DEPARTMENT OF THE INTERIOR

THE RATIONALE FOR ASSESSMENT OF UNDISCOVERED, ECONOMICALLY-RECOVERABLE OIL AND GAS IN SOUTH-CENTRAL NEW MEXICO: A GEOLOGIC OVERVIEW AND PLAY ANALYSIS OF TWO FAVORABLE AREAS

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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ABSTRACT AND SUMMARY

Two speculative oil and gas plays have been identified for the U.S. Geological Survey's national assessment covering the area of south-central and west-central New Mexico. There is currently no petroleum production from the assessed province. Because it overlaps two physiographic provinces, this assessment province is highly diverse geologically. The plays have favorable attributes of source and reservoir rocks and trapping mechanisms, plus compatible tectonic, thermal, and burial histories to produce commercial oil and/or gas. The first area is a highly speculative unconventional play exploiting coalbed methane in Upper Cretaceous strata. It is in the Colorado Plateau of western Cibola County on the southern flank of the Zuni Mountains beneath the Quaternary basalt field in North Plains Valley. The second area is a geographically-large conventional petroleum play in the Basin and Range Province of south-central New Mexico which encompasses the late Paleozoic Orogrande basin.

Methane sorbed in coal undergoing metamorphism can be a major resource of gas. In the first play, shallow, thermogenic coalbed methane has probably been generated within nonmarine Upper Cretaceous strata which contain coal lenses and stringers and other beds with disseminated carbonaceous material. These beds have potential for generating an in-situ gas resource from sub-bituminous and high-volatile C bituminous coal by means of devolitalization. The play predominately emphasizes Dakota, Gallup, and Lower Crevasse Canyon (Dilco Coal Member) Formation reservoirs.

The coalbed methane play is in an area of high present-day heat flow. Data from surrounding outcrops indicate that geothermal temperatures and hence the maturation level (based on depth of burial) since the Late Cretaceous has not reached the threshold for peak oil generation. Quaternary basalt less than 5 million years old covers the entire play

area. The coupling of the favorable stratigraphic framework containing known coal seams and other type III hydrocarbon material with a favorable thermal history makes this a potential gas-producing area.

The Orogrande basin in south-central New Mexico constitutes the second petroleum play; it encompasses an area of 8,800-9,000 square miles. Potential reservoirs are primarily Pennsylvanian and Permian, and secondarily Mississippian. Some structural traps may have formed as a result of Late Paleozoic and Laramide compression and folding, but the traps with greatest potential are probably the algal bioherms of Mississippian through Permian age. Rocks of this time interval are about 3,500 to 6,500 ft thick. There is also a wide range in the depths of occurrence of potential reservoirs, i.e. from 2,000 to 20,000 ft due to the widespread basin-and-range block-faulting. Factors which detract from the area's potential include high-angle normal faulting in Middle to Late Cenozoic time, some late-forming traps, and possible flushing by fresh water.

South-central New Mexico is a frontier exploration province; it has been restrictive because nearly 50 percent of the play is on military land. Incentive is thus low with respect to geophysical surveying and drilling. The high percentage of shows of oil and gas, given the light drilling activity, might indicate that economic hydrocarbons are "in the system". Some stratigraphic similarities exist between this mostly shallow-water cratonic basin and the deeper-water, petroliferous Delaware basin in southeastern New Mexico.

INTRODUCTION

General Statement and Purpose

This report has been prepared for the U.S. Geological Survey's national petroleum assessment. The area of investigation (province #92) roughly includes the southwestern quadrant of New Mexico excluding Hidalgo, Luna, southern Grant, and southwestern Dona Ana counties (fig 1). Information presented herein is the qualitative component of quantitative estimates in the national assessment. A brief geologic framework and history has been synthesized for each of the two plays identified in order that deductions can be drawn about causal relationships. Outcrop information has been taken from the state geologic map of New Mexico (Dane and Bachman, 1965) and subsurface well data from the Well History Control System (Petroleum Information Corp, 1984). Some regional stratigraphic information was obtained from Frazier and Schwimmer (1987). Due to the highly diverse geology of the assessment area, which covers two physiographic provinces (fig. 2), separate sections on the tectonic and depositional settings are included for each of the two play areas.

Scope and Depth of Report

This report is a condensation of two detailed play analyses by the author. Although many of the approximately one-thousand references in my data base were consulted, only the essential or most representative ones have been cited; these provide the basic rationale, with balance among disciplines, consistent with resource assessment on a national scale. Geophysical studies supporting assessment rationale, comparative hypotheses on tectonic evolution, local structural complexities, and stratigraphic nomenclature problems have been either treated superficially or omitted.

