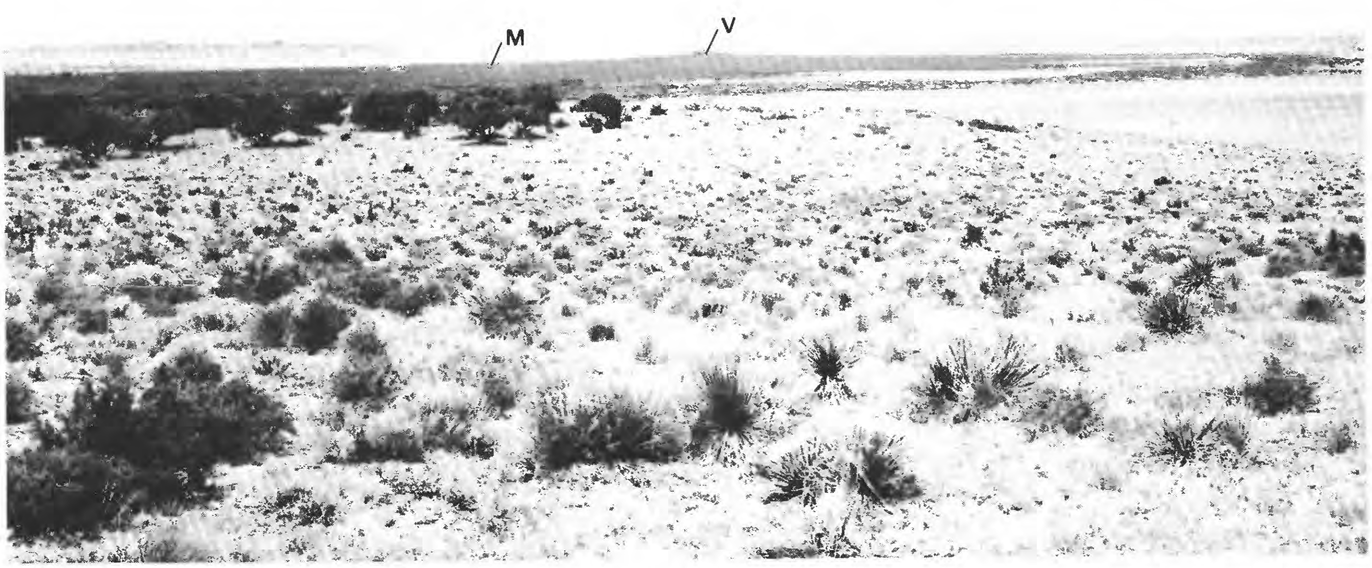

FIGURE 3.—The Malpais (M) in the middle background, a Quaternary volcanic flow in the north-central Tularosa Valley, showing vent (V). Photograph by R.T. Hill, circa 1899.

FIGURE 4.—Geographic index of the Rio Grande region and vicinity.

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.

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GEOLOGY

By WILLIAM D. JOHNSON, JR., JOHN W. HAWLEY[1], WILLIAM J. STONE[1], FRANK E. KOTTLOWSKI[1], CHRISTOPHER D. HENRY[2], and JONATHAN G. PRICE[2]

Many authors have contributed to an understanding of the geology, structure, volcanics, and tectonics of the Rio Grande region in south-central New Mexico and adjacent Trans-Pecos Texas, but in this brief synopsis of the geology and structure of the region, only a selected number of reports are cited in the text. In particular, we have relied on the summary report on Paleozoic and Mesozoic strata of south-central New Mexico by Kottlowski (1963a); on reports by William R. Seager, R.E. Clemons, and C.E. Chapin, particularly for data on the Tertiary volcanics and tectonism; and on the work of John W. Hawley on the Tertiary and Quaternary deposits and geomorphic history of the Rio Grande valley of New Mexico.

STRATIGRAPHY

Outcrops of sedimentary rocks within the Rio Grande region range in age from Precambrian to Holocene. Representative stratigraphic sections within the region are shown on plate 2. Cenozoic rocks consist of sequences of conglomerate, sandstone, mudstone, and siltstone, derived from adjacent mountain masses, interbedded with basalt and andesite flows and silicic tuffs. Bolson deposits fill the major basins to thicknesses possibly as great as 3,000 m near the New Mexico–Texas State line. Igneous activity in response to the early Tertiary Laramide orogeny and to middle Tertiary volcanic and tectonic processes resulted in the implacement of plutonic bodies, especially along the northeastern and southwestern margins and near the southern end of the region. Volcanic activity continued into the Quaternary.

PRECAMBRIAN ROCKS

Precambrian rocks, which have been described in south-central New Mexico by Condie and Budding (1979), crop out in the Franklin, Caballo, and Los Pinos Mountains, Fra Cristobal Range, Joyita Hills, and at San Diego Mountain, bordering the eastern side of the Rio Grande valley; on the flanks of the Organ, San Andres, and Oscura Mountains in the central part of the Rio Grande region; and in limited outcrops in the southern Hueco Mountains and adjacent hills in the southeastern part of the region (fig. 4).

The oldest Precambrian rocks are metamorphic rocks, mainly phyllite, schist, quartzite, and arkosite, and minor metaigneous and metavolcanic rocks and gneiss. These are intruded by plutons, 1,400–1,500 m.y. old, dominantly of quartz monzonite and granite; syenite composes a small intrusive body in the Sacramento Mountains. Locally, the plutons are cut by mafic dikes, probably of Tertiary age, although those in the Franklin Mountains probably are of Precambrian age. In the Franklin Mountains (fig. 4) which contain the most complete section of Precambrian rocks in the Rio Grande region of Texas (Harbour, 1972), the oldest rocks are limestone, hornfels, chert, and dolomite of the Castner Limestone. These are intruded by diabase sills and overlain by basalts of the Mundy Breccia. The thick Lanoria Quartzite overlies the older units and, in turn, is overlain by rhyolites of the Thunderbird Group (Thomann, 1981) which are ash-flow tuffs that are intruded by, but probably comagmatic with, the Red Bluff Granite (Thomann, 1981). The greatest thickness of Precambrian bedded rocks in the Rio Grande region is about 9,500 m in the central San Andres Mountains (Condie and Budding, 1979).

PALEOZOIC ROCKS

Paleozoic rocks, which overlie Precambrian rocks on a prominent unconformity, crop out in most mountain ranges in the New Mexico part of the Rio Grande region and in the Franklin, Hueco, Finlay, and Malone Mountains in Texas. The sequence is characterized primarily by marine carbonate rocks in the older geologic units and by a progressive increase in the abundance of clastic rocks and gypsum from Pennsylvanian into Permian beds. Deposition was centered in the Orogrande basin, which opened to the south-southwest and generally coincided with the present Tularosa and Hueco Basins. Paleozoic sedimentary rocks near El Paso have a thickness in excess of 2,400 m (Kottlowski, 1963a).

The Bliss Sandstone of latest Cambrian and Early Ordovician age, the initial deposit of the Paleozoic sequence, is quartz sandstone, in part glauconitic, containing thin interbeds of siliceous and oolitic hematite, shale, and limestone. It was deposited in a shallow, encroaching sea. The Bliss is missing across the northern part of the Rio Grande region owing to erosion largely

[1]New Mexico Bureau of Mines and Mineral Resources.
[2]Texas Bureau of Economic Geology.

during Early Pennsylvanian time but perhaps also to erosion during several early Paleozoic intervals. The Bliss has a maximum thickness of 110 m in Texas in the southern Hueco Mountains (Beard, 1983). Overlying the Bliss are the silty limestones of the El Paso Group of Early Ordovician age. The limestones are varied and have been erratically and irregularly dolomitized. The lower beds include arenaceous limestones and interbeds of micaceous and glauconitic sandstone, which are gradational downward into the Bliss. The El Paso thins across the region from a maximum of 485 m in the Franklin Mountains (Cloud and Barnes, 1946), northward to zero thickness in southern Socorro, extreme southwestern Lincoln, and northwestern Otero Counties, N. Mex., and southeastward to zero thickness in southern El Paso and western Hudspeth Counties, Tex., due to pre-Montoya and Devonian, Pennsylvanian, and Permian erosion. Because of differential erosion, the uppermost beds of the El Paso Group are progressively younger from north to south.

Disconformably overlying the El Paso Group are limestone, dolomite, and sandstone of the Montoya Group of Middle and Late Ordovician age. Except for the basal sandstones, the Montoya apparently was deposited as a limestone but has since been irregularly dolomitized. About 50 percent of the group is limestone in the Hueco Mountains in the southeastern part of the Rio Grande region; elsewhere, dolomite predominates. The Montoya is divided into various formations in southern New Mexico (pl. 2). In the Sacramento Mountains, however, beds in this part of the section are divided into the Montoya Formation and overlying Valmont Dolomite; these two units are correlative with the four formations of the Montoya Group elsewhere in the region. The basal Cable Canyon Sandstone of the Montoya Group has a thickness of about 10 m in central Sierra County but is missing in the southern part of the Rio Grande region. The Upham Dolomite, which overlies the Cable Canyon, has a basal arenaceous phase that is laterally and vertically gradational from the sandstone. Generally, the dolomites of the Montoya Group are not porous, but locally the Cable Canyon Sandstone and the basal part of the Upham are porous. In the Rio Grande region, the Montoya ranges from zero thickness in southern Socorro and northwestern Otero Counties, N. Mex., and southern El Paso and western Hudspeth Counties, Tex., as a result of pre-Silurian, Devonian, Pennsylvanian, and Permian erosion, to more than 150 m in southern Otero County, N. Mex., and northwestern Hudspeth County, Tex.

The Fusselman Dolomite of Silurian age is aphanitic to coarsely crystalline and locally has well-developed secondary porosity. In the Rio Grande region, the Fusselman thins northward in a remarkedly uniform pattern beneath the pre-Devonian unconformity and is absent north of the central part of the San Andres Mountains. In the southeastern part of the region, distribution of the formation is restricted by pre-Wolfcampian (Early Permian) erosion. The maximum thickness of 195 m is in the Franklin Mountains (Harbour, 1972).

With the onset of the Devonian, sedimentation in the region underwent a pronounced change from a carbonate to an argillaceous regime. The Devonian sequence is a relatively thin, but widespread, blanket of fossiliferous, lithified, calcareous mud that overlaps older Paleozoic beds. The Devonian beds, divided into as many as five formations (pl. 2), comprise three rather distinct facies that occur in east-trending belts across the Rio Grande region (Kottlowski, 1963a). The southern belt, which contains the oldest Devonian rocks, consists of cherty limestone of late Middle Devonian age (Harbour, 1972) overlain by sandy siltsone and black fissile shale. The middle belt is dark-gray to black fissile shale equivalent to the lower part of the widespread Percha Shale, which comprises most of the Devonian section west of the Rio Grande. On the north, a silty facies of latest Middle and Late Devonian age includes limy and dolomitic siltstone, silty shale, and silty limestone. The northern extent of Devonian beds is limited across northern Sierra and Otero Counties, N. Mex., by pre-Pennsylvanian and pre-Permian unconformities. Devonian strata may be missing locally in the extreme southeastern part of the region due to pre-Permian erosion. In the Jarilla Mountains area of the Tularosa basin in southwestern Otero County, N. Mex., the Devonian is thin or absent due to pre-Mississippian erosion. Devonian strata generally range in thickness from 0 to 470 m, but in a local depositional basin in southeastern Doña Ana County, N. Mex., they are as much as 670 m thick.

Mississippian rocks in the Rio Grande region are more widespread than any of the older Paleozoic units. They extend as far north as central Socorro County, N. Mex., although Mississippian strata are missing throughout much of central Sierra County, and in north-central and southwestern Otero County, N. Mex. The oldest rocks, the Caballero Formation of Kinderhookian age, are interbedded limy clastics, mainly shale, siltstone, and silty limestone, which were deposited in a narrow east-trending basin across the middle of the region. The overlying Lake Valley Limestone of Osagean age, which comprises most of the Mississippian of the region, is a series of crinoidal, bioclastic, cherty limestone, shale, and some siltstone. In all except the basal part, the limestone commonly contains extensive biohermal structures. Because of extensive and irregular erosion after deposition of the Lake Valley, the formation is thickest in the Sacramento and central San Andres Mountains, and is missing to the south in the Franklin and Hueco Mountains, and throughout much of the northern and northwestern parts of the region. Throughout much of the southern part of the region, the noncherty to slightly cherty limestones of the Las Cruces Formation (Osagean and Meramecian) (Harbour, 1972) overlie and fill deep erosional depressions in the Lake Valley or rest on the post-Devonian unconformity. The Las Cruces, however, is missing in and south of the Hueco Mountains. Where the Lake Valley is not deeply eroded, the Las Cruces is thin or missing, and the Rancheria Formation (Meramecian and Chesterian) rests directly on the Lake Valley. The Rancheria Formation was deposited throughout most of the southern one-half of the Rio Grande region and is thickest in the Franklin Mountains. The formation is mainly black, cherty, silty to sandy limestone, and locally massive, crinoidal limestone, and minor siltstone and shale lenses. The uppermost Mississippian rocks are those of the Helms Formation of Chesterian age, composed of calcareous shale, limy sandstone, and argillaceous and oolithic limestone deposited in a shallow-marine environment. The Helms occurs in an east-trending belt that approximately coincides with that of the underlying Rancheria. Both formations are missing in the area around the Jarilla Mountains. Regionally, Mississippian rocks thicken southwestward across New Mexico and are more than 610 m thick in the southwestern corner of the State (LeMone and others, 1983). In the Rio Grande region, they reach a maximum thickness of about 230 m in southwestern Otero County, N. Mex., along the axis of the Orogrande basin (LeMone and others, 1983). Pre-Permian erosion removed Mississippian strata from the southernmost part of the region.

Erosion during latest Mississippian and earliest Pennsylvanian time resulted in a pronounced disconformity or angular unconformity between Precambrian to Upper Mississippian rocks. Depositional environments during the Pennsylvanian were markedly affected by their tectonic positions relative to subsiding basins and rising uplifts (Armstrong and others, 1979). The Pedernal uplift, which rose during late Paleozoic time, probably extended from the vicinity of the Texas State line in Otero County, N. Mex., northward through Lincoln and Torrance Counties, N. Mex., and supplied clastic sediments to basins within or close to the Rio Grande region. The largest and deepest basin, filled with more than 990 m of Pennsylvanian sediments (Kottlowski, 1963a), was the Orogrande. The San Mateo and Lucero basins in southwestern and central Socorro County, respectively, accumulated about 825 m of Pennsylvanian sediments (Kottlowski, 1963b), and the Estancia basin, which is just north of the Rio Grande region, contains even thicker Pennsylvanian deposits. The Lower and Middle Pennsylvanian sequences are largely normal-marine, stable-shelf limestone throughout much of the southern part of the region, and grade northward into interbedded calcareous shale and fossiliferous limestone west of the Pedernal uplift. In Late Pennsylvanian time, clastics shed from the uplift became more abundant, and wedges of arkosic and feldspathic sandstones extended westward as much as 97 km from the mountain mass. Several thick gypsum beds were deposited in the upper part of the Pennsylvanian sequence in the southern part of the Orogrande basin. The Pennsylvanian strata recorded cyclical changes in environments of deposition—a distinctive feature of upper Paleozoic strata throughout the United States. The Pennsylvanian units in various mountain ranges of the Rio Grande region are shown on plate 2.