PROVINCE #92

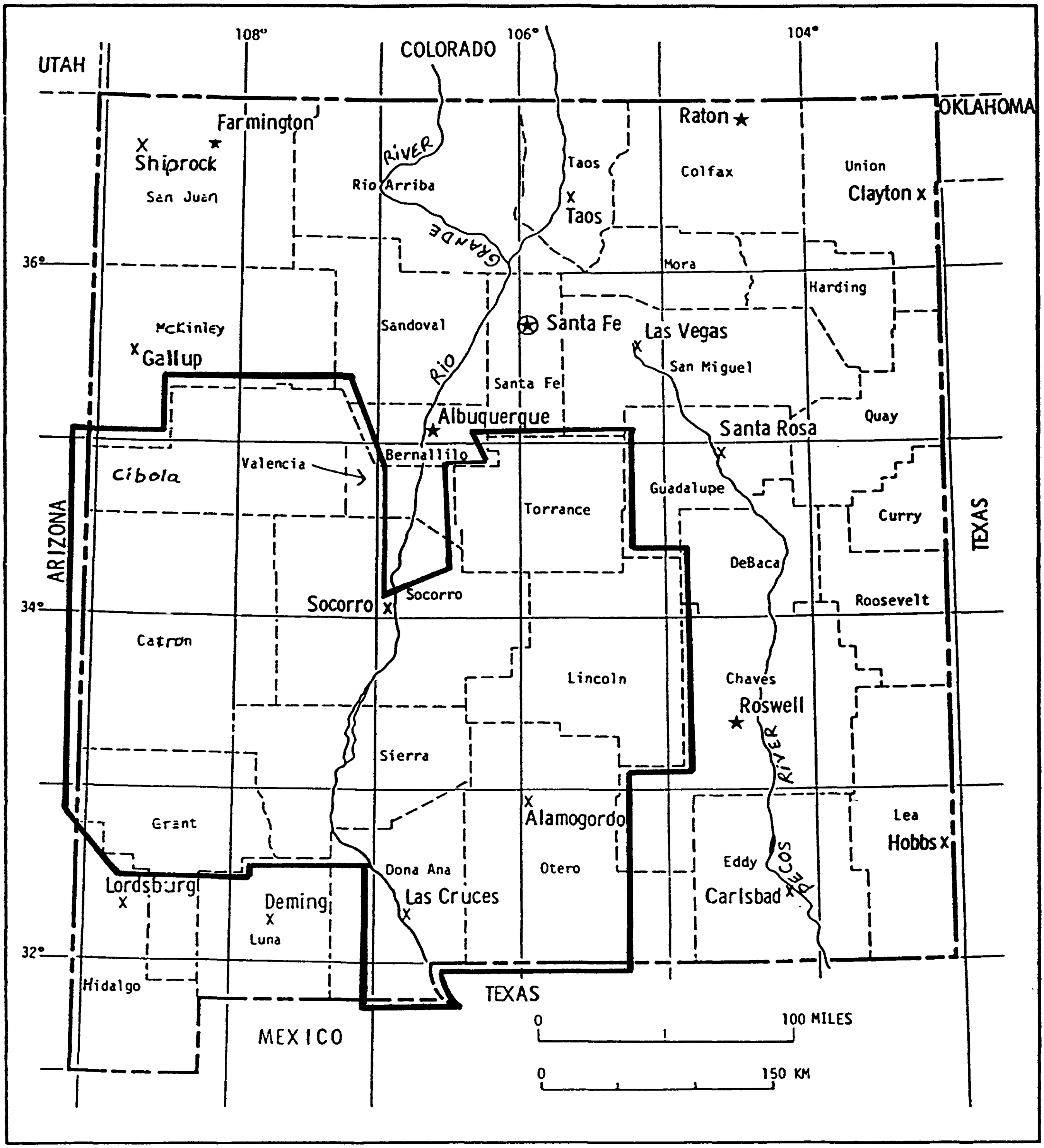

Figure 1--Map showing area assessed in south-central and west-central New Mexico. Heavy line encloses U.S. Geological Survey province #92.

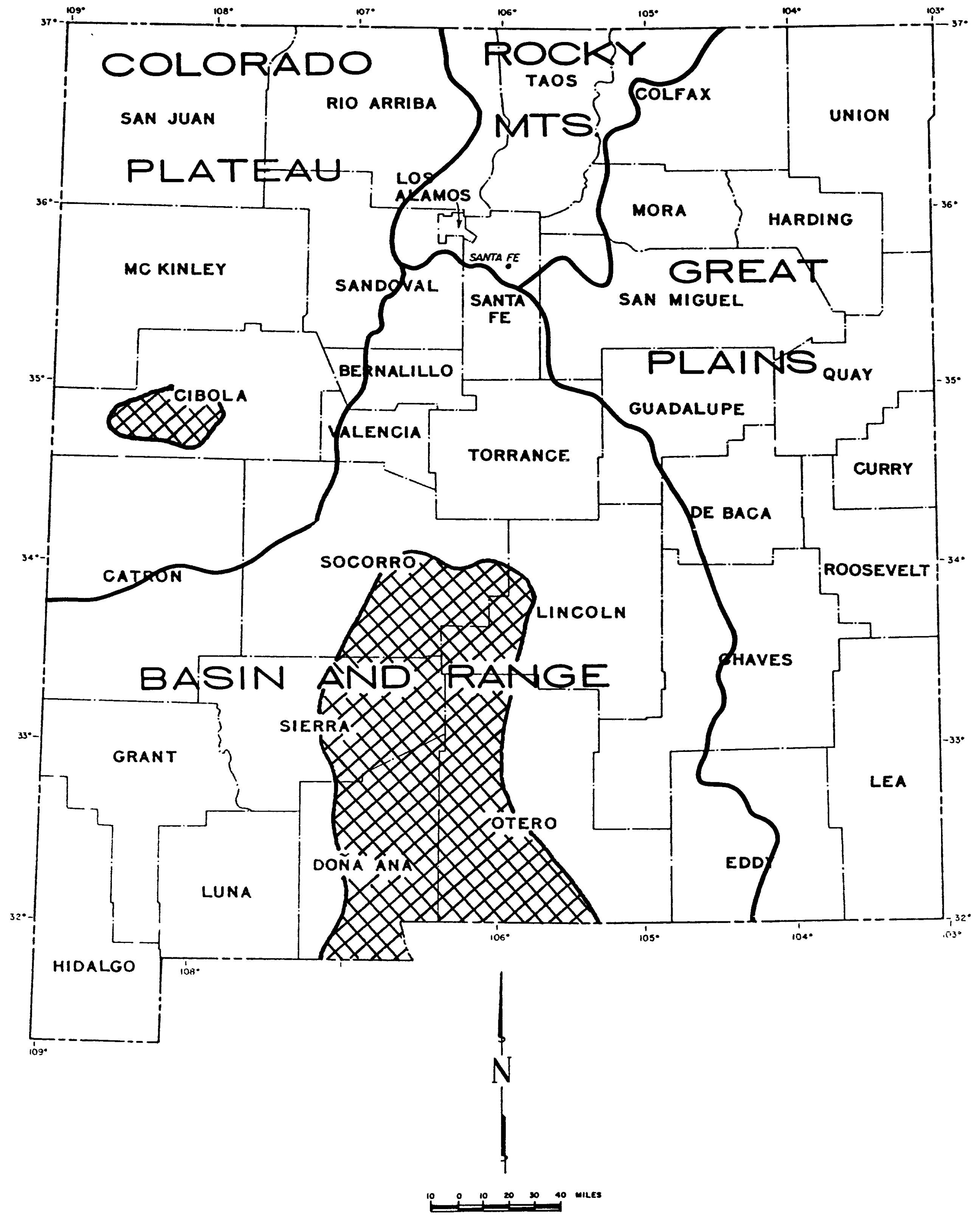

Figure 2--Map showing two speculative petroleum plays and physiographic provinces of New Mexico. Plays are cross-hatched.