Pennsylvanian and Lower Permian beds have been assigned to the Magdalena Group or Formation throughout most of the Rio Grande region, but more recently, in the Los Pinos Mountains (Myers and others, 1984) and northward in the Manzano Mountains (Myers, 1973), Atokan (basal Pennsylvanian) rocks are assigned to the Sandia Formation, and the remaining Pennsylvanian strata and the Lower Permian beds below the Abo Formation constitute the Madera Group.

To the south in the San Andres–Organ Mountains the Lower and Middle Pennsylvanian strata are mostly carbonate rocks of the Lead Camp Limestone (Bachman and Myers, 1969). The basal part of the Lead Camp grades northward into the sandstone and shale typical of the Sandia Formation. Rocks of similar age in the Sacramento Mountains have been given local geologic names (Pray, 1961) (pl. 2). The great thickness of terrigenous clastic rocks, as much as 610 m, deposited as deltaic sediments in the Orogrande basin and in the smaller San Mateo and Lucero basins mostly from the Pedernal uplift during the Late Pennsylvanian (Virgilian) and Early Permian (Wolfcampian), are included in the Panther Seep Formation, which crops out from the northern San Andres Mountains southward to the Franklin Mountains and on the eastern side of the region in the Hueco Mountains. Interbedded with the clastic rocks are shallow-water marine limestone, black carbonaceous shale deposited under anaerobic conditions, and in the upper part, beds of gypsum resulting from a shallow-water hypersaline environment. The depositional environment of the Late Pennsylvanian persisted into the Early Permian, and beds of the Panther Seep generally are transitional into the interbedded Lower Permian marine limestones and red beds of the Bursum and Hueco Formations. Locally, in the San Andres mountains, however, the basal part of the Bursum indicates cut-and-fill deposition on the Panther Seep (Kottlowski, 1975).

The Orogrande basin, which persisted throughout the Early Permian, was open to the south, was deepest in southeastern Doña Ana and adjacent Otero Counties, N. Mex., and was surrounded by broad shelf areas, particularly on the northeast and southeast. The Bursum and Hueco Formations contain both shelf deposits, including locally thick bioherms, and laterally equivalent basinal facies of silty limestone, sandstone, black shale, and porcellanite, which thickens southward in the basin. Overlying and interfingering with these formations are the widespread terrigenous, clastic red beds of the Abo Formation. In the northeastern part of the Rio Grande region, in the Gallinas and northern Sacramento Mountains, the Abo Formation lies with pronounced unconformity on rocks as old as Precambrian; in the Los Pinos Mountains and several other mountain ranges near the Rio Grande valley, however, the contact between the Bursum Formation and the overlying Abo is without conspicuous unconformity. Southward-thinning wedges of Abo sediments intertongue with marine shale and limestone of the Hueco in cyclic succession. The Abo locally is 300–425 m thick in mountain ranges along the northern and western boundaries of the region. In the Hueco Mountains, a westward-thinning wedge of coarse clastic rocks, derived from the southern part of the Pedernal uplift, occurs in the basal Hueco Formation. It grades upward into marine beds deposited in a shoal environment on the western side of the Diablo platform (Jordon, 1975), which was in the general area of the present-day Diablo Plateau in Trans-Pecos Texas.

Gradational above the Abo are the friable, in part feldspathic, sandstone, siltstone, argillaceous limestone, and gypsum beds of the Yeso Formation of Leonardian (late Early Permian) age. In a well west of Jicarilla Peak near the Lincoln-Socorro County line, N. Mex., the Yeso, 1,400 m thick, contains 275 m of salt. In the northeastern part of the Rio Grande region the Glorieta Sandstone, as much as 94 m thick, overlies the Yeso Formation. Southward the Glorieta Sandstone wedges out, and fossiliferous, petroliferous limestone, and in places thick beds of sandstone and siltstone, of the San Andres Limestone (Leonardian) rest directly on the Yeso. Thick beds of gypsum occur in the lower part of the San Andres Formation in central Socorro County, N. Mex. Leonardian strata in the southernmost part of the Rio Grande region in Texas are represented by about 510 m of marlstone, limestone, and conglomerate in the Finlay Mountains, and in the nearby Malone Mountains by a markedly different sequence, mostly of gypsum (Albritton and Smith, 1965). In the Rio Grande region the youngest Permian strata, of probable Guadalupian age, are assigned to the Bernal Formation, and its equivalent, the Artesia Formation. The Bernal, which rests on the eroded, karsted surface of the San Andres Limestone throughout a limited area in southwestern Lincoln County and adjacent parts of Socorro County, N. Mex. (Smith, 1964), consists of about 60–107 m of mainly red, limy sandstone and some shale. Post-Permian erosion has greatly affected the thickness and distribution of Permian units in south-central New Mexico and adjacent Trans-Pecos Texas. The greatest thickness of Permian strata, probably about 1,830 m, appears to be in southwestern Lincoln County, N. Mex.

MESOZOIC ROCKS

Mesozoic rocks in the Rio Grande region are represented by scattered Triassic outcrops in the northern part, by very limited Jurassic strata in the Malone Mountains of Trans-Pecos Texas, and by widespread Cretaceous sediments. Mesozoic sedimentation centered in the deep Chihuahua trough of northern Mexico, which extended at least as far north as the El Paso area. The northeastern limb of the trough generally followed a line from El Paso to the Quitman Mountains and was bordered on the east by the Diablo platform.

Triassic strata are restricted by pre-Cretaceous erosion to the northwestern and northeastern parts of the Rio Grande region. The Dockum Formation or Group, primarily of reddish, calcareous, micaceous claystone and siltstone, containing laminae of feldspathic sandstone and beds of fine-grained sandstone, is about 150 m thick in the area east of Socorro but only about 15–30 m thick in the northern San Andres Mountains. In the area around Jicarilla Peak, Triassic strata of the Dockum Group consist of the crossbedded sandstone and pebble conglomerate of the Santa Rosa Sandstone about 45–75 m thick, and the overlying Chinle Formation, 60–120 m thick, of siltstone, mudstone, and claystone, and lenses of sandstone and limestone-pebble conglomerate (Budding, 1964; Smith, 1964).

Upper Jurassic beds in the Malone Mountains (Albritton and Smith, 1965), assigned to the Malone Formation, lie on Permian rocks with angular unconformity. The Malone consists of a lower member of sandstone, siltstone, shale, and conglomerate, and an upper member of limestone, which together are about 120–300 m thick. The Jurassic sedimentary rocks are allochthonous rocks that have been transported as much as 80 km from the southwest.

In the Malone Mountains, Lower Cretaceous beds rest conformably on Jurassic rocks, but in outcrops elsewhere in the Rio Grande region, Cretaceous strata are unconformable on older rocks. The thickest sequence of Cretaceous rocks in the region, about 4,260 m, occurs in the southern Quitman Mountains (Jones and Reaser, 1970), and about 80 percent of the sequence is Lower Cretaceous strata. Both the total Cretaceous section and individual formations (pl. 2) thicken substantially from the Diablo Plateau westward into the former Chihuahua trough along the Rio Grande valley. The Lower Cretaceous rocks in the Quitman Mountains are dominantly massive sandstone and conglomerate and thin-bedded to massive limestone, deposited in environments ranging from nonmarine coastal plain to marine carbonate-shelf or platform shelf-margin. The Upper Cretaceous strata in the Quitman Mountains consist of about 800 m of fissile shale, containing some marly limestone and sandstone in the basal part. To the north in the vicinity of El Paso, more that 1,500 m of Cretaceous beds have been penetrated in the subsurface of the Hueco bolson (Uphoff, 1978).

In the New Mexico part of the Rio Grande region, Cretaceous strata are largely of Late Cretaceous age, although the late Early Cretaceous Sarten Sandstone occurs throughout much of western Doña Ana County, where it has been mapped with the Dakota Sandstone of early Late Cretaceous age. Upper Cretaceous strata crop out in a narrow area extending from central Socorro County southward across Sierra County into western Doña Ana County, largely within the Jornada del Muerto, but have been removed from most mountain ranges within the area. In addition, Upper Cretaceous rocks are preserved in a small area centered on southwestern Lincoln County. The basal Upper Cretaceous rocks are sandstone and some shale and siltstone, and have generally been assigned to the Dakota Sandstone. About 79 m of the Sarten and Dakota Sandstones occur in the southern San Andres Mountains (Seager, 1981).

The Mancos Shale overlies and in places intertongues with the upper part of the Dakota Sandstone. The Mancos is divided into lower and upper marine shale units by the intertonguing Tres Hermanos Formation (Hook and others, 1983), consisting of upper and lower marine sandstones separated by a medial unit of marine to nonmarine shale and sandstone. The Tres Hermanos is 85 m thick (Hook and others, 1983) southeast of Socorro in the northern Jornada del Muerto and about 60 m thick to the southwest in the Caballo Mountains (Molenaar, 1983a). The combined thickness of the Mancos Shale (lower unit) and the Tres Hermanos Formation is as much as 345 m near the Joyita Hills (Molenaar, 1983a).

The upper shale unit of the Mancos, the D-Cross Tongue of the Mancos, grades upward into or intertongues with the Gallup Sandstone, the basal formation of the Mesaverde Group, in the northern part of the Jornada del Muerto, in the Caballo Mountains (Molenaar, 1983a) and probably in the southern San Andres Mountains (Seager, 1981). In other parts of the Rio Grande region sandstone tongues mapped in the basal Mesaverde also may be correlative with the Gallup. The Gallup Sandstone is a thin, but widespread, regressive marine and nonmarine sequence that has been studied in detail by Molenaar (1973, 1974, 1983a, b). It is overlain by the Crevasse Canyon Formation of the Mesaverde Group, a nonmarine sequence dominantly of sandstone and lesser shale, siltstone, and some local coal beds. In the Rio Grande region the greatest thickness of Mesaverde strata, about 762 m, is in the Caballo Mountains (Kelley and Silver, 1952). In the structural low between the Caballo Mountains and the Fra Cristobal Range, the Mesaverde is overlain by possibly as much as 1,000 m of nonmarine clastic rocks and abundant volcanic debris of the McRae Formation. Late Cretaceous fossils have been collected from the lower part of the McRae, but the exact age of the upper part is uncertain.

CENOZOIC ROCKS

Tectonic instability, expressed by the increasingly greater proportions of clastic rocks and volcanic debris deposited in the basinal areas of the Rio Grande region towards the end of the Cretaceous, culminated in the early Tertiary with uplift, igneous activity, and deep erosion of Laramide mountain masses.

Lower Cenozoic deposits, commonly hundreds of meters of boulder conglomerate and interbedded siltstone, sandstone, and mudstone, rest on steeply tilted and deeply eroded Mesozoic and Paleozoic beds, and in places even on the Precambrian. These clastics were deposited in basins adjacent to rising Laramide uplifts in the area of the present Rio Grande rift (Chapin and Seager, 1975; Cather and Johnson, 1984; Seager, 1983b). In the middle Cenozoic, volcanic calderas, such as in the Organ, Doña Ana, and Quitman Mountains within the Rio Grande region, and the large volcanic and tectonic depression in the Goodsight Mountains–Cedar Hills area, just west of the region (fig. 4), contributed thick piles of mostly andesitic volcaniclastic rocks, andesitic, rhyolitic, and trachyitic lava flows as much as 60 m thick, and laharic breccias. The volcanic debris grades into finer clastic rocks in more distant parts of adjoining basins. Commonly, the volcanic rocks buried older Tertiary clastic rocks. Upper Cenozoic clastic and volcanic deposits, as much as several thousand meters thick, were deposited in deep structural basins of the Rio Grande rift that began to form in Late Oligocene and Early Miocene time (Chapin, 1979). Cenozoic deposits are designated by many different names, with stratigraphic nomenclature evolving as more field studies are completed (pl. 2).

LOWER AND MIDDLE TERTIARY CLASTIC AND VOLCANIC ROCKS

The thick sequence of lower to upper Cenozoic rocks deposited in the Laramide and Rio Grande rift basins is well represented in the Rincon Hills area (pl. 2) by about 1,340 m of volcanic and volcaniclastic rocks and fanglomerate of Eocene and Oligocene age. The basal deposit, the Love Ranch Formation, consists of conglomerate, composed of cobbles and boulders of Paleozoic limestone, in a matrix of sandstone and mudstone. The overlying thick, cyclic sequence of tuffaceous mudstone and siltstone, boulder-cobble conglomerate, and andesitic-plagioclase sandstone, and locally freshwater limestone and travertine deposits, constitute the Palm Park Formation (Kelley and Silver, 1952). The lithologic assemblage indicates spring, stream, floodplain, and possible mudflow deposition on piedmont slopes draining andesitic volcanic highlands (Seager and Hawley, 1973). Laharic breccia, containing clasts of andesitic rocks, is conspicuous to the southeast on the flanks of the Doña Ana Mountains at the southern end of the Jornada del Muerto (Seager and others, 1976).

Unconformably overlying the Palm Park is the Thurman Formation (Kelley and Silver, 1952) of Oligocene to early Miocene age. The lower one-half of the Thurman consists of andesite-cobble conglomerate, tuffaceous sandstone, mudstone, and air-fall and ash-flow tuffs. Above, and in part, intertonguing with the clastic rocks is about 122 m of basaltic andesite flows of the Uvas Basaltic Andesite (26 m.y. old) (Clemons and Seager, 1973). To the south, the Uvas fills the volcanic and tectonic depression in the Goodsight Mountains–Cedar Hills area (fig. 4). Above the Uvas, the upper part of the Thurman is interbedded tuffaceous sandstone and claystone containing scattered cobbles and pebbles of volcanic and igneous rocks. The Thurman grades upward into the basal Santa Fe Group and probably represents deposition in a broad, alluvial plain which occasionally was covered by shallow lakes (Seager and Hawley, 1973).

MIDDLE TERTIARY VOLCANIC AND PLUTONIC ROCKS

Volcanic activity in the Organ Mountains area, described in detail by Seager (1973, 1981), began in the late Eocene, extending into the early Miocene, and peaked in the Oligocene, resulting in a sequence of tuffs and lava flows more than 3 km thick (pl. 2). The lower 610 m of the volcanic rocks are mostly andesitic to dacitic; the upper 2,745 m, which were erupted during the Oligocene, are mostly rhyolitic. The rhyolitic sequence is comagmatic with the Organ batholith, which includes three phases of plutonic rocks: the oldest, quartz monzonite; quartz monzonite porphyry of intermediate age; and the youngest, granite.

In the Doña Ana Mountains area, Tertiary volcanic and plutonic rocks record two episodes of volcanic and plutonic activity, which were synchronous with events in the nearby Organ Mountains (Seager and others, 1976). Andesite porphyry was intruded in the late Eocene, and lava flows and volcanic debris formed an epiclastic apron on the flanks of the volcanic centers. Eruption of at least 762 m of ash-flow tuffs and the accompanying collapse of the Doña Ana cauldron occurred during the Oligocene. Continuing volcanic activity and sedimentation within the cauldron resulted in an additional 335 m or more of rhyolitic to andesitic sedimentary rocks, tuff, and breccia. In the final phases of volcanism the area was intruded by dikes of monzonite porphyry and some basaltic andesite and basalt.

The Quitman Mountains caldera, which formed about 36 m.y. ago (McDowell, 1979), was filled with 1,065 m of rhyolitic to trachytic lava flows and ash-flow tuff, and subsequently, intruded by a pluton and ring dike composed mainly of quartz monzonite and some granodiorite (Albritton and Smith, 1965).

Intrusive bodies also form a series of prominent stocks, domed plugs, and laccoliths in the northeastern part of the Rio Grande region extending from Sierra Blanca Peak on the south to the Gallinas Peak area on the north (Perhac, 1970). Additional intrusive bodies occur in the northern San Andres and adjacent Oscura Mountains, in the Jarilla Mountains in the Tularosa Valley, and southward along the eastern side of the region in the Hueco and northern Quitman Mountains. A considerable range in composition is represented, from alkali syenite and porphyritic trachyte through monzonite to gabbro.

UPPER TERTIARY AND QUATERNARY CLASTIC AND VOLCANIC ROCKS

In the various intermontane basins along the Rio Grande rift in south-central New Mexico and Trans-Pecos Texas, the bolson deposits, above the top of the Thurman and equivalent formations, are included in the Santa Fe Group. The upper limit of the Santa Fe is placed at the top of the youngest basin-fill predating the initial entrenchment of the Rio Grande valley. Thus, the group ranges in age from early(?) Miocene to middle Pleistocene. The Santa Fe has been divided into variously named formations, depending largely on the location of the type localities within the rift. For detailed discussion of the lithology and nomenclature of the Santa Fe Group, the reader is referred to Strain (1966), Hawley (1975, 1978), Hawley and Kottlowski (1969), Hawley and others (1969), Chapin and Seager (1975), Seager and Hawley (1973), and Gile and others (1981).

In the Rincon Hills (Seager and Hawley, 1973), at least 1,105 m of mainly locally derived clastic rocks of the Santa Fe Group are exposed and are included in four formations (pl. 2), of which all except the upper one are of Tertiary age. The basal unnamed unit of the Santa

Fe consists of conglomeratic sandstone, mudstone, and conglomerate of fluvial origin. The base of the unit is marked by the first appearance of conglomerate or conglomeratic sandstone above the white tuffaceous sandstone of the upper part of the Thurman Formation. The overlying Hayner Ranch Formation forms a resistant unit, in the lower part composed of interbedded conglomeratic sandstone, mudstone, sandstone, and conglomerate, characterized by conspicuous cobbles and boulders of Uvas Basaltic Andesite and ash-flow tuff cobbles. Lithologies in the upper part of the Hayner Ranch are similar to those in the lower part, but thick beds of conglomerate are missing, and pebbles and cobbles of granite, chert, and limestone supplement the volcaniclastic rocks.

In the Rincon Hills the Rincon Valley Formation (Seager and Hawley, 1973) is locally conformable on the Hayner Ranch, but elsewhere along the Rio Grande valley in this part of New Mexico, the Rincon Valley Formation rests with angular discordance on faulted, older Santa Fe beds and on strata as old as the Palm Park Formation. Where the base is conformable, the Rincon Valley consists of a gypsiferous basin-floor facies of laminated to thin-bedded slightly conglomeratic siltstone, sandstone, claystone, and gypsum. Where the formation overlaps older beds, fanglomerate constitutes the unit, and it coarsens and thickens in the direction of greater angular discordance. The fanglomerate consists of massive, poorly stratified pebbles, cobbles, and boulders of Paleozoic limestone and sandstone and, to a lesser extent, volcanic rocks. Both facies of the Rincon Valley are separated from the overlying Camp Rice Formation by a major unconformity of regional extent. The Rincon Valley is probably late Miocene and Pliocene in age. To the south in the Cedar Hills area (fig. 4), the lower part of the formation contains a basalt flow dated at 9 m.y. (Seager and others, 1975, 1984).

In the southern part of the Jornada del Muerto, the Santa Fe strata are more than 305 m thick and consist of basin-floor deposits of gypsiferous lake beds(?) (Doty, 1963) overlain by fluvial deposits of the ancestral Rio Grande. The latter facies forms most of the Camp Rice Formation (Pliocene to middle Pleistocene) (Seager and Hawley, 1973), which is the upper unit of the Santa Fe Group. To the north in the central part of the Jornada del Muerto, the floor of the basin is not a graded surface sloping gently to the south but is divided into several subbasins; within those subbasins Santa Fe beds generally are thin or absent (Kelley and Silver, 1952). At the northern end of the Jornada del Muerto basin, the Santa Fe Group is at least 610 m thick (Weir, 1965); in that area post–Santa Fe deposits include lake beds and basalt flows.

In the Tularosa basin the sediments of the Santa Fe are predominantly clay and silt and much gypsum, which intertongue with wedges of alluvial-fan deposits along the basin margins. This basin merges southward with the Hueco bolson near the Texas–New Mexico State line. Kottlowski (1955) records a thickness of 244–1,494 m of Santa Fe beds in the Tularosa basin. Santa Fe strata of Tertiary age in the Hueco bolson of Trans-Pecos Texas are represented by the Fort Hancock Formation (Pliocene and possibly lower Pleistocene) and unnamed Miocene deposits. The northern part of the Hueco bolson contains about 2,750 m of upper Cenozoic fill in a structural depression adjacent to the Franklin Mountains. The Fort Hancock, named and described by Strain (1966, 1969), represents deposition in a closed basin periodically occupied by large lakes. The formation is mainly composed of claystone, siltstone, silt, sand, and gypsum, and these basin-floor facies intertongue laterally with alluvial-fan deposits. The Fort Hancock is overlain by Camp Rice Formation also originally described by Strain (1966). The contact between the two formations, dated about 2–2.5 m.y. (Gile and others, 1981, their table 7 and fig. 8), is partly disconformable and partly gradational.

Pliocene to middle Quaternary deposits in the Rio Grande region mainly represent continued fluvial aggradation in the intermontane basins associated with the Rio Grande rift system and culmination of Santa Fe Group deposition (Hawley and others, 1969, 1976). Gravel, sand, and silt, contributed both by the ancestral Rio Grande and by erosion of nearby mountains, were deposited on broad, basin floors under both fluvial and lacustrine conditions. Alluvial fans and rock-pediments developed on the flanks of the mountains and coalesced to form broad, piedmont alluvial slopes. On the lower parts of these slopes the alluvium intertongued with and overlapped the sediments on the basin floors. The major stratigraphic unit, in terms of areal extent, thickness, and age span, is the Camp Rice Formation. Deposition of the Camp Rice terminated with the onset of entrenchment of the Rio Grande valley in the middle Pleistocene. Integration of the upstream and downstream reaches of the Rio Grande and establishment of through-flowing drainage to the Gulf of Mexico was the apparent cause of valley incision. Prior to integration, the upstream reach of the Rio Grande flowed into large lakes in northern Mexico and westernmost Texas (Strain, 1966; Hawley and Kottlowski, 1969). The Camp Rice has a maximum measured thickness of 100 m in the vicinity of San Diego Mountain (Seager and others, 1971) but probably is at least 200 m thick to the south in the Mesilla bolson, west of the Organ and Franklin Mountains.

The post–Camp Rice fill in the Rio Grande valley primarily is alluvial-fan and terrace deposits that have been eroded into a number of erosional surfaces representing major intervals of valley entrenchment and partial backfilling. In places, the present Rio Grande valley floor lies as much as 150 m below relict constructional surfaces on Camp Rice strata (Gile and others, 1981). Alluvial deposits in the present flood plain have a maximum thickness of about 24 m.

In those internally drained basins, such as the Tularosa and much of the Jornada del Muerto, that are not integrated with the Rio Grande system, the late Quaternary fill is thin and composed largely of playa and alluvial-plain sediments. The playa sediments commonly are gypsiferous, and in places, as at White Sands National Monument, fine, gypsiferous sand and gypsum are being blown into prominent dunes. Dune sand also is widespread in the western part of the Jornada del Muerto. Playa deposits are at least 40 m thick locally in the northern Jornada del Muerto just west of the Oscura Mountains (Neal and others, 1983). Part of the floor of the northern Tularosa basin is mantled by a long sheet of basaltic lava, about 50 m thick and probably of late Holocene age. A large area of Quaternary basalt also occurs in the west-central part of the Jornada del Muerto, and small areas of Pliocene basalt cap mesas adjacent to the Los Pinos Mountains (Bachman and Mehnert, 1978).

STRUCTURE

Many of the major structural features of the Rio Grande region formed during Laramide orogeny were variously modified by middle Tertiary volcanism and by later Tertiary basin and range faulting and epeirogenic uplift, and are still evolving during the Quaternary.

Structurally, the western side of the Rio Grande region is dominated by the Rio Grande rift with its complex intrarift uplifts and basins of late Cenozoic age, which commonly were superposed on moderately deformed Laramide structures. Only a very generalized outline of the rift structure within the Rio Grande region is presented herein, and for detailed information the reader is referred to the many papers written on the tectonic evolution, seismicity, and igneous geology of the rift, such as the volume edited by Rieckert (1979), and the syntheses of Chapin and Seager (1975) and by Seager (1975).

One segment of the Rio Grande rift in the study area (fig. 5) begins north of Socorro in the Rio Grande valley and extends southward, apparently terminating in northern Mexico near El Paso. Another north-trending segment of the rift system includes the Tularosa and Hueco basins (Woodward and others, 1978). The northern part of the rift along the Rio Grande valley is characterized by a series of major, en-echelon, north-northeast-trending grabens, commonly referred to as basins, separated by complex transverse structures (Chapin, 1979). To the south along the rift, the area has undergone more extension, and the basins are wider and the trend more northerly. The mountain ranges bordering both sides of the Rio Grande valley are major, tilted fault blocks that are aligned with the basins. Steep normal or reverse faults, having dips of 70–90°, border the mountain blocks, and throws on the faults range from about 600 m to an estimated 3,000 m. In most mountain ranges along the eastern side of the river valley, the uplifted and faulted blocks are tilted to the east, and Precambrian rocks are in contact with valley fill. These uplifts include, from north to south, the southern Manzano and Los Pinos Mountains, the Joyita Hills, and San Pasqual platform, the Fra Cristobal Range, and the Caballo Mountains (figs. 4, 5). Bordering the eastern side of these uplifts, except the Joyita Hills, is the broad basin of the Jornada del Muerto, which in its southern extent is part of the Rio Grande rift. The major fault zone bordering the western side of the Caballo Mountains transects the southern end of the mountains and extends southeastward through the Doña Ana Mountains, to the western side of the Organ Mountains, separating a series of uplifted blocks along the southern Rio Grande rift from grabens on the eastern side of the fault within the southern part of the Jornada del Muerto basin. Gravity data indicate vertical offset of nearly 2,400 m along the fault zone at the southern Organ Mountains (Seager, 1981). Regionally, the fault zone bounds the western side of a large west-dipping structural block that includes the southern Jornada del Muerto basin and the adjoining Organ and San Andres Mountains to the east.

At the southern end of the Caballo Mountains the character of the Rio Grande rift changes—it splits into a south-trending arm, the Mimbres basin, which follows a general course across the area east of Deming, N. Mex. (fig. 5), and into a southeast-trending arm (the Mesilla basin) along the general course of the river valley (Seager and Morgan, 1979; Seager and others, 1982). The next uplifted block on the eastern side of the Rio Grande, south of the Caballo Mountains, is the one underlying the Doña Ana Mountains. This block extends southeastward to join the prominent uplift of the San Andres, Organ, and Franklin Mountains. The Doña Ana block is bordered on the north by a large basin at the southern end of the Jornada del Muerto basin, and on the south by the large Mesilla basin which occupies the area, largely west of the river valley, from Las Cruces, N. Mex., southward into Mexico. Most of the structural features of the Doña Ana Mountains are of volcanic and tectonic origin, reflecting the onset of volcanism in the late Eocene, cauldron collapse and resurgence in the middle Oligocene, and uplift and

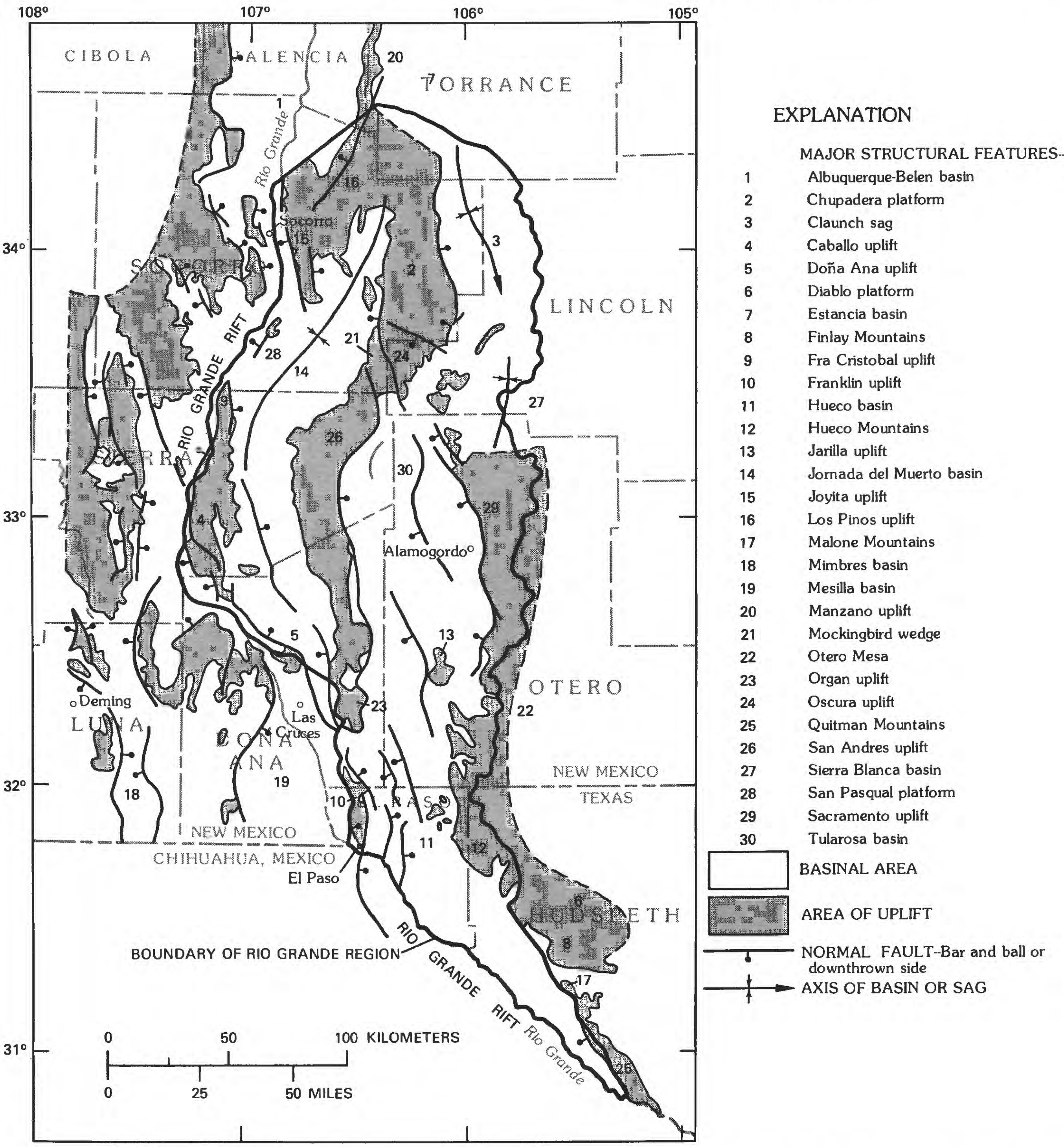

FIGURE 5.—Major structural features in the Rio Grande region and vicinity (modified from Woodward and others, 1978, and from Kelley, 1979).

westward tilting of the cauldron complex in the late Tertiary (Seager and others, 1976).