GENERAL TECTONIC AND DEPOSITIONAL SETTINGS

Cretaceous Coalbed Methane Play of West-central New Mexico

Paleozoic Era

During the Proterozoic the play area was part of the Precambrian highlands; during the Paleozoic Era it was the southwestern-most part of the Transcontinental arch (TCA), an arm of the Canadian Shield positive area, extending southwestward from Minnesota (fig. 3 and 4). For paleogeographic examples of the arch in the play, see Eardley (1951), Stokes (1958), Lessentine (1965), Dott and Batten (1971), Mallory (1972), Stearn and others (1979), Woodward and Ingersoll (1979), Dickinson (1981), Lane (1982), Nydegger (1982), and Kluth (1986). The TCA in northeastern Arizona and northwestern New Mexico is variously called the Defiance-Zuni uplift, plateau, highland, and arch. It is an area where thin accumulations of Paleozoic strata were intermittently deposited on low alluvial plains and in shallow epeiric seas which onlapped basement uplifts (fig. 5). These strata were periodically eroded creating many rapid stratigraphic pinchouts and disconformities surrounding the arch. Many times during the Paleozoic Era the area was a local source of clastic sediments (fig. 6). Late Paleozoic uplift with intraplate deformation (fig. 7), is related to progressive collision of the North and South American plates. This rejuvenated erosion particularly during the Pennsylvanian Period when the Ancestral Rockies became a prominent tectonic feature (Kluth and Coney, 1981; Kluth, 1986). Permian strata, primarily red beds with some gypsum, impure carbonates, and eolian sandstones, generally thin or pinchout against the Zuni uplift from all sides (see Peterson, 1980). Late Paleozoic paleogeography alternated between a shallow marine shelf and a coastal plain where sabkha and fluvial environments prevailed. Figure 8 shows southeastward thickening of

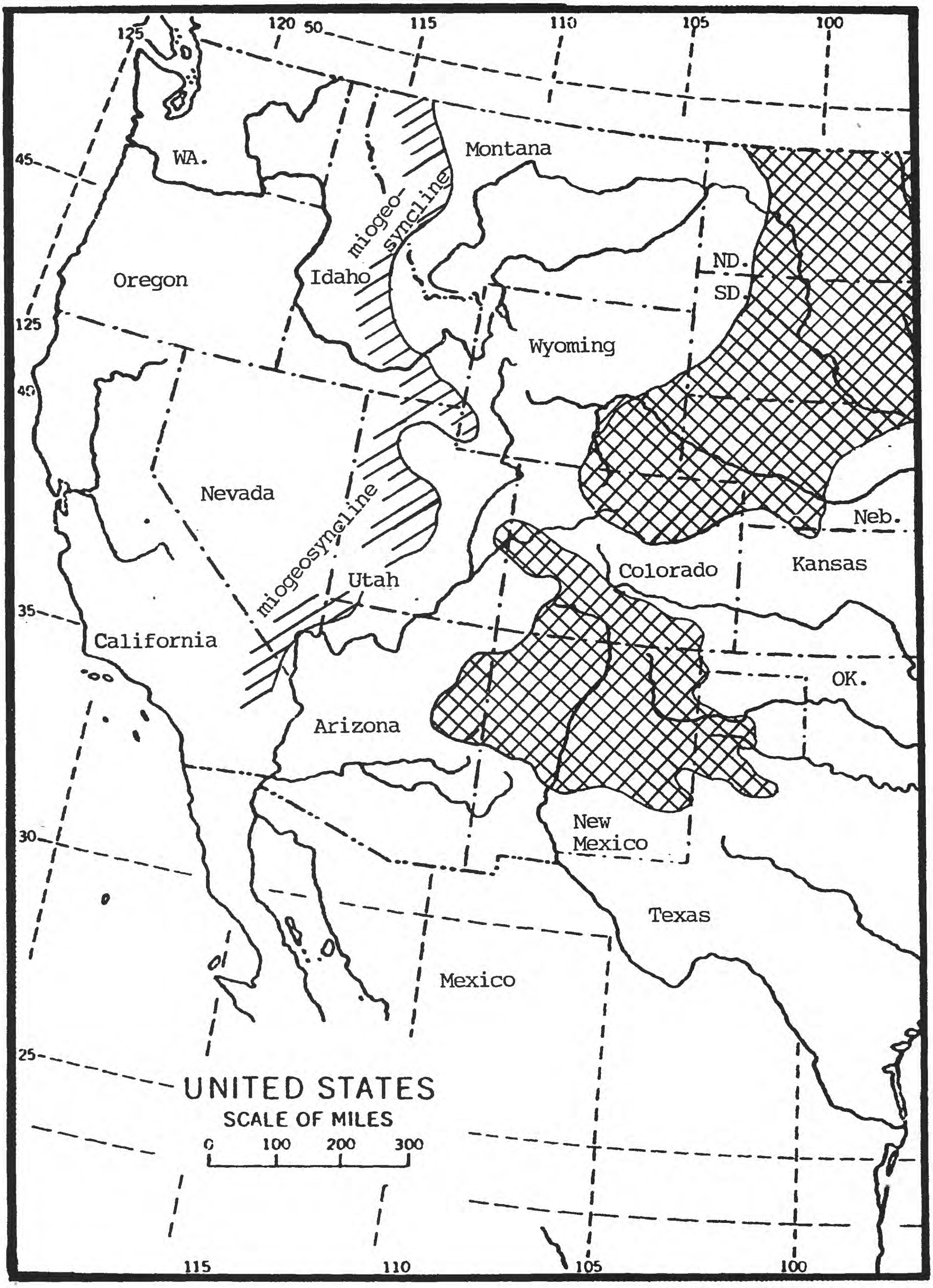

Figure 3--Map showing the Paleozoic transcontinental arch during the Cambrian Period. The arch is cross-hatched. (After Lessentine, 1965).