The central part of the Rio Grande region is bisected into two large basins, the Tularosa basin on the east and Jornada del Muerto basin on the west, by prominent topographic and structural features extending southward from Chupadera Mesa on the north through the Oscura, San Andres, and Organ Mountains to the Franklin Mountains at El Paso. Chupadera Mesa, a broad plateau capped by Permian limestone, is a platform area with slightly dipping rocks that passes southward into northeast-dipping beds of the Oscura uplift. The Oscura uplift forms the eastern limb of a faulted anticline, called the Mockingbird wedge by Kelley (1979), whose western limb lies to the south at the northern end of the San Andres Mountains (Kottlowski and others, 1956). A graben occurs on the faulted crest of the anticline. Within the Oscura uplift, the rocks are broken along steep normal faults into a series of blocks, and on the western face of the uplift Precambrian granite is juxtaposed against upper Paleozoic strata (Bachman, 1968). A major fault zone trends obliquely through the Mockingbird Hills, and may extend southeastward across the northern Tularosa basin to merge with concealed faults along the western face of the Sacramento Mountains or, more likely, trends southward down the basin and passes west of the Jarilla Mountains.

The structure of the San Andres Mountains was described in general by Kottlowski and others (1956) and later in more detail by Seager (1981), Bachman and Myers (1969), and Bachman and Harbour (1970). The basic structure is a west-tilting fault block that was uplifted vertically 1.5-3 km along the east-bounding fault zone during the late Tertiary (pl. 2). On the eastern face of the block, Precambrian rocks are in contact with the fill in the adjoining Tularosa basin. Within the fault block, steep normal faults commonly pass into low-angle gravity faults, indicating that the complex structure probably resulted from repeated tectonic movement. In the southern part of the range a prominent thrust-and-fold zone was the site of vertical uplift of a southern San Andres–Organ Mountains block during the Laramide orogeny.

As in the nearby Doña Ana Mountains, the Organ Mountains have been much affected by volcanic activity that began in the late Eocene, peaked in the Oligocene, and lasted into the Miocene. First, great volumes of volcanic debris buried the Laramide structures, then the Organ batholith intruded the volcanic pile as well as the Precambrian cores of the Laramide structures. During the late Tertiary, several periods of faulting resulted in uplift of the eastern side of the entire San Andres–Organ–Franklin chain of mountains. The zone of bounding faults is narrow, the faults dip 65–70°, and the throw probably is locally at least 3,600–4,500 m. The fault bordering the eastern side of the Organ Mountains appears to be one of the most recently active faults in New Mexico; the most recent displacement occurred in the last 5,000 yr (Seager, 1980, 1981).

The Franklin Mountains (pl. 2) to the south on the New Mexico–Texas State line have the same trend as the Organ Mountains, and may have a somewhat similar structural history of Precambrian deformation and intrusion, repeated uplift and erosion during Paleozoic and Mesozoic, and evolution of the present mountains by Cenozoic deformation. Harbour (1972) attributed the folding and thrust faulting in the northern Franklin Mountains to early Tertiary compression and subsequent uplift of the mountain block along normal faults with throws of 120–550 m. According to Lovejoy (Lovejoy and Seager, 1978), however, the Franklin Mountains are bounded on the west by an upthrust and on the east by a reverse fault with total throw of about 9,000 m.

The broad, deep Tularosa basin (pl. 2, fig. 5), which is east of the San Andres–Franklin uplift, represents the crestal part of a collapsed, faulted anticline of which the San Andres–Organ Mountains form the western limb and the Sacramento–Oscura Mountains the eastern limb (Kottlowski and others, 1956). The anticlinal structure probably originated at an early compressive stage of Tertiary tectonic activity, but later extension caused collapse by vertical movement along the faults bounding the San Andres and Sacramento mountain blocks, and probably also along crestal faults now hidden by valley fill. Seager (1981) has given a detailed interpretation of the structure in the western part of the Tularosa and Hueco basins, adjacent to the San Andres, Organ, and Franklin Mountains (pl. 2), to explain the tilting of the mountain blocks and the asymmetry of the basin floor that slopes westward to closed depressions near the base of the mountain chain. Gravity data (Mattick, 1967) indicate as much as 2,750 m of bolson fill in the western part of the Hueco basin. The boundary faults along the eastern side of the Tularosa basin have much less displacement. Rather than being relatively flat, the floors of the basins have considerable topographic relief reflecting an array of fault blocks. A system of minor faults cutting the surface of the bolson fill, indicate these hidden structures. In the southern part of the basin, exposures in the Jarilla Mountains indicate a faulted anticline intruded by Tertiary granitic rocks (Schmidt and Craddock, 1964). The scattered small outcrops of Paleozoic rocks in the basin north of the Jarilla Mountains probably are the tips of upthrown fault-blocks penetrating the basin fill. To the north, the Tularosa basin may terminate against the structural trend that passes through the gap between the San Andres Mountains and the Oscura Mountains, but they may pass into the broad synclinal trend of the Sierra Blanca basin and Claunch sag. To the south, the Tularosa basin continues into the Hueco bolson of Trans-Pecos Texas.

The Hueco bolson is a deep, asymmetrical basin bounded on the west by the fault zone along the eastern side of the Franklin Mountains, which locally has displacement of as much as 5,500 m (Henry and Gluck, 1981). South of the Franklin Mountains, the boundary extends into Mexico west of and approximately parallel to the Rio Grande. Displacement on boundary faults on the eastern side of the basin, adjacent to the Hueco Mountains, is down to the west and much less than on the west side. The bedrock floor is broken by a series of stepped fault blocks, and their positions commonly are indicated by discontinuous west-facing scarps (Seager, 1983a). In this part of the Hueco basin, the surface of the bolson is cut by minor faults with east-facing scarps (Seager, 1980). To the south, the irregular eastern boundary of Hueco bolson is marked along much of its length by normal faults with displacement down to the west. The bounding fault is best shown along the western side of the Quitman Mountains at the southern end of the Rio Grande region. The present boundary of the basin marks the northeastern margin of the Chihuahua trough, a deep sedimentary basin that formed in Late Triassic or Early Jurassic time during events related to the opening of the Gulf of Mexico (Muehlberger, 1980). The trough margin was the site of Laramide deformation, which produced north-northwest-trending, tight and overturned folds, and rocks in the trough were thrust northeastward along decollements (pl. 2). The Quitman and Malone Mountains are at the northern end of a large-scale, nearly recumbent anticline that extends for a long distance southward into northern Mexico (Jones and Reaser, 1970; Berge, 1981). In the Oligocene, volcanism in the northern Quitman Mountains resulted in a thick sequence of volcanic rocks and implacement of the Quitman pluton. To the north in the Hueco Mountains, laccoliths and plugs or stocks also were intruded at this time. The Basin and Range block faulting that resulted in the formation of the Quitman, Malone, and Finlay Mountains and adjoining basins at the southern end of the Rio Grande region, began during the late Oligocene and early Miocene, and movement along normal faults has continued to the present (Henry, 1979). The Sacramento Mountains, the principal structural feature along the eastern side of the Rio Grande region, form the eastern boundary of the Tularosa basin. The uplift is bounded on the west by a zone of steep normal faults with estimated displacements ranging from 2,130 m in the central part of the zone to 1,220 m at the northern and southern ends (Pray, 1961). The uplifted block dips eastward at about 1°, but at its northern and southern ends, the dip increases to several degrees. The mountains end rather abruptly to the south as they descend into the broad, flat tableland of the Otero mesa. To the south of the mesa, on the New Mexico–Texas State line, is the broad, faulted arch of the Hueco Mountains (King and others, 1945).

In the northeastern part of the Rio Grande region, north of the Sacramento Mountains, the area is a broad north-northwest-trending synclinal structure, extending from the Sierra Blanca basin on the south, through the Claunch sag and into the Estancia basin north of the region (Kelley and Thompson, 1964). Outlining the syncline on the east are a series of large laccoliths, stocks, and smaller intrusives that locally have caused folding and faulting. Small intrusive bodies also occur within the syncline. This structure merges westward into the gently dipping rocks of the Chupadera platform.

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POTENTIAL HOST MEDIA FOR RADIOACTIVE WASTE

By K.A. Sargent

Media considered to have potential for isolation of high-level radioactive waste in the Rio Grande region, New Mexico and Texas, include intrusive rocks such as granite and other coarse-grained plutonic rocks, ash-flow tuff, especially where densely welded and having a thickness greater that 100 m, and basalt and basaltic andesite lava flows where greater that 100 m thick. Other, less abundant rock types that have potential may occur in the region. These include laharic and mudflow breccia, certain shallow intrusive bodies such as rhyolite and dacite domes and laccoliths, and certain argillaceous beds if thick enough and relatively undisturbed. Salt and other evaporitic deposits appear to have little or no potential as host media in this region. In addition to the above-mentioned rock types, 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 Rio Grande region, New Mexico and Texas, are shown on plate 3.

INTRUSIVE ROCKS

Granitic rocks are widespread in the Rio Grande region. They crop out in all the mountain ranges in the region and along many of the low divides [see Hills and Sargent (1984) for summary report on granitic rocks].

To the south in the Texas part of ground-water unit RG–01 near El Paso, an extensively jointed and deeply weathered syenite stock intrudes Cretaceous limestone. Small Tertiary intrusive stocks, laccoliths, and sills of syenite occur in the Hueco Mountains of Texas. A stock and ring dike of quartz monzonite occurs in the Quitman Mountains in Texas. A group of very small syenite dikes and sills occur west of the Finlay Mountains.

The Jarilla Mountains, north of Orogrande in the Tularosa Valley, contain a large stock of quartz monzonite of Tertiary age. The stock is extensively argillized and sericitized, and veins with sulfide and copper mineralization have been reported.

Tertiary intrusive rocks occur as small stocks, laccoliths, dikes, and sills on the western flank of the Sacramento Mountains from Alamogordo to Carrizozo. Higher in the range, at altitudes mostly above 2,286 m, a large Tertiary monzonitic stock (Rialto stock) crops out in the vicinity of Sierra Blanca Peak, and a smaller syenitic stock (Three Rivers stock) occurs about 15 km to the north. A relatively large Tertiary laccolith or stock of quartz syenite porphyry occurs at Carrizo Mountain, about 20 km northeast of Carrizozo. Other Tertiary intrusive bodies occur in the area but may be too small for further consideration. The Jicarilla stock, a monzonite porphyry of Tertiary age, crops out north of Carrizozo and forms Ancho Peak. Laccoliths and sills of Tertiary diorite and syenite near Tecolote may be too limited in size for further consideration. Two relatively large exposures near Gallinas Peak are trachytic and rhyolitic laccoliths more than 150 m thick. East of Gallinas Peak, a small exposure of latite is possibly a stock and would need further examination to define its extent.

The Organ Mountains contain both Oligocene and Precambrian granitic rocks. The younger rock is a quartz-monzonite batholith, 32–34 m.y. old, that occupies part of the Organ caldera complex. The rocks of Precambrian age are quartz-monzonite plutons, locally extensively fractured and altered, and intruded by numerous Precambrian dikes.

In the southern San Andres Mountains, Precambrian syenogranite and quartz monzonite intrude older Precambrian rocks. Locally the intrusives are extensively fractured and altered. To the north, the Precambrian syenogranites and quartz monzonites are locally foliated and need closer evaluation. At Salinas Peak, a Tertiary sill of very fine grained rhyolite is as much as 750 m thick. Precambrian quartz monzonites crop out in the northern San Andres Mountains and are exposed discontinuously to the north into the Oscura Mountains. Small outcrops of Tertiary granite occur north of the Oscura Mountains and west of Chupadera Mesa. Locally the Precambrian rocks are foliated.

In the Caballo Mountains and the Fra Cristobal Range, both located just east of the Rio Grande, quartz monzonites, syenites and granites of Precambrian age crop out on the lower slopes of the western escarpments. Those in the northern Caballo Mountains are locally gneissic.

In the northwestern part of the Jornada del Muerto, several granitic masses occur, mostly of Precambrian age. These include the Tajo pluton, La Joyita pluton, two plutons near the Los Pinos Mountains, and one pluton in the southern Manzano Mountains. Tertiary dikes and sills occur in numerous small exposures.

TUFFS AND LAHARIC BRECCIAS

Tuffs and laharic breccias occur almost exclusively in ground-water unit RG–02. In the northern part of the Jornada del Muerto, ash-flow tuffs and volcaniclastic rocks occur. The ash-flow tuffs are of Oligocene age and may be as much as 700 m in aggregate thickness. Volcaniclastic rocks of Tertiary age occur possibly in extensive deposits in the subsurface of the Jornada del Muerto. West of the Rio Grande, nearer the source area, these rocks are as much as 600 m thick. In the Caballo Mountains, laharic mud-flow breccia and interbedded sedimentary rocks of the Eocene Palm Park Formation (Kelley and Silver, 1952) crop out and presumably underlie a large part of the basin area in the southern part of ground-water unit RG-02, where this unit is as much as 600 m thick. Laharic mud-flow breccias have minimal permeability (John W. Hawley, New Mexico Bureau of Mines and Mineral Resources, oral commun., 1981), and are potential repository host rocks. A photograph of an outcrop of laharic breccia is shown in figure 6.

Ash-flow tuff and breccia of middle Oligocene age as much as 800 m thick occur near the Doña Ana Mountains and areas near the Doña Ana cauldron. Some of these flows may extend into the southern part of ground-water unit RG-02. Similarily, thick tuffs were extruded from the Organ cauldron and probably extend into the southern part of ground-water unit RG-02 and into the western part of ground-water unit RG-01.

A densely welded tuff, the Square Peak Volcanics of Oligocene age, occurs in the Quitman Mountains caldera in the southern part of ground-water unit RG-01 and is reported to exceed 1,000 m in thickness. The ash-flow tuffs and laharic breccia of the Rio Grande region were summarized by Jenness and others (1984).

BASALTIC ROCKS

Basaltic rocks occur in the western part of ground-water unit RG-02. In the Los Pinos Mountains and Fra Cristobal Range and along the Rio Grande adjacent to the Fra Cristobal Range, upper Tertiary and lower Quaternary olivine basalts occur but are probably less than 100 m thick. Basaltic andesite of unknown thickness occurs in the basin area in the southern part of ground-water unit RG-02. About 25 km southwest of the town of Grama, N. Mex., 25-27-m.y.-old andesitic flows from the Sierra de Las Uvas volcanic field crop out. To the south, these flows are as much as 240 m thick. Minor, small masses of basaltic rocks occur as plugs in the northern part of ground-water unit RG-02. Johnson (1984a) summarized the basaltic rocks of the Rio Grande region.

ARGILLACEOUS ROCKS

Argillaceous rocks of Paleozoic and Mesozoic age occur primarily in the northern part of the region (Johnson, 1984b). These include the Abo Formation of

FIGURE 6.—Photograph of an outcrop of laharic breccia in Eocene Palm Parks Formation (Kelley and Silver, 1952) in Selden Canyon, northwest of Radium Springs, N. Mex. Nonsorted, subangular andesitic boulders as much as 3 m in diameter are embedded in a matrix of ash, crystals, pebbles, and cobbles. Unit dips to right (west) 15-20°. Photograph by M.S. Bedinger, 1984.

Permian age and the Panther Seep Formation of Permian and Pennsylvanian age, each of which ranges in thickness from about 0 to 550 m. These formations crop out in the San Andres and Sacramento Mountains and in the hills northeast and southwest of the Los Pinos Mountains; they also underlie the basin areas.

Argillaceous rocks of Cretaceous age include the Mancos Shale and Mesaverde Formations. These rock units are as thick as 150–760 m and crop out in ground-water units RG–01 and RG–02. These shales underlie much of the basin areas. No thick shales are known in the region south of the latitude of the Organ Mountains.

Shales in the Rio Grande region are largely undeformed by folding and faulting and warrant consideration as potential repository host media. The thick shales in the region offer flow retarding barriers along the ground-water flow paths as well as excellent potential for sorption of radionuclides.

UNSATURATED ZONE

Areas of prospective thicknesses of the unsaturated zone greater than 150 m occur in the Organ, San Andres, and Oscura Mountains, a large area of Chupadera Mesa, the Sacramento Mountains southeast of Alamogordo, Otero Mesa, and a large area in the Hueco Mountains of New Mexico and Texas extending south along the eastern edge of the ground-water unit RG–01 to the Quitman Mountains.

The unsaturated zone includes unconsolidated and partly consolidated alluvium and basin fill in an area east of Chupadera Mesa and in an extensive area extending south from near Otero Mesa to the Hueco and Finlay Mountains in Texas.

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QUATERNARY TECTONISM

By K.A. Sargent, John W. Hawley[3], Christopher D. Henry[4], William J. Stone[3], and Frank E. Kottlowski[3]

The discussion of Quaternary tectonic conditions in the Rio Grande region includes brief sections on seismicity, heat flow, faulting, volcanism, and vertical crustal movement. A generalized map (fig. 7) depicts each of these features. The late Cenozoic tectonic setting is described in more detail by Callender and others (1983), Seager and Morgan (1979), and Seager and others (1984).

SEISMICITY

Fewer than ten earthquakes were reported in the Rio Grande region by Algermissen and others (1983). Two have Richter-scale magnitudes (surface wave) of 5 to 6, and one has a magnitude of 4 to 5 (fig. 7). The remaining earthquakes have magnitudes of less than 4. A swarm of earthquakes of magnitudes less than 4 occurs near Socorro, N. Mex., in the northwestern part of the region (Sanford and others, 1983). Another swarm of earthquakes with magnitudes of less than 4 magnitude occurs near the region south of El Paso in Mexico. Three earthquakes of less than 4 magnitude occur in Otero County. One area, centering on Socorro has a strain release of 10. Reilinger and others (1980) and Sanford (1983) believe that the Socorro area is underlain by an active magma body.

HEAT FLOW

Eighteen heat-flow measurements were reported by Sass and others (1976) and by J.H. Sass (written commun., 1982) in the Rio Grande region. The western edge of the region is close to where Sass places the 2.5 HFU line (fig. 7). The major part of the Rio Grande region is east of the 2.5 HFU line and has heat flow ranging from 1.5 to 2.5 HFU. Three seemingly anomalously large heat-flow values are shown in figure 7. These occur east of the area where heat flow exceeds 2.5 HFU. The most northerly measurement has a value of 3.10 HFU and is considered regionally anomalous by Sass probably because six surrounding values (not shown) range from 1.75 to 2.28 HFU. The other two anomalously large heat-flow values are from work by Taylor and Roy (1980). One, having a value of 8.3 HFU, is near the Texas–New Mexico State line (lat 32° N.) where thermal waters are believed to rise along a fault zone at the edge of the Hueco bolson. The other, having a HFU value of 4.5, is from a mineral exploration drill hole in Tertiary diorite in the Finlay Mountains near the southeastern part of the region. Additional baseline heat-flow data has been published by Decker and Smithson (1975) and by Reiter and others (1978) for the Rio Grande rift area.

QUATERNARY FAULTING

A compilation of Quaternary faults for the Basin and Range province (Nakata and others, 1982) shows numerous faults in the southern two-thirds of the Rio Grande region (fig. 7). The longer faults are parallel to or coincide with north-trending older faults. In addition, Quaternary faults located at the boundary between basins and mountain fronts have the same type of displacement as the older faults. Numerous other north-trending faults occur in the Tularosa basin and Hueco bolson, and transect basin alluvium (Seager, 1980; Henry and Gluck, 1981); the major boundary fault along the eastern side of the Franklin Mountains is one such fault. The faults displace the upper part of the Camp Rice Formation, which is about 0.5 m.y. old (Seager, 1981). The youngest known displacement, no more than 5,000 yr old and possibly less than 2,000 yr old (John W. Hawley, written commun., 1984), is on a segment of a range-front fault on the western side of the Tularosa basin between the Organ and Franklin Mountains. Individual scarps commonly are 5–10 m high. The rest of the mapped Quaternary faults are probably older than 10,000 yr.

LATE CENOZOIC VOLCANICS

Several extensive areas of Quaternary basalt flows occur in the Rio Grande region as shown on figure 7 (Aldrich and Laughlin, 1981; Luedke and Smith, 1978). The Jornada basalt flow is the largest, 38 km east to west and 19 km north to south, and contains a volcanic vent dated at 0.76 m.y. (Bachman and Mehnert, 1978). Weber (1963) briefly described the flow and vent area and reported that water pumped from Crater Well, located about 1.6 km southwest of the vent, indicated abnormal heat flow in that area. Immediately north of the Jornada flow is the Mesa Prieta (Black Mesa) flow, which is a small flow dated at 2.2 m.y. (Bachman and

[1] New Mexico Bureau of Mines and Mineral Resources.
[2] Texas Bureau of Economic Geology.

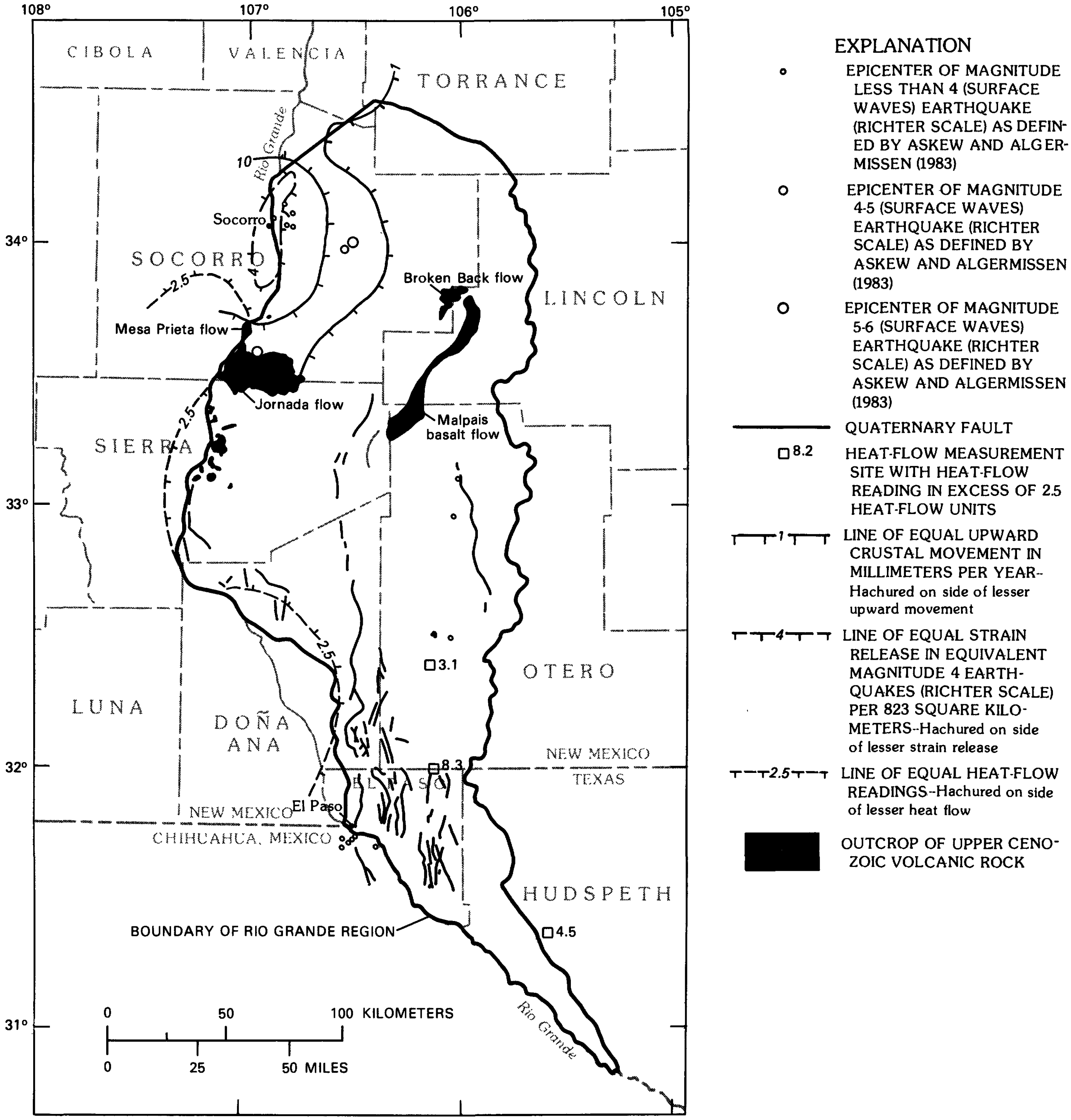

FIGURE 7.—Quaternary tectonic features in the Rio Grande region and vicinity.

Mehnert, 1978). Both the Jornada and Mesa Prieta flows lie in river sands and gravels of the uppermost part of the Santa Fe Group (Weber, 1963; Hawley, 1978, p. 96 and 102). The Malpais (Carrizozo) basalt flow in the Tularosa basin is about 72 km long and its source vent at the northern end of the flow probably is no older than 10,000 yr (Luedke and Smith, 1978; Weber, 1963, 1964). Northwest of the Malpais (Carrizozo) flow is the Broken Back flow (Weber, 1963); it is olivine basalt and underlies the Malpais (Carrizozo) flow. Two source vents occur on the northwestern side of the Broken Back flow.

More than a dozen isolated patches of olivine basalt occur 15–30 km south of the large Jornada flow. These flows, with at least 13 source vents, have ages ranging from 2.1 to 2.9 m.y. (Bachman and Mehnert, 1978; Hawley, 1978, p. 89–96), and although these are older than Quaternary age, they are recognized as being tectonically young. One very small basaltic flow and a vent of Quaternary age occur just north of the Jarilla Mountains southwest of Alamogordo, N. Mex. Basalts in the southern Hueco bolson mapped as Quaternary by Albritton and Smith (1965) were subsequently identified as being about 30 m.y. old (McDowell, 1979).

VERTICAL CRUSTAL MOVEMENT

Gable and Hatton (1983) show the Rio Grande rift area was undergoing uplift at the rate of about 2 m per 10,000 yr (0.2 mm/yr), based on geology, paleobotany, and radiometric dating (fig. 7). Uplift of 5 mm/yr is indicated by geodetic-leveling data collected between 1911 and 1951 for a small area centering on Socorro, N. Mex. Analysis of repeated levelings indicate uplift of more than 50 mm from 1951 to 1980 measured relative to benchmarks south of Socorro (Larsen and Reilinger, 1983, p. 120). Reilinger and others (1980) and Sanford (1983) ascribe crustal doming to an underlying magma body. However, the same rates of uplift have been reported in releveling studies in the Valentine, Tex., area (Ni and others, 1981) and on the Diablo Plateau (Reilinger and Brown, 1980) to the southeast of the Rio Grande region. The consistency of the three studies indicates a regional phenomenon rather than local magmatic uplift. The general area of uplift coincides well with strain-release lines of Algermissen and others (1983), although the zone of greater heat flow shown by Sass and others (1976) is farther south.

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GROUND-WATER HYDROLOGY

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

HYDROGEOLOGIC UNITS

The stratigraphic units in the region, discussed in the "Geology" section of this report, 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. The hydraulic properties of the hydrogeologic units used in areal and cross-sectional models are given in tables 1 and 2, respectively.

Basin fill in the Rio Grande region consists of older fill, probably of Miocene to Pleistocene age and assigned to the Santa Fe Group, and overlying younger alluvial fill. The older fill consists of nonindurated to semi-indurated sedimentary and volcanic rocks, including (1) laharic breccias, composed of mudflows and volcanic rocks; (2) clay and silt with evaporites and basalt flows interbedded with sand and gravel in the central parts of the basins; and (3) gravel, sand, and silt deposited as alluvial fans near the mountain ranges. The older fill is overlain by younger alluvial fill consisting largely of silt, sand, and gravel deposited by the Rio Grande.

During late Pliocene or Pleistocene time, the ancestral Rio Grande at some time flowed through a gap between the Franklin and Organ Mountains southeast of Las Cruces, N. Mex. (Hawley and Kottlowski, 1969, p. 91). The alluvial fill deposited by the ancestral Rio Grande in the southern part of ground-water unit RG-01 is relatively well sorted. Strain (1965) described a fluvial deposit of the Rio Grande in the Hueco bolson that is 27.5 m thick and composed of gravel, sand, silt, volcanic ash, and caliche. The Hueco bolson is located in the Texas part of ground-water unit RG-01 north of El Paso.

The permeability of the basin fill in New Mexico is quite variable due to the heterogeneity of the material. In the Tularosa basin, permeability generally is small in the lower and central parts of the fill, with the most permeable sections high on the alluvial fans near the adjacent mountain ranges. In the Hueco bolson near the Franklin and Organ Mountains in Texas, the permeability of the basin fill is moderate to large and yields water to large-capacity wells (Knowles and Kennedy, 1958). The sand and gravel in the basin fill in the Hueco bolson are thickest and coarsest near the Franklin and Organ Mountains. The sand becomes fine grained and thinner to the east, and very little water-yielding sand is found near the Hueco Mountains (Knowles and Kennedy, 1958).

The maximum thickness of the basin fill in the Jornada del Muerto (ground-water unit RG-02) is 200-300 m, where the section consists of about 80 m of younger alluvial fill over the older basin fill. The thickness of fill in ground-water unit RG-01 increases from the north to south on the undulating pre-Cenozoic base. The basin fill is about 1,300 m thick at Lake Lucero and attains a probable maximum thickness of about 2,500 m in southern New Mexico and in the Hueco bolson of Texas.

Basalts of Quaternary and Tertiary age occur at the surface and interbedded with basin fill. Basalt is not widely distributed and probably has a maximum thickness of 100 m.

Tuff of Tertiary age occurs as a component of the older basin fill as interbedded ash-flow tuff, tuffaceous sandstone, conglomerate, and sandstone.