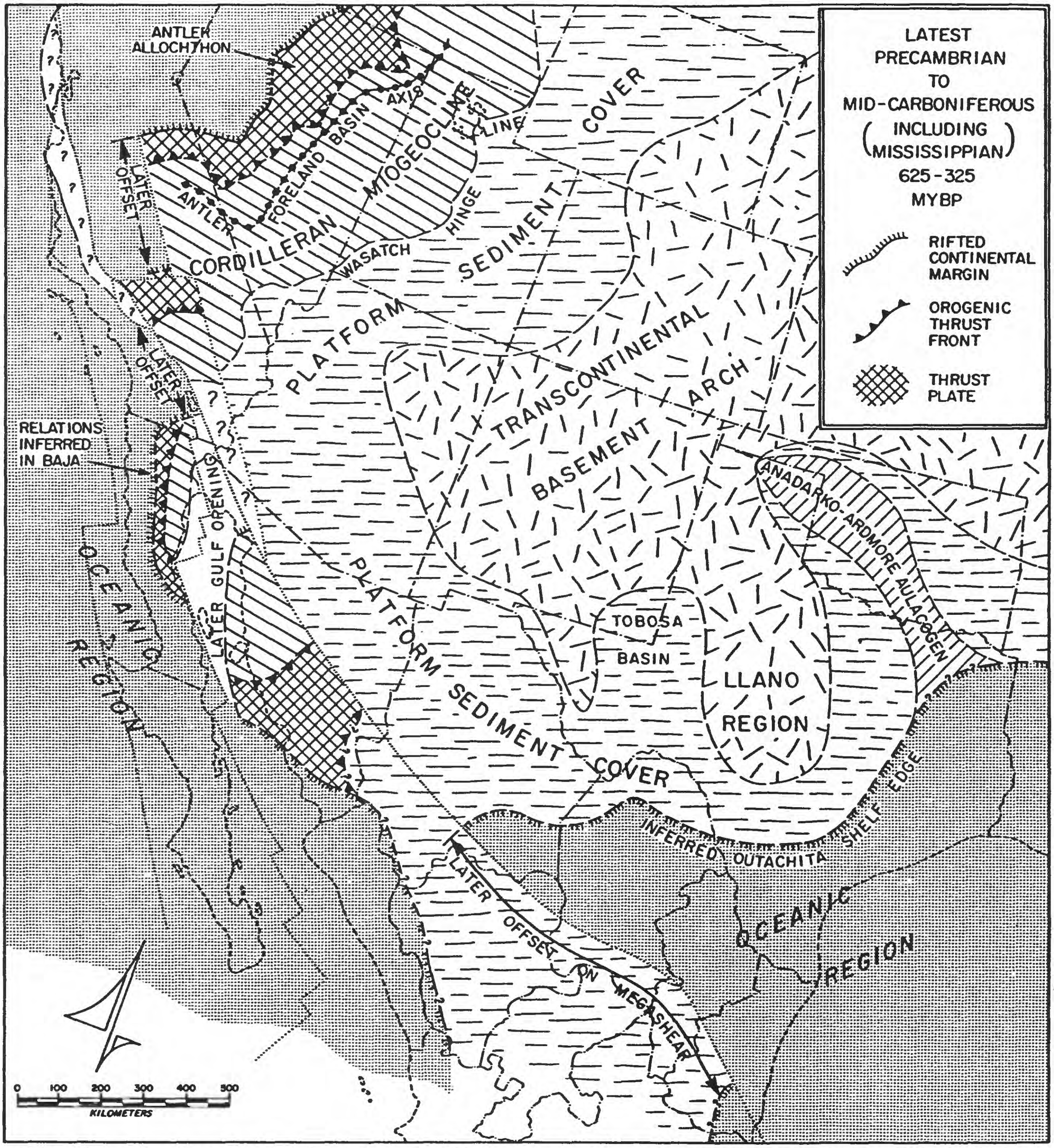

Figure 4-- Paleotectonic map of southern Cordillera, latest Precambrian to mid-Carboniferous (Mississippian-Pennsylvanian boundary) time, 625-325 myBP. Rifted continental margins to northwest and southeast of transcontinental arch of Precambrian basement formed 600-650 myBP in Cordilleran region and 500-525 myBP (Late Cambrian) in Ouachitan region. Cordilleran miogeocline is continental terrace sequence deposited along passive continental margin from latest Precambrian to latest Devonian (350 myBP) time. Wasatch hinge line marks zone of gradation between miogeolinal wedge and thinner platform succession towards continental interior. Thrust plate riding over seaward margin of miogeocline is Roberts Mountains allochthon, a subduction complex of mainly oceanic strata emplaced during Antler orogeny near end of Devonian time. Deep Antler foreland basin formed in front of thrust complex in Nevada by depression of miogeoclinal terrace under the load of the nearby allochthon. On Ouachitan margin, Anadarko-Ardmore aulacogen and Tobosa basin formed by Cambrian incipient rifting of continental block inland from prominent re-entrants in rifted continental margin. Ouachita shelf edge inferred from extent of Ouachita system in subsurface. Relations in Mojave region and Mexico interpretive. (From Dickinson, 1981).