Laharic breccias, which may be as much as 600 m thick, do not crop out but underlie the alluvial fill in much of the Jornada del Muerto. The laharic breccias are volcaniclastic materials deposited as mudflows and volcanic debris deposited on the flanks of volcanoes. The deposits in the Jornada del Muerto are fine grained and semi-indurated and have small permeability.

Undifferentiated volcanic rocks crop out in small areas in the northern parts of ground-water units RG-01 and RG-02. These rocks include quartz latite, rhyolite, and andesite.

The consolidated, coarse-grained clastic rocks primarily consist of thick sandstone of Permian age. The coarse-grained clastic rocks are interbedded with gypsum, siltstone, and limestone. The thickness of these units is as great as 800 m, and they are widely distributed at the surface and in the subsurface in the northern part of the Rio Grande region.

Stratigraphic units that are composed predominantly of carbonate rocks of Pennsylvanian and Permian age, range in thickness from 150 to 400 m. These rocks include limestone, dolomite and gypsum, and lesser siltstone and shale. Carbonate rocks are widespread in the subsurface, particularly in the southern part of the region and crop out in the Sacramento and San Andres Mountains.

Consolidated, fine-grained clastic rocks, composed of silt and argillaceous materials of Pennsylvanian, Permian, and Cretaceous age are widespread at the surface and in the subsurface. Thickness of the individual units is as great as 760 m.

The crystalline-rock hydrogeologic units include metamorphic and intrusive igneous rocks. Metamorphic rocks of Precambrian age include gneiss and schist; they crop out on the eastern flank of the San Andres Mountains and underlie the entire region at depth. Granitic intrusive rocks of Tertiary age are intermediate to silicic in composition and fine to coarse grained. The intrusives, which occur as stocks, laccoliths, dikes, and sills, crop out in the mountain ranges.

GROUND-WATER FLOW REGIME

Annual average precipitation in the Rio Grande region ranges from 100 mm or less in the northern part of the basin area in ground-water unit RG-02 and in the southern part of the area in ground-water unit RG-01, to 350-400 mm in the San Andres Mountains and Chupadera Mesa, and 500 mm or more in the Sacramento Mountains. Mean annual free-water-surface evaporation in the basins is about 1,750 mm/yr.

Recharge to ground water occurs largely through permeable rocks in the mountain ranges and through the permeable fill at the periphery of the basins. Chupadera Mesa in the northern parts of ground-water units RG-01 and RG-02 in underlain by limestone of the San Andres Formation. The karst topography (fig. 8), described by Smith (1957), probably is a recharge area. Weir (1965, p. 30) estimated the recharge to the northern part of ground-water unit RG-02 by calculating the ground-water underflow through a section of the basin. Weir estimated that between 6 and 7 percent of the precipitation is recharged to ground water in the northern part of ground-water unit RG-02. Weir (1965, p. 31) also estimated the recharge to the northern part of

FIGURE 8.—View of Chupadera Mesa toward the west-southwest along the strike of outcropping limestone beds showing karst topography. Photograph by John W. Hawley, 1984.

ground-water unit RG–01, assuming that it was equal to the discharge of Malpais Spring and Salt Creek, to be about 1 percent of the precipitation. The ground-water basins of both areas contain parts of Chupadera Mesa and receive about the same precipation. Although both estimates are subject to considerable uncertainty, it is likely that the ground-water discharges to Malpais Spring and Salt Creek do not represent the total recharge to the ground-water basin upgradient from these discharge points. Meinzer and Hare (1915, p. 259) reported the flow as "several second-feet" (1 second foot equals 1 cubic foot per second, which equals about 1,700 L/min). Weir (1965) reported the flow of Malpais Spring as 5,700 L/min and McLean (1970) measured Malpais Spring flow as 836 L/min.

The long flow system of ground-water unit RG–01 has intermediate discharge areas, playas and springs, between the ground-water divide at the upper end and the natural terminal discharge, at the Rio Grande. Intermediate discharge from ground-water unit RG–01 is by seepage to Salt Creek and Malpais Spring, evapotranspiration from shallow ground water at Lumley Lake and Lake Lucero, and withdrawal by wells in the Hueco bolson near El Paso and at various places in the New Mexico part of the basin. The ground-water gradient to the south of these discharge areas at Salt Creek and Malpais Spring is relatively slight, 0.0007, compared to that upgradient from these intermediate discharge areas. It is inferred that most recharge occurs in the areas north and east of these intermediate discharge areas where the annual precipitation is greater than to the south. Withdrawal by wells in New Mexico was about 50 hm^3 during 1980, and withdrawal from the Hueco bolson in Texas was about 90 hm^3 during 1980. In addition to the relatively large Malpais Spring, discharge also occurs from many small cold springs in the Sacramento Mountains and a few small cold springs in the San Andres Mountains. Discharge from thermal springs in ground-water units RG–01 and RG–02 (pl. 5), indicates convection of geothermal heat by ground-water flow.

Discharge from ground-water unit RG–02 occurs almost exclusively from basin fill to the Rio Grande. Water levels are believed to be at depths greater than can be affected by evapotranspiration from the water table, ground-water withdrawal from unit RG–02 is small (about 0.02 hm^3 during 1980), and spring flow is from a very few small springs mostly in the mountain areas.

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 series of reports (Bedinger, Sargent, and others, 1989). The relative velocity of ground water in the hydrogeologic units is shown on plate 4. 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 that were used to estimate relative ground-water velocities are given in table 1.

Because of the variability of hydraulic characteristics within a rock type, the relative ground-water velocity can easily be one or more orders of magnitude greater or less than the relative velocity values shown on plate 4. The range of hydraulic properties of different rock types is given in Chapter A in the "Hydraulic properties of rocks" section by Bedinger, Langer, and Reed (1989).

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 and modified from the lithologic and hydrologic description of the units; it was further modified during the iterative runs and design modification of the cross-sectional models.

TABLE 1.—*Hydraulic properties of hydrogeologic units used in areal ground-water flow analysis*

[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; ---, not available]

Hydrogeologic unit	Map symbol (pl. 4)	K/ϕ (meters per day)	Hydraulic gradient
Ash-flow tuff	t	1×10^{-1}	0.03
Basin fill in the southern part of ground-water unit RG–01.	a	6×10^{1}	.0007
Basin fill, remainder of area.	a	6×10^{1}	.003
Carbonate rocks	c	1×10^{1}	.003
Coarse-grained clastic rocks.	s	2×10^{-1}	.03
Fine-grained clastic rocks.	f	3×10^{-9}	---
Granitic rocks	g	2×10^{-1}	.03
Gypsum	y	1×10^{1}	.003
Lava flows	b	3×10^{0}	.03
Metamorphic rocks	m	2×10^{-1}	.03
Volcanic rocks, undifferentiated.	v	1×10^{-1}	.03

Relative ground-water traveltimes and flow paths along which the relative traveltimes were calculated are shown on plate 5, as are major discharge areas, the Rio Grande, and the large ground-water withdrawal area near El Paso. Traveltimes in the shale units were not calculated because no hydraulic-head data are available for this unit. Ground-water velocity in shale probably is three to five orders of magnitude slower than in the other hydrogeologic units (pl. 4).

The hydraulic characteristics of the basin fill in the Jornada del Muerto and in the central part of the Tularosa basin reflect the general fine-grained character of the fill material. However, the velocity of ground-water travel in the basin fill is faster than in other rock units. The intermediate discharge areas shown in the Tularosa basin and the relative short flow paths from the Jornada del Muerto to the Rio Grande tend to keep the relative traveltime less than 1 everywhere in the basin fill. The longest relative traveltimes on plate 5 are greater than 20 in ground-water unit RG–01 and 10–20 in ground-water unit RG–02. These traveltimes are attributed to long flow paths in coarse-grained clastic rocks of Pennsylvanian age. These relative traveltimes probably are conservatively short and may realistically be longer due to the presence of fine-grained and evaporitic interbedded deposits in the units.

The relative traveltimes indicated on plate 5 from water-table divide to discharge area are conservative because actual flow paths of ground water in recharge areas dip below the water table and therefore, both flow paths and traveltimes are much longer. The relative traveltimes at the water table are useful for comparing relative traveltimes at shallow depths below the water table between nearby points and in areas where flow paths are parallel to the water table. A more realistic estimate of relative traveltimes between widely spaced points, such as from near a water-table divide to a discharge area, is given in the following analysis of cross-sectional models.

CROSS-SECTIONAL MODELS

Cross-sectional models were used to analyze ground-water flow in selected areas of the region. The mathematical model used is described in Chapter A (Bedinger, Sargent, and others, 1989). The location of the modeled sections and the model parameters and results are shown on plate 6. The values of hydraulic properties of the rock units in the modeled sections used in analysis of the ground-water flow are given in table 2.

Distribution of rock units, relative traveltimes, and stream functions are shown in the sections (pl. 6). Relative traveltimes are given in intervals of 1 order of magnitude from 10^1 and longer. Relative traveltimes indicate the relative time of travel from points on the line to the discharge area. Stream functions show the directions of ground-water movement and relative quantity of flow in the section below the flow line.

The 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 seen from the sections, the flow paths in the upstream parts (divide areas) of the flow systems dip steeply into the flow system and take the longest flow paths to the discharge areas. Relative traveltimes from the divide areas to discharge areas are as great as 10^5 or 10^7. Commonly, the areas of long relative traveltimes have surface areas that are restricted

TABLE 2.—*Hydraulic properties of hydrogeologic units used in cross-sectional models*
[K, hydraulic conductivity, in meters per day; ϕ, effective porosity; ---, not used]

Rock type	Symbol (pl. 6)	Hydrogeologic sections on plate 6 *A–A'* K	*A–A'* ϕ	*B–B'* K	*B–B'* ϕ
Coarse-grained basin fill	a	1×10^{0}	1.2×10^{-1}	3×10^{0}	1.2×10^{-1}
Fine-grained basin fill	A	2×10^{-3}	3.6×10^{-1}	2×10^{-3}	3.6×10^{-1}
Carbonate rocks	c	3×10^{-3}	1×10^{-2}	3×10^{-3}	1×10^{-2}
Fine-grained clastic rocks	f	5×10^{-7}	2.2×10^{-1}	5×10^{-7}	1.2×10^{-1}
Crystalline rocks (metamorphic and granitic), upper part of section.	G	5×10^{-4}	3×10^{-3}	5×10^{-3}	3×10^{-3}
Crystalline rocks (metamorphic and granitic), lower part of section.	g	3×10^{-7}	1×10^{-4}	3×10^{-7}	1×10^{-4}
Coarse-grained clastic rocks	s	3×10^{-2}	1.8×10^{-1}	3×10^{-2}	1.8×10^{-1}
Gypsum	y	---	---	6×10^{-1}	1.2×10^{-1}
Basaltic lava flows	b	5×10^{-1}	1.5×10^{-1}	---	---

at the water table but enlarge with depth. This indicates that there should be 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 of 10^5 or greater exist at the water table in all sections. Areas with traveltime from 10^5 to 10^8 exist within 1,000 m of the water table in section A–A', and areas with traveltime of 10^6 exist within 1,000 m of the water table in section B–B'.

QUALITY OF GROUND WATER

The quality of water in the Rio Grande region is characterized by maps showing the areal distribution of dissolved solids (fig. 9) and predominant chemical constituents in solution (fig. 10). These maps are generalized from those of Thompson and Nuter (1984) and Thompson and others (1984), which were compiled from data in water-quality files of the U.S. Geological Survey (WATSTORE), published reports, and, in the Texas part of the region, from the files of the Texas Department of Water Resources. The data primarily are from nongeothermal springs and wells less than 150 m deep completed in alluvial and basin-fill deposits. In areas where data were not available, the water-quality characteristics were estimated from the position in the ground-water flow system and the lithology of the local bedrock.

The dissolved-solids concentration generally is more than 1,000 mg/L throughout the region. The areas of ground water having less that 1,000 mg/L dissolved solids include the area northeast of El Paso in and east of the Franklin Mountains, in the southern part of the Jornada del Muerto, in and east of the Organ and southern San Andres mountains, along the northwestern region boundary from the Socorro County line northward to north of Socorro, in the eastern part of the San Andres mountains, in the area between the San Andres mountains and the Chupadera Mesa, and in a large part of the Sacramento Mountains.

Ground water containing dissolved-solids concentrations of more than 3,000 mg/L to as much as 25,000 mg/L is found in the northern and central part of the Tularosa Valley in New Mexico, and along the Rio Grande in Texas. Elsewhere in the region, ground water at depths of less than 150 m contains between 1,000 and 3,000 mg/L dissolved solids.

Sulfate-type water is the most common, occurring in about 68 percent of the region. Chloride-type water is common in the central and southern Tularosa basin in New Mexico, near the Rio Grande in Texas, and in a large area of the north-central Texas part of the region. Chloride-type water occurs in about 15 percent of the region, generally in areas corresponding to the areas where dissolved solids are greatest. Sodium-bicarbonate-type water, which occurs in about 10 percent of the region, is in scattered areas along the western and southern borders of the region. Calcium-magnesium-bicarbonate-type water, which occurs in about 10 percent of the region, is primarily in scattered areas in the San Andres, Organ, and Sacramento Mountains.

PLEISTOCENE HYDROLOGIC CONDITIONS

The Pleistocene climate in the Rio Grande region was probably characterized by greater precipitation, lower temperature, and less potential evapotranspiration that at present. Leopold (1951), from studies of Pleistocene lake levels in the Estancia basin, the basin adjoining the Rio Grande region on the north, estimated that mean annual precipitation was 50–70 percent greater, mean annual temperature was 6.6 °C lower, and annual evaporation was 23–50 percent less during the Pleistocene than at present. Reeves (1966), from information on Pleistocene lakes in the Llano Estacado of western Texas, estimated that during the glacial climate, mean annual precipitation was 89 percent greater, mean annual temperature was 5 °C lower, and mean annual evaporation was 27 percent less than at present. The existence during the late Pleistocene of lakes in both the Tularosa basin (Lake Otero) and the Jornada del Muerto (Lake Trinity) indicates that similar climatic conditions existed throughout the Rio Grande region. Lake Otero is estimated to have had an area of 470 km^2 and a maximum lake-surface altitude of 1,200 m above sea level, which is about 20 m above the present basin floor (Williams and Bedinger, 1984). The present depth of ground water is less that 6 m, below the surface of the basin floor. The Pleistocene level of Lake Otero was thus a higher and larger discharge area for ground water. Lake Trinity, described by Neal and other (1983), had an area of 200 km^2 and a maximum lake-surface altitude of 1,431 m above sea level, which is about 6 m above the present basin floor.

With a 50–80 percent increase in precipitation and less evaporation, recharge to ground water during the glacial climate could have been as great as two or more times the present recharge.