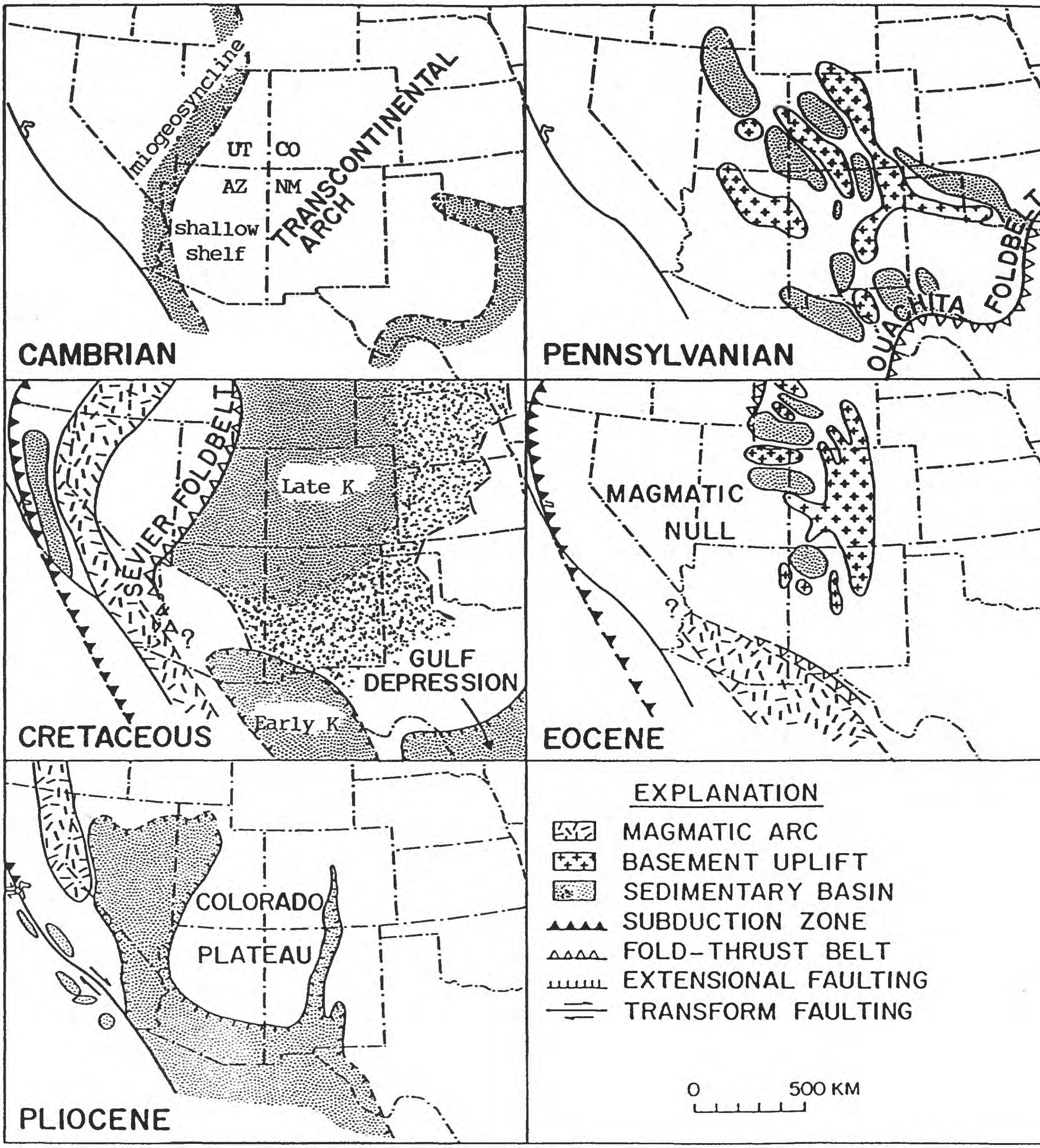

Fig. 5 --Schematic paleotectonic setting of southwestern United States. The maps are not palinspastically restored. (Modified from Woodward and Ingersoll, 1979).

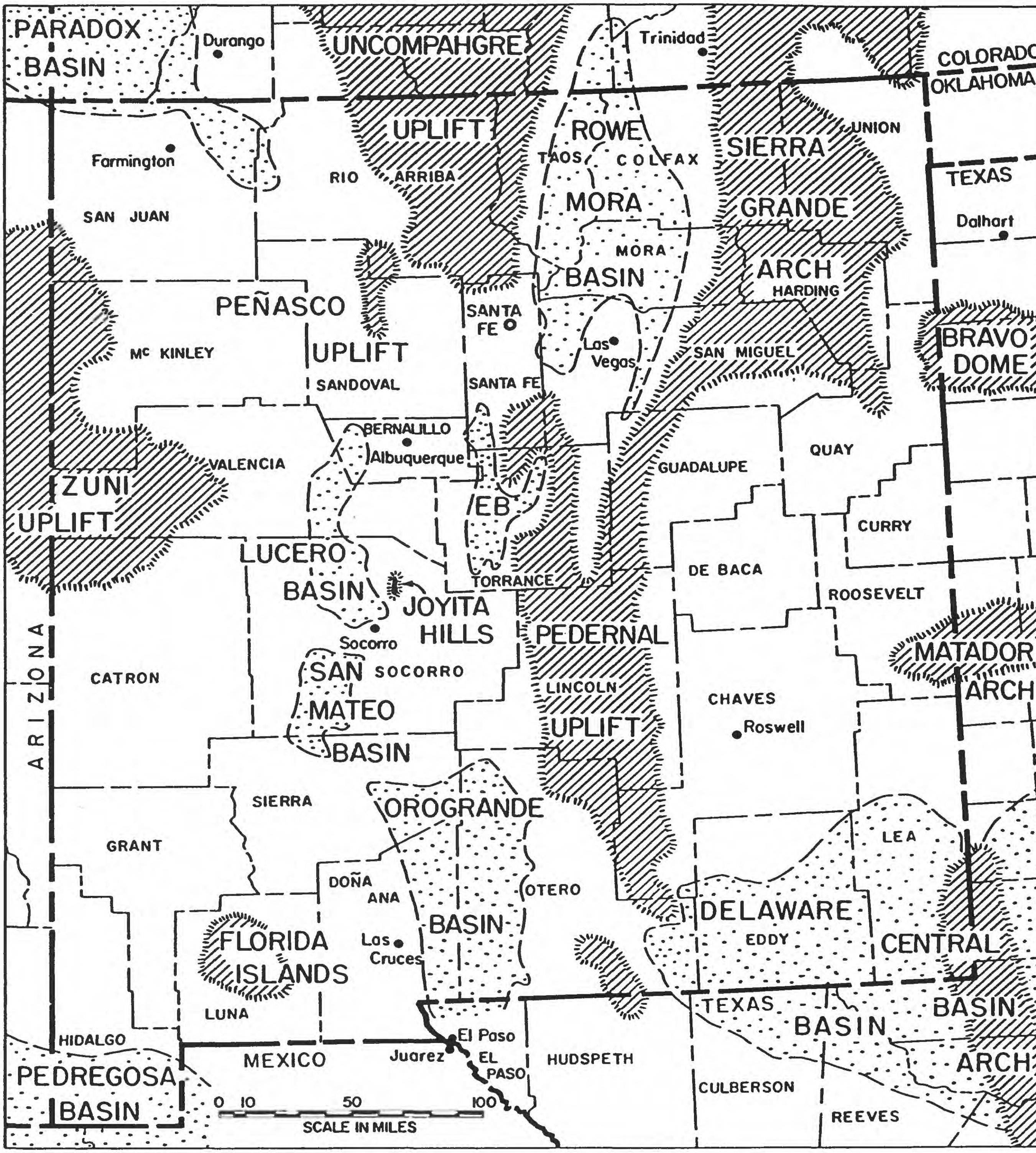

Figure 6-- Pennsylvanian paleogeographic map of New Mexico. EB is Estancia basin. (From Kottlowski and Stewart, 1970).

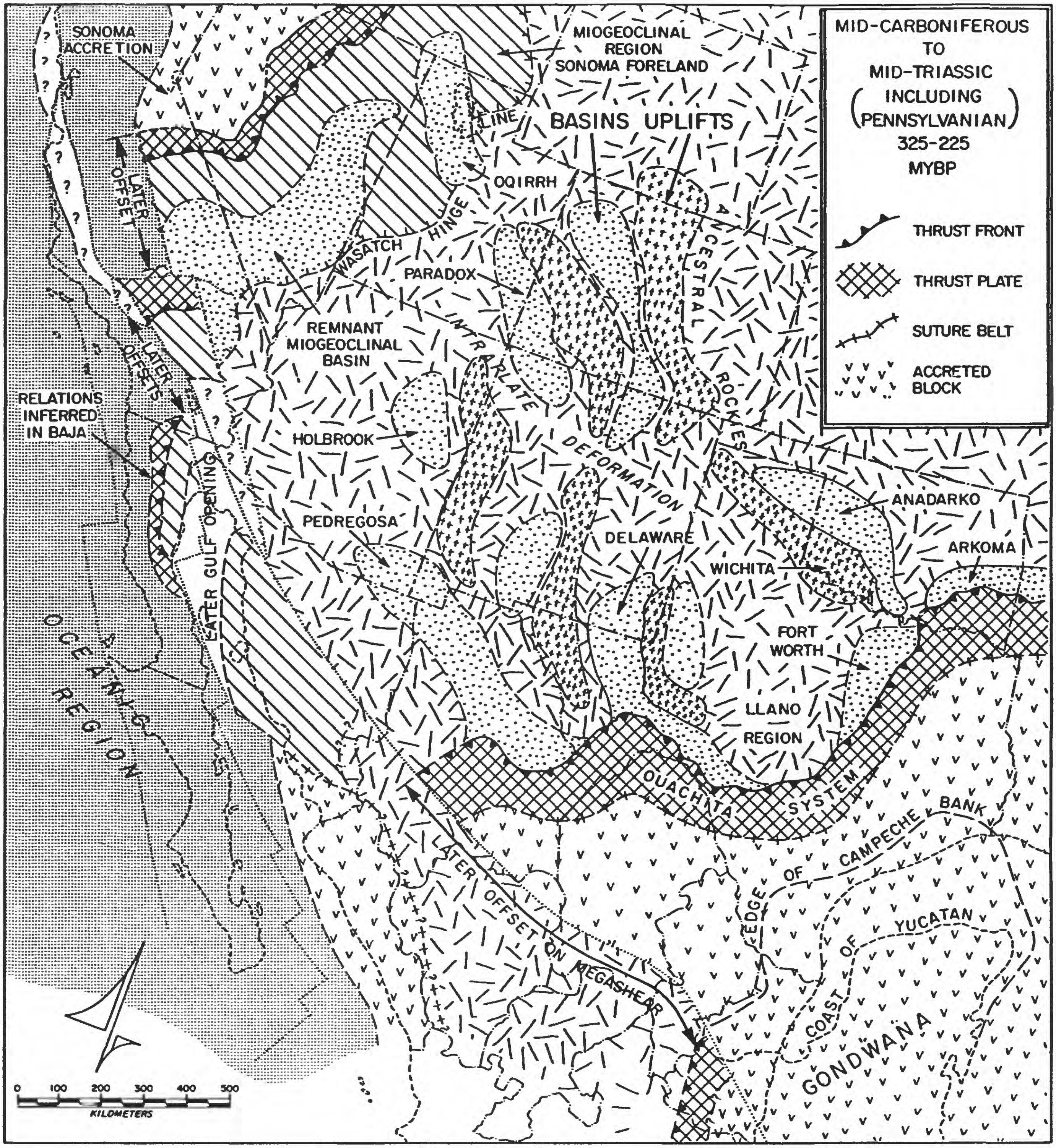

Figure 7— Paleotectonic map of southern Cordillera, mid-Carboniferous (Mississippian-Pennsylvanian boundary) to mid-Triassic (end of Middle Triassic) time, 325-225 myBP. On southeast, Ouachita system is subduction complex of Paleozoic oceanic strata thrust over previously passive continental margin during Ouachita orogeny in Pennsylvanian and earliest Permian time, 325-275 myBP (note Arkoma and Fort Worth foreland basins). Coast of modern Yucatan and edge of present Campeche Bank shown in approximate positions occupied within Pangaea, from mid-Permian to mid-Triassic time (275-225 myBP), after suturing of Gondwanan crustal blocks to the craton along the Ouachita collision belt. Pennsylvanian and Early Permian uplifts and basins of Ancestral Rockies and related systems across southern Cordillera as far as Oquirrh and Pedregosa basins formed by intraplate deformation under stresses induced by Ouachita collision orogeny. Younger thrust plate on Cordilleran margin is Golconda allochthon, a subduction complex of upper Paleozoic oceanic strata emplaced during Permo-Triassic Sonoma orogeny (275-225 myBP), when composite arc terranes were also accreted to the continental margin. Relations in Mojave region and Mexico interpretive or speculative, or both. (From Dickinson, 1981).