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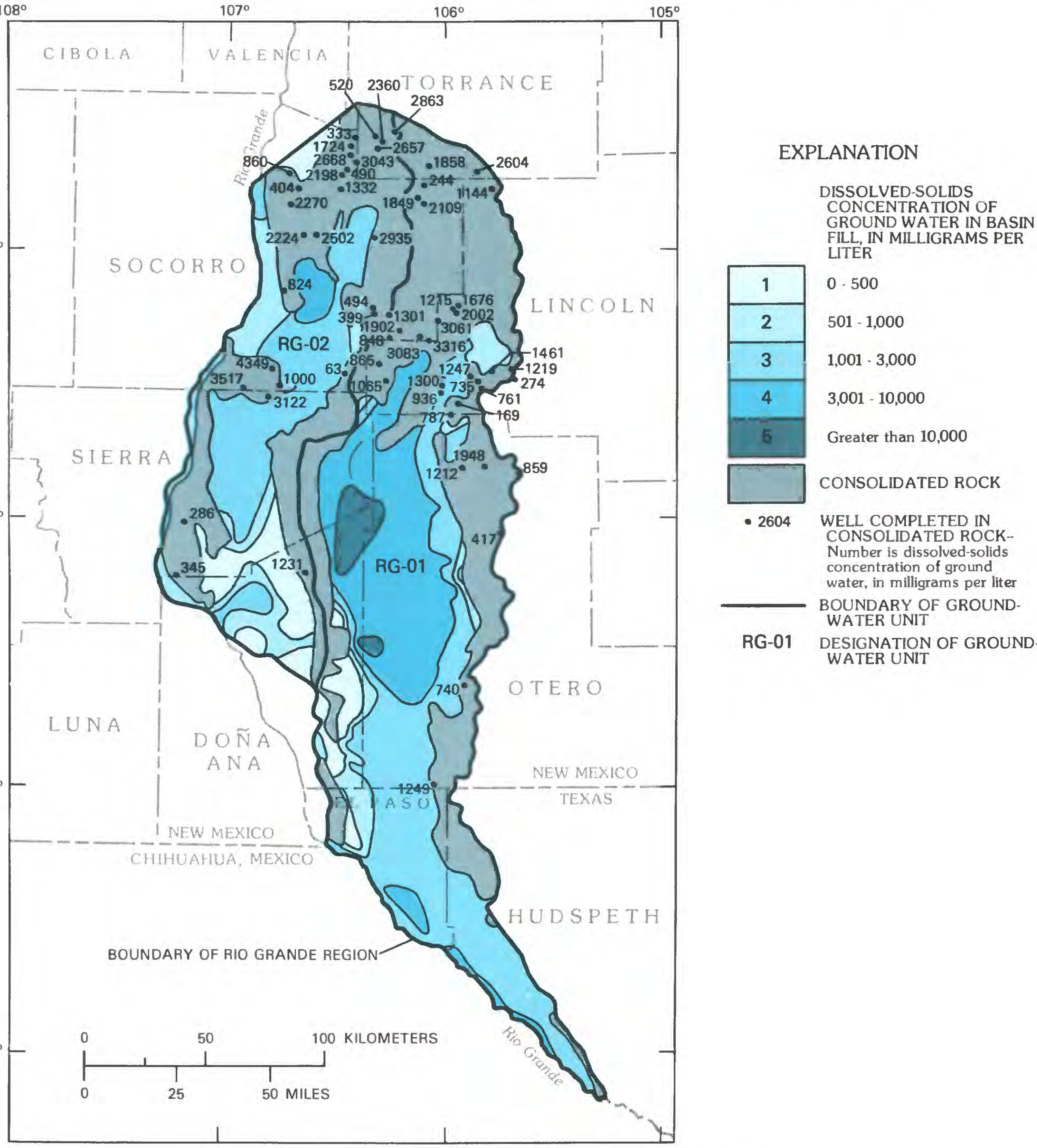

FIGURE 9.—Dissolved-solids concentration in ground water.

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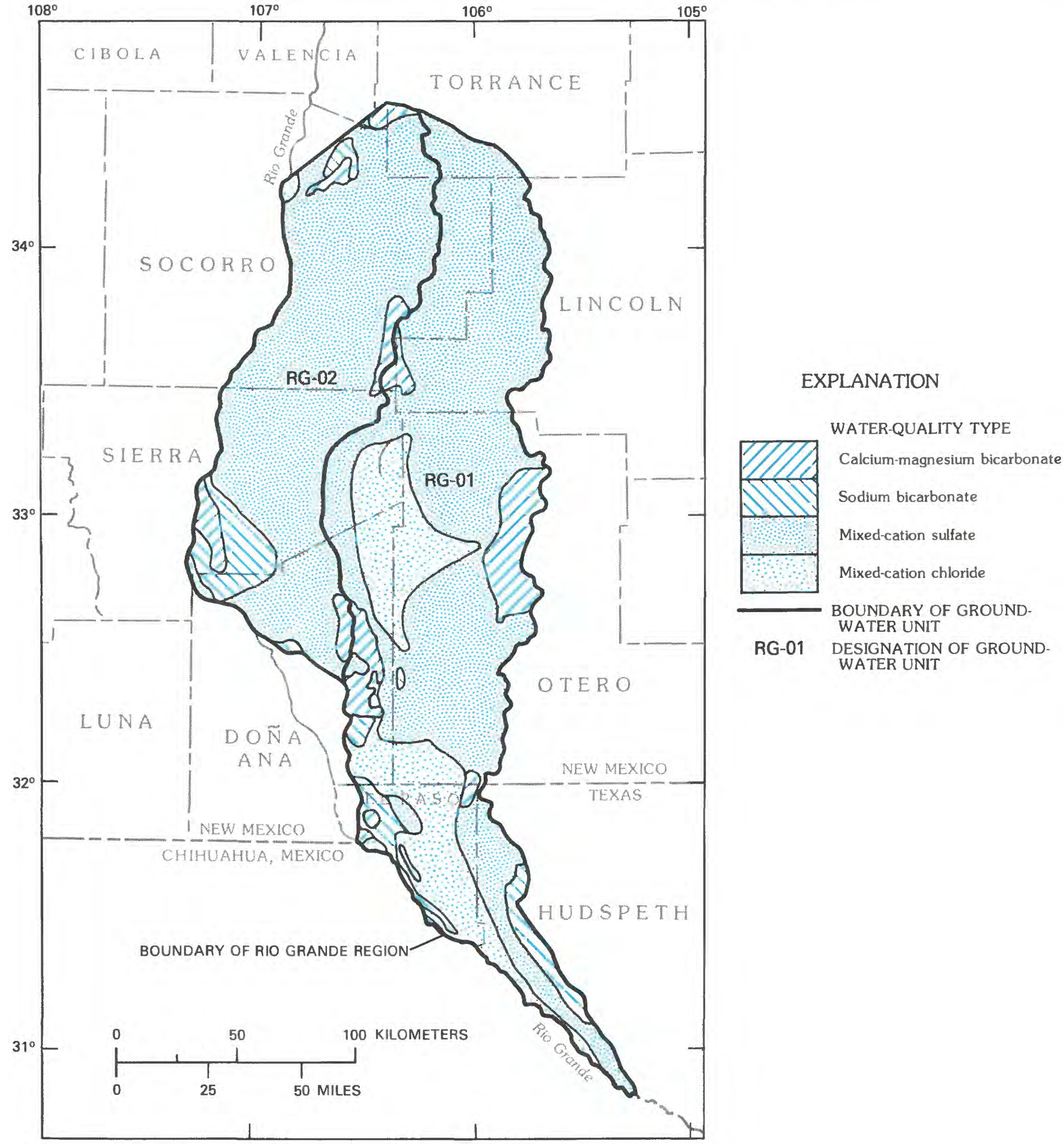

FIGURE 10.—Chemical types of ground water.

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MINERAL AND ENERGY RESOURCES

By B.T. Brady

More than 40 mining districts occur in the Rio Grande region of New Mexico and Texas (Frodey-Hutchins, 1983). These mineralized areas commonly contain base metals, and to a lesser extent, precious metals in veins and replacement deposits. The most important commodities produced from mines in these districts include lead, copper, molybdenum, iron, manganese, gold, silver, barite, and fluorite (Logsdon, 1982). Zinc and tungsten are metals of secondary importance, and small quantitites of bismuth, tellurium, uranium, thorium, vanadium, and rare-earth elements were produced locally as byproducts. Perlite, scoria, pumice, high-calcium limestone, and gypsum deposits are also of importance, mainly to local markets. Several shallow geothermal wells occur in the Rio Grande region and yield water with temperatures generally less than 50 °C. Four coal fields and one coal occurrence are located in the Rio Grande region (Tabet and Frost, 1978; Kottlowski and others, 1956). Several petroleum exploration holes have been completed in the area; however, none of these boreholes have produced significant quantities of oil, natural gas, carbon dioxide, or helium.

METALLIC MINERAL RESOURCES

The names of metal mining areas mentioned herein are those described by Frodey-Hutchins (1983) and by Henry and others (1983); the locations of these areas are shown on plate 7. The boundaries of the districts generally indicate the known limits of prospects or mines and do not delineate the extent of mineralized rock. Several deposits of different ages and types may occur within a single district, and no attempt was made to categorize the districts by metallogenic systems. The majority of the base- and precious-metal deposits in the Rio Grande region contain low- to moderate-temperature mineral assemblages, which occur in replacement deposits, fracture-controlled vein systems, or fissure fillings. Several mines in the Rio Grande region have been productive; however, the value and tonnage of ores mined to date generally has been small. The Organ and Orogrande districts are extensively developed, and mines in these areas have yielded ores valued between $1 million and $10 million (Mardirosian, 1977). A brief summary of the principal types of occurrences for the mineral deposits in each district is listed in table 3.

NONMETALLIC MINERAL RESOURCES

Nonmetallic and industrial mineral or rock occurrences are distributed throughout the study area. These deposits, excluding natural aggregates and building stone, generally have been mined on a small scale. At least 30 varieties of industrial rocks or minerals are currently known to occur in the Rio Grande region (U.S. Geological Survey, 1965; Logsdon, 1982), however, the most important industrial mineral commodities are barite, fluorite, and gypsum.

Barite is the primary commodity in 27 deposits in the Rio Grande region. This mineral commonly occurs in fissure veins, and as a gangue constituent in several fluorspar deposits (Talmage and Wootton, 1937), Permian red-bed copper deposits, and copper-bearing veins in the Sierra Caballo (Harley, 1934). Barite also is associated with base-metal vein deposits in the Chupadera and Goodfortune Creek districts, Socorro County, N. Mex. (Lasky, 1932). Barite production in New Mexico from 1918 to 1960 came from mines in eight districts in Doña Ana, Sierra, and Socorro Counties. About 31,773 Mg (megagrams, metric tons) of barite were shipped from the Hansonburg district between 1951 and 1960, and this accounted for 94 percent of the entire State barite production from 1918 through 1960 (Williams and others, 1964).

Fluorspar exists in several modes in the Rio Grande region, but the principal deposits occur in fissure veins, jasper bodies, and stratiform replacement deposits. Smaller deposits of fluorite are located in breccia pipes or zones and in stockwork deposits. Mines in 18 of the 45 presently known fluorspar districts in the study area have produced small shipments intermittently. The principal past-productive fluorspar deposits are located in the Caballo Mountains, south-central Sierra County, the San Andres Mountains, eastern Doña Ana County, and the Gallinas Mountains, northwestern Lincoln County, N. Mex. More than 10,000 Mg of fluorspar were produced from veins in Paleozoic limestones at the Illinois Group mines in the Caballo Mountains. Additionally, at least 10,000 Mg of cumulative fluorspar production came from vein deposits in Precambrian granite at the Independence Mine, Lyda-K Mine, and Red Cloud prospect in the Caballo Mountains. Several thousand metric tons of fluorspar were mined from similar vein deposits in Precambrian granite and schist at the Tonuco Mine in the San Andres Mountains. The geologic characteristics and production history of the fluorspar deposits in New Mexico are discussed in detailed reports by McAnulty (1978), Williams (1966), Gillerman (1964), and Rothrock and others (1946).

Gypsum, gypsite, and anhydrite form extensive outcrops or occur at depth throughout a significant area in the Rio Grande region. The Pennsylvanian and

TABLE 3.—*Mineral resource areas, by county (excluding coal)*

[Elements listed in the commodities column are abbreviated as follows: Ag, silver; Au, gold; Ba, barium; Be, beryllium; Bi, bismuth; Cu, copper; Fe, iron; Hg, mercury; Mg, magnesium; Mn, manganese; Mo, molybdenum; Pb, lead; Sn, tin; Te, tellurium; Th, thorium; U, uranium; V, vanadium; W, tungsten; Zn, zinc. Data from Frodey-Hutchins (1983) unless otherwise noted]

County	Mining area	Commodities	Description of deposit and host rock	References
New Mexico				
Doña Ana	Bear Canyon	Barite, Pb, V	Replacement deposits in Silurian Fusselman Dolomite.	Dunham, 1935; File and Northrop, 1966.
	Black Mountain No. 1.	Ag, Au, barite, Bi, Cu, fluorite, Pb, Zn.	Replacement deposits in Silurian Fusselman Dolomite.	Dunham, 1935; File and Northrop, 1966.
	Doña Ana Mountains.	Ag, Au	Fissure-filling deposits in rhyolite dike, cutting andesite.	Dunham, 1935; File and Northrop, 1966.
	Gold Camp	Ag, Au, barite, Bi, Cu, fluorite, Mo, Pb, Te, W, Zn.	Veins in Precambrian granite, commonly along dikes.	Dunham, 1935; File and Northrop, 1966; Lasky and Wootton, 1933.
	Hembrillo	Barite, Cu, talc	Replacement deposits associated with shear zones in Cambrian and Ordovician Bliss Sandstone and El Paso Group.	Dunham, 1935; File and Northrop, 1966.
	Northern Franklin Mountains.	Fluorite, gypsum, jarosite, Pb.	Jarosite replacement deposits in shear zones in Pennsylvanian limestone of the Magdalena Group; lead and fluorspar ore bodies in Silurian Fusselman Dolomite; bedded gypsum in Pennsylvanian rocks or Permian Hueco Formation.	Dunham, 1935; File and Northrop, 1966.
	Organ	Ag, Au, barite, Bi, Cu, fluorite, Mo, Pb, Te, W, Zn.	Fissure veins in quartz monzonite; replacement veins in Pennsylvanian limestone of the Magdalena Group; contact-metamorphic deposits along contact zone of quartz monzonite and limestone.	File and Northrop, 1966; Lasky and Wootton, 1933.
	Organ Mountains.	Ag, Au, barite, Bi, Cu, fluorite, Mo, Pb, Te, W, Zn.	Fissure veins in quartz monzonite; replacement deposits in Pennsylvanian limestone of the Magdalena Group, along contact of quartz monzonite and limestone, and in other Tertiary intrusive rocks.	Dunham, 1935; Lasky and Wootton, 1933; McAnulty, 1978.
	Rincon	Barite, fluorite, Mn, W.	Vein deposits in Tertiary extrusive rocks.	Dunham, 1935; File and Northrop, 1966.
	San Andrecito (San Andres Mountains).	Cu	Deposits along faults and fissures, in or near Precambrian granite and schist, in vicinity of quartz monzonite and other intrusive rocks.	File and Northrop, 1966; Lasky, 1932.
	San Andres Canyon (San Andres Mountains).	Barite, Pb	Deposits along faults and fissures, in or near Precambrian granite and schist, in vicinity of quartz monzonite and other intrusive rocks.	File and Northrop, 1966; Lasky, 1932.
	South Canyon	Mg?, Mn	Deposits in dolomite xenoliths within mass of quartz monzonite.	Dunham, 1935; File and Northrop, 1966.
	Tonuco Mountain.	Ba, fluorite	Veins in Precambrian rocks.	Dunham, 1935; File and Northrop, 1966.