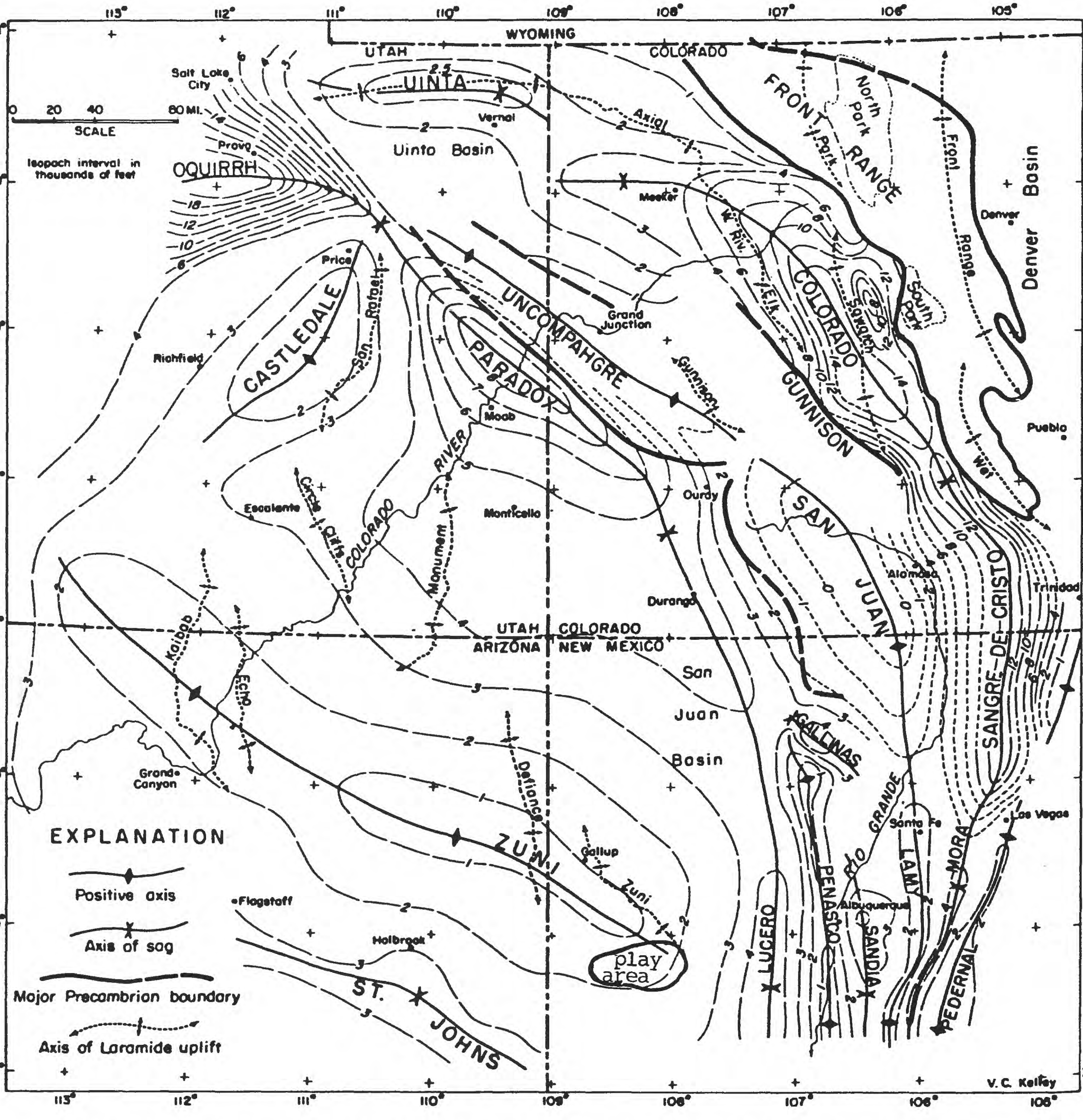

Figure 8--Permo-Pennsylvanian isopach and structural map of the Colorado Plateau and Eastern Rockies and trends of some major Laramide uplifts. (From Fassett, 1975).

Permo-Pennsylvanian strata off the Zuni uplift and location of the 2,000 foot isopach line in the play.

Mesozoic Era

Mostly red beds accumulated during the Triassic and Jurassic periods in west-central New Mexico; depositional environments included alluvial-fluvial plains, hilly lowlands, floodplains, and shallow sandy seas. By Jurassic time a northwest-trending magmatic arc had developed in southern Arizona (fig. 9). This deformation, uplift, and heating resulted from subduction of the Farallon plate along the Pacific margin. Compressive plate motion created an expansive retroarc sedimentary basin (fig. 10) which extended from the northern third of Arizona and northwestern New Mexico into Canada (Coney, 1978; Dickinson, 1981). Coastal lowlands that had developed in the Early and Middle Cretaceous were repeatedly inundated by the Western Interior seaway to the north and northeast (fig. 11 and 12) during the Late Cretaceous Epoch. At this time the Cordilleran Mountains, a major Mesozoic sediment provenance, had been rising to the southwest in central Arizona and southwestern New Mexico.

Five major northeast-southwest transgressive-regressive cycles of Late Cretaceous age have been documented in New Mexico; the two earliest ones have been preserved in the rock record across the play area. Refer to the time-stratigraphic nomenclature chart, figure 13a and b, showing the formations deposited in the San Juan basin and noting that subsequent erosion has removed the youngest cycles in the southern basin. During the Late Cretaceous, thick, widespread marine shale was deposited in an epicontinental sea; landward to the southwest, fluvial sandstone, paludal coals, and coastal plain-floodplain clastics were deposited. The reader is referred to the following literature for a more extensive account of Cretaceous stratigraphy and depositional cycles in this general area: Sears (1945),