TABLE 3.—*Mineral resource areas, by county (excluding coal)*—Continued

County	Mining area	Commodities	Description of deposit and host rock	References
Lincoln	Gallinas Mountains.	Ag, barite, Cu, Fe, fluorite, Pb, rare earths, Zn.	Deposits mainly in brecciated or extensively fractured zones within Permian Yeso Formation, intruded by syenite and monzonite porphyry of Tertiary age.	File and Northrop, 1966; Griswold, 1959.
	Jicarilla	Ag, Au, barite, Cu, Fe, W.	Veins and placer deposits within area of Tertiary monzonite and monzonite-porphyry intrusives surrounded by Permian sedimentary rocks.	File and Northrop, 1966; Griswold, 1959.
	Nogal	Ag, Au, barite, Cu, Mo, Pb, Zn.	Deposits in Tertiary volcanics (mostly andesite); also disseminated sulfide deposits in monzonite stock.	File and Northrop, 1966; Griswold, 1959.
	Tecolote Iron	Fe	Replacement deposits in Permian San Andres Limestone and Yeso Formation sedimentary rocks, near syenite, monzonite, and diorite intrusions.	Griswold, 1959; Sheridan, 1947.
	White Oaks	Au, fluorite, Fe, U, W.	Deposits along contact between monzonite intrusives of Lone Mountain and Paleozoic sedimentary rocks; also in belt of extrusive and intrusive Tertiary(?) rocks and in adjacent Cretaceous sedimentary rocks.	File and Northrop, 1966; Griswold, 1959.
Otero	Orogrande	Ag, Au, Cu, Fe, Pb, turquoise, W.	Deposits along bedding and in fractures of Carboniferous limestones near intrusive mass of monzonite prophyry.	File and Northrop, 1966; Lindgren and others, 1910.
	Sacramento (High Rolls).	Barite, Cu, marble, Pb.	Deposits in discontinuous beds, between red shale of Permian Abo Formation; also found with calcite and barite, in Permian San Andres Formation.	File and Northrop, 1966; Jerome and others, 1965.
	Three Rivers	Fe	Hematite and magnetite replacement deposits in Permian San Andres Limestone near syenite intrusions.	File and Northrop, 1966; Mardirosian, 1977.
	Tularosa	Ag, alabaster "onyx," Au, Cu.	Deposits along beds in Carboniferous(?) limestone and sandstone, and veinlets in limestone, sandstone, and diorite porphyry.	File and Northrop, 1966; Lindgren and others, 1910.
Sierra	Bearden Canyon.	Barite, Cu, Pb, Zn.	Veins in Pennsylvanian limestone of the Magdalena Group.	File and Northrop, 1966.
	Caballo Mountains.	Barite, Cu, Fe, fluorite, Mo, Pb, rare earths, Th, U, V.	Fissure veins in Pennsylvanian limestone of the Magdalena Group and Permian San Andres Limestone; probably associated with Tertiary monzonite intrusive.	File and Northrop, 1966; Harley, 1934.
	Derry	Barite, fluorite, Mn, Th, U.	Fissure-filling and replacement deposits in Paleozoic limestone mostly of Pennsylvanian age.	File and Northrop, 1966; Lasky and Wootton, 1933; McAnulty, 1978.
	Fra Cristobal	Au, Cu, Mn, Pb, Zn.	Deposits mainly in Precambrian rocks; also in Pennsylvanian, Permian, and Cretaceous rocks.	File and Northrop, 1966; Harley, 1934; Mardirosian, 1977.

TABLE 3.—*Mineral resource areas, by county (excluding coal)*—Continued

County	Mining area	Commodities	Description of deposit and host rock	References
Sierra —Continued	Goodfortune Creek.	Ag, Cu	Veins along contact of Precambrian granite with Cambrian quartzite.	File and Northrop, 1966; Lasky, 1932.
	Grandview Canyon.	Barite, Cu, W	Deposits in Precambrian granite and schist along contact with gabbro dikes.	File and Northrop, 1966; Lasky, 1932.
	Lava Gap	Barite, fluorite	Veins in Pennsylvanian limestone of the Magdalena Group.	File and Northrop, 1966; Johnston, 1928.
	Pittsburg	Au, barite, fluorite.	Placer deposits in Quaternary gravels.	File and Northrop, 1966; Harley, 1934.
	Salinas Peak	Barite, Cu, fluorite, Pb.	Veins along fault contact between intrusives and Pennsylvanian limestone of the Magdalena Group.	File and Northrop, 1966; Lasky, 1932.
	Sulphur Canyon	Cu, fluorite	Deposits in Precambrian chlorite-enriched schists.	File and Northrop, 1966; Lasky, 1932.
Socorro	Carthage	Cu, Pb	Cavity fillings along fault zone in limestone of the Magdalena Group.	File and Northrop, 1966; Lasky and Wootton, 1933;
	Chupadera	Barite, Cu, fluorite, Pb, U.	Deposits in sandstone of Pennsylvanian age and in Yeso Formation, Glorieta Sandstone, and San Andres Formation.	File and Northrop, 1966; Lasky and Wootton, 1933.
	Estey	Cu	Stratabound deposits in Permian red beds of the Abo Formation; also in cross fractures and joints.	Griswold, 1959; Johnston, 1928.
	Hansonburg	Barite, Cu, fluorite, Pb.	Deposits along faults and open-space fillings in fissures and fault breccia cavities in Pennsylvanian limestone of the Magdalena Group.	File and Northrop, 1966; Lasky, 1932.
	Jones	Fe	Contact-metamorphic deposits in Permian Yeso Formation, Glorieta Sandstone, and San Andres Formation, adjacent to monzonite dike.	Lindgren and others, 1910.
	Joyita Hills	Barite, fluorite, Pb.	Fissure veins in volcanic rocks and in limestone and quartzite of Magdalena Group, near contact with Precambrian granite.	File and Northrop, 1966; Lasky, 1932.
	Mockingbird Gap.	Barite, Cu, Pb, Zn.	Fault fissures in Precambrian and Paleozoic rocks.	File and Northrop, 1966; Lasky and Wootton, 1933.
	Rayo	Cu	Red-bed deposits in loosely cemented Permian Abo Sandstone.	File and Northrop, 1966; Lasky and Wootton, 1933.
	Scholle	Ag, Cu, U	Red-bed-type deposits in Permian Abo Sandstone.	File and Northrop, 1966; Lasky and Wootton, 1933.
Texas				
El Paso	Franklin Mountains.	Cu, Sn, W	Quartz veins in Precambrian granite and in related placer deposits.	Garner and others, 1979; Killeen and Newman, 1965; Sellards and Baker, 1934.
Hudspeth	Briggs	Anhydrite, gypsum	Deposits of Permian age.	Albritton, 1938; Withington, 1962.
	Sierra Blanca	Be, fluorite	Replacement deposits in Cretaceous limestone adjacent to contacts with Tertiary rhyolitic intrusions.	McAnulty, 1974, 1980.

Permian Panther Seep Formation contains two gypsum-bearing horizons that range from 3 to 30 m thick in the southern San Andres and northern Franklin Mountains in Doña Ana County, N. Mex. (Kottlowski and others, 1956). Gypsum was mined by the El Paso Cement Co., from a deposit in the northern Franklin Mountains (Weber, 1965). The rocks of Permian age contain at least 192 m of gypsum with interbedded limestone lenses in the Malone Mountains, Hudspeth County, Tex. (Albritton, 1938). This gypsum presumably is rehydrated anhydrite (Sellards and Baker, 1934, p. 625) that was deposited during recurrent evaporation in a restricted lagoon along the northern edge of the Permian Sea (Albritton, 1938). This deposit has been mined at the northern part of the Malone Mountains for use in the manufacture of building plaster and as a set retarder in Portland cement.

A substantial proportion of New Mexico's gypsum resources are in the Permian Yeso Formation, which underlies large areas in central New Mexico. The occurrence of clastic interbeds, solution-collapse features, and deformed strata and the presence of a resistant cap rock may locally deter gypsum production from the Yeso Formation (Weber, 1965). Cenozoic gypsum beds occur locally as lacustrine deposits, as compacted and recrystallized gypsiferous dune sands, and as caliche zones in the Tularosa basin (Weber and Kottlowski, 1959). Holocene dune sands in and adjacent to White Sands National Monument contain several billion metric tons of relatively pure gypsum (Weber and Kottlowski, 1959).

GEOTHERMAL RESOURCES

The Rio Grande rift, which trends north through the center of New Mexico, contains volcanic rocks of Quaternary age and several thermal springs that occur in areas of Quaternary faulting. There are no Known Geothermal Resource Areas (KGRA), Known Geothermal Resource Fields (KGRF), or thermal springs with temperatures in excess of 50 °C in the Rio Grande region (Swanberg, 1980). The lower Rio Grande basin may have potential for discovery of low-temperature geothermal waters (less than 100 °C); however, geothermal data are few at present and consequently, evaluation of the geothermal resources is difficult (Swanberg, 1980).

Shallow geothermal wells with temperatures greater than 50 °C, high heat flow (>2.5 HFU) (Reiter and others, 1979), and high thermal gradients (≥50 °C/km) occur near San Diego Mountain at the southern end of the Jornada del Muerto and at the Fort Bliss Military Reservation in New Mexico and Texas. Warm water (≤36 °C) from the Rio Grande Valley is used by the El Paso Water Utility at the Canutillo well field (Alvarez and Buckner, 1980). The geothermal area on the eastern flank of the Hueco Mountains contains several wells that produce water with a temperature generally less than 38 °C from depths of 146–330 m (Henry and Gluck, 1981). A well 137 m deep on the Fort Bliss Military Reservation, Tex., yielded water as hot as 58 °C (Woodruff and others, 1982.)

A summary of the geothermal characteristics of the Rio Grande rift was prepared by Reiter and others (1979). Summers (1976) described the thermal waters in the Rio Grande region, and the heat-flow characteristics of the area are discussed by Reiter and others (1975). Further discussion of current geothermal activity in New Mexico is contained in a report by Hatton and Peters (1982). The geothermal-resource potential of Trans-Pecos Texas has been described in reports by Henry (1979), Roy and Taylor (1979), and Roy and others (1983).

COAL, OIL, AND GAS RESOURCES

Four coal fields, or parts thereof, the Jornada del Muerto, Carthage, Engle, and Sierra Blanca fields, and several coal occurrences occur within the Rio Grande region of the Basin and Range province of New Mexico (Brady, 1983).

The Jornada del Muerto coal field is located in eastern Socorro County, 3 km northeast of the Carthage coal field. Upper Cretaceous coal-bearing strata presumably correlative with the Dilco Coal Member of the Crevasse Canyon Formation (Tabet, 1979) crop out along the faulted western limb of a south-plunging anticline. Coal exposed at the surface in the northern part of the field is 510 mm thick, and at the Law Mine near the center of the field, coal attains a maximum thickness of 710 mm (Tabet, 1979). The majority of these coals in the Mesaverde Group are thin and lenticular and seldom exceed 1 m in thickness. The thickest coal bed penetrated by any test hole was 2.1 m. Many of the thin coals contain common shale partings or interbeds. Chemical analyses of coal from the Law Mine indicate a high-volatile C bituminous rank with a minimal ash content and 1.3 percent total sulfur. A sample of this coal yielded more than 17 L of light oil per metric ton of coal (Reynolds and others, 1946). Much of the coal lies more than about 300 m below the surface, and underground mining of these beds, which dip 20°–40° SW, would be difficult utilizing currently available technology. No production data are available for the Jornada del Muerto coal field; however, the coals in this field are chemically similar to nearby coking coals in the Carthage field.

The Carthage coal field has an area of about 26 km^2 along the northwestern margin of the Jornada del Muerto basin in eastern Socorro County. Two principal coal beds occur on the extensively faulted nose of an anticline within the lower 30 m of the Mesaverde Group. The Carthage bed, which commonly varies between 1.5 and 1.8 m thick, is the lowermost coal bed and the principal mining target. A thin subeconomic rider bed is separated from the Carthage bed by about 0.3 m of interburden (Tabet and Frost, 1978). An unnamed bed, which occurs 9–12 m stratigraphically above the Carthage bed, has a maximum thickness of 2.1 m and has not been mined (Read and others, 1950). Mining was confined to uplifted fault blocks that are extensively fractured internally. Most of the readily accessible coal has been mined out (Tabet and Frost, 1978). High-volatile bituminous coal from the Carthage bed made excellent coke (Gardner, 1910), and early shipments were utilized by smelters in southwestern New Mexico and northern Mexico (Kottlowski, 1965).

The Sierra Blanca coal field has an area of about 1,165 km^2 in southwestern Lincoln and northern Otero Counties. Upper Cretaceous coal-bearing sediments of the Mesaverde Group crop out around the western, southern, and eastern margins of the Sierra Blanca range. Lenticular bituminous coals seldom exceed 760 mm thick. Extreme local variations in bed thickness have been reported (Wegemann, 1914), however, and coal beds 2.1 m in maximum thickness have been mined locally (Kottlowski, 1965). Coal beds are disrupted by several faults and are intruded by numerous diorite dikes and sills of the Sierra Blanca igneous complex (Fisher, 1904; Bodine, 1956). The principal production came from the Capitan and White Oaks coal districts along the eastern edge of the Sierra Blanca syncline; however, numerous other mines were active in the field for short times. More than 544,680 Mg of coal were mined prior to 1906 (Griswold, 1959), and about 2.7 Mg of coal resources remain in the field (Bodine, 1956).

The Engle coal field is in central Sierra County along the eastern side of the Fra Cristobal Range and Caballo Mountains, Thin beds of carbonaceous shale and lenticular coal commonly 200–380 mm thick occur in the lower part of the Mesaverde Group (Kelley and Silver, 1952; Kottlowski, 1965). The coal-bearing rocks dip steeply and are locally overturned along the mountain front. Dips decrease significantly eastward beneath the base of the Jornada del Muerto basin. Coal less than 3.6 m thick was penetrated by several boreholes at depths between 227 m (Darton, 1922) and 1,092 m (Tabet, 1980). Small quantities of subbituminous coal were shipped from the Southwest Lead Co. prospect in sec. 12, T. 24 S., R. 4 W., to mines near Palomas Gap to reduce metallic ores (Kelley and Silver, 1952). Two other prospects have been driven along surface coal exposures, but no production has been recorded from either property. There are presently no known occurrences of bituminous impregnated rock in the Rio Grande study area (Foster, 1965).

Black shale from the upper part of the Pennsylvanian Magdalena Formation near Scholle reportedly yields 141 L of oil per metric ton of shale when burned (Winchester, 1933). No additional occurrences of oil shale in the Rio Grande region have been described to date.

More than seventy dry oil and gas exploration holes have been completed in the Rio Grande region (U.S. Geological Survey and New Mexico Bureau of Mines and Mineral Resources, 1981; Foster and Chavez, 1983a,b,c; Bieberman and Chavez, 1983a,b,c; Brady, 1983). Shows of oil or gas or both were noted from eight holes, which range in depth from 155 to 1,209 m; there has been no production to date from these boreholes. Additionally, there are no known seeps of oil or gas in the Rio Grande region.

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