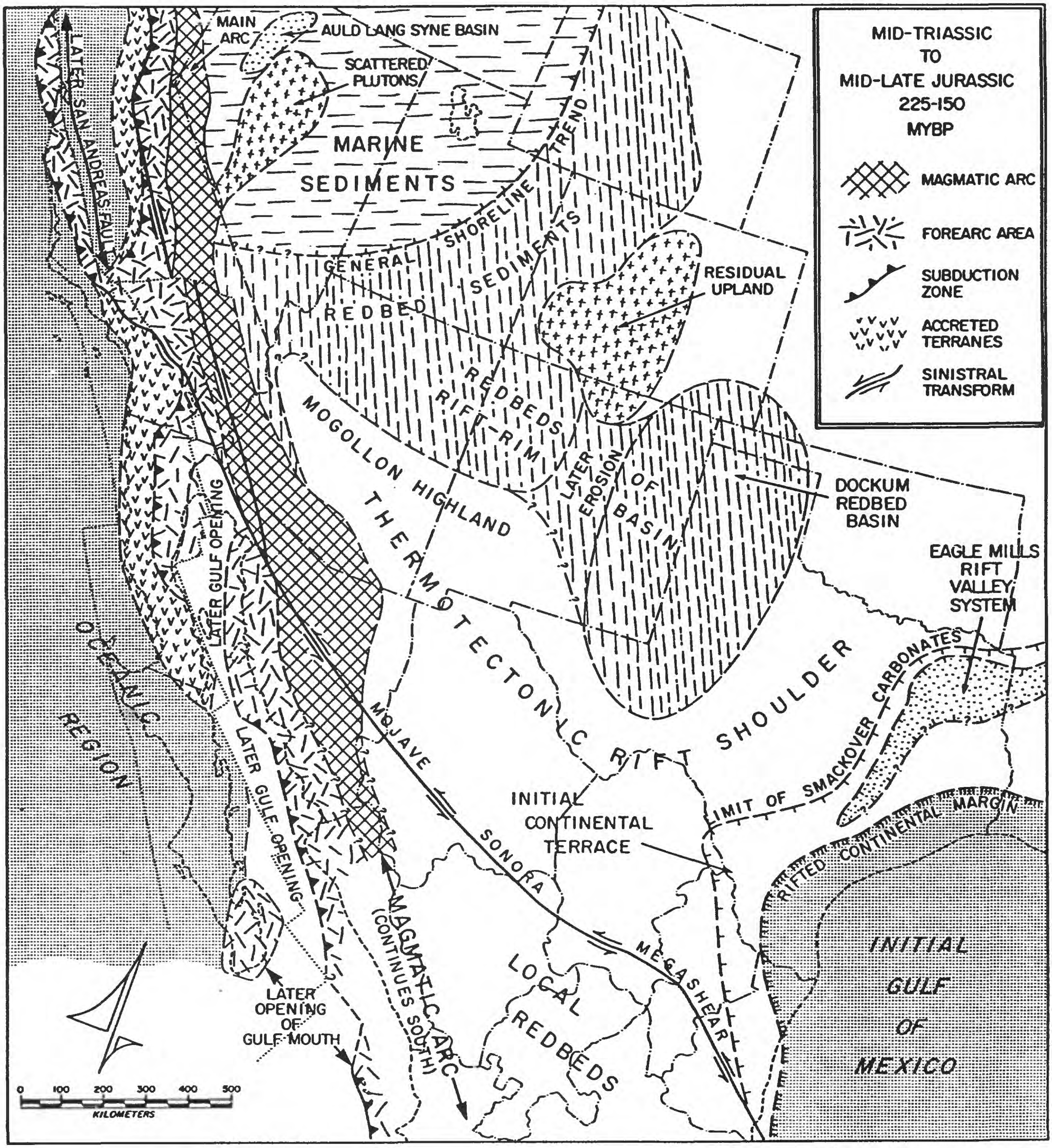

Figure 9--Paleotectonic map of southern Cordillera, mid-Triassic (end of Middle Triassic) to mid-Late Jurassic time, 225-150 myBP. In Texas, rift-valley clastics overlain by Upper Jurassic carbonates form basal horizons of Gulf Coast sediment prism whose deposition along rifted continental margin was initiated by Early to Middle Jurassic opening of oceanic Gulf of Mexico. Coordinate slip of 750-850 km on Mojave-Sonora megashear or paleotransform displaced pre-Late Jurassic terranes across Mexico. Thermotectonic uplift of edge of rifted continental block formed Mogollon highlands and related uplands separating the Gulf depression and related lowlands from an extensive rim basin, which filled with redbeds from the Colorado Plateau area to west Texas. Early to Middle Jurassic arc magmatism formed the initial volcanoplutonic complexes of the circum-Pacific arc-trench system along the Cordilleran margin. Mid-Late Jurassic accretion of intra-oceanic island arc terranes to the Cordilleran margin caused the subduction zone to step outward from locations now inland to locations near the present coast. Probable extension of Cordilleran magmatic arc southward into central Mexico not well controlled. (From Dickinson, 1981).

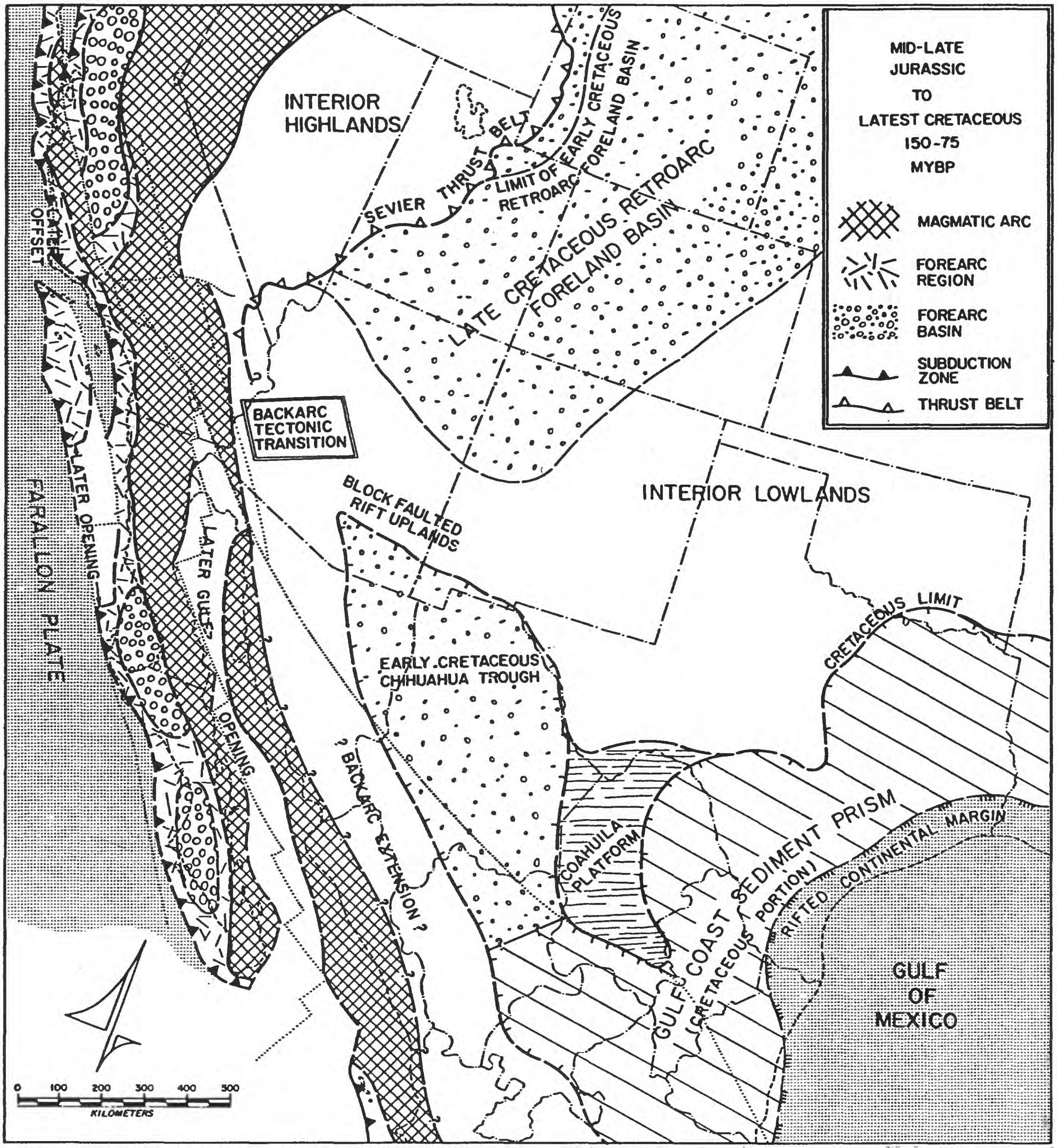

Figure 10—— Paleotectonic map of southern Cordillera, mid-Late Jurassic to latest Cretaceous (Campanian-Maestrichtian boundary) time, 150-75 myBP. Continued subsidence of rifted continental margin adjacent to Gulf of Mexico was accompanied by marked Cretaceous transgression of flank of continental block. Marine invasion of Chihuahua Trough through passage connecting with Gulf of Mexico south of Coahuila Platform extended by mid-Cretaceous time (100 myBP) as far as region of backarc extension in Arizona where Bisbee Group was deposited. Farther north, backarc contraction along Sevier thrust belt induced mainly Late Cretaceous (100-75 myBP) subsidence in Rocky Mountain retroarc foreland basin as broad flank of continental block was flexed downward beneath tectonic load of foreland thrust sheets. Broad and continuous magmatic arc along Cordilleran margin formed major batholiths in Sierra Nevada and Peninsular Ranges, while major forearc basins developed in Great Valley of Alta California and beneath Vizcaino Desert in Baja California. Accretionary Franciscan subduction complex grew in bulk and width within Coast Ranges of Alta California and along coastal fringe of Baja California. (From Dickinson, 1981).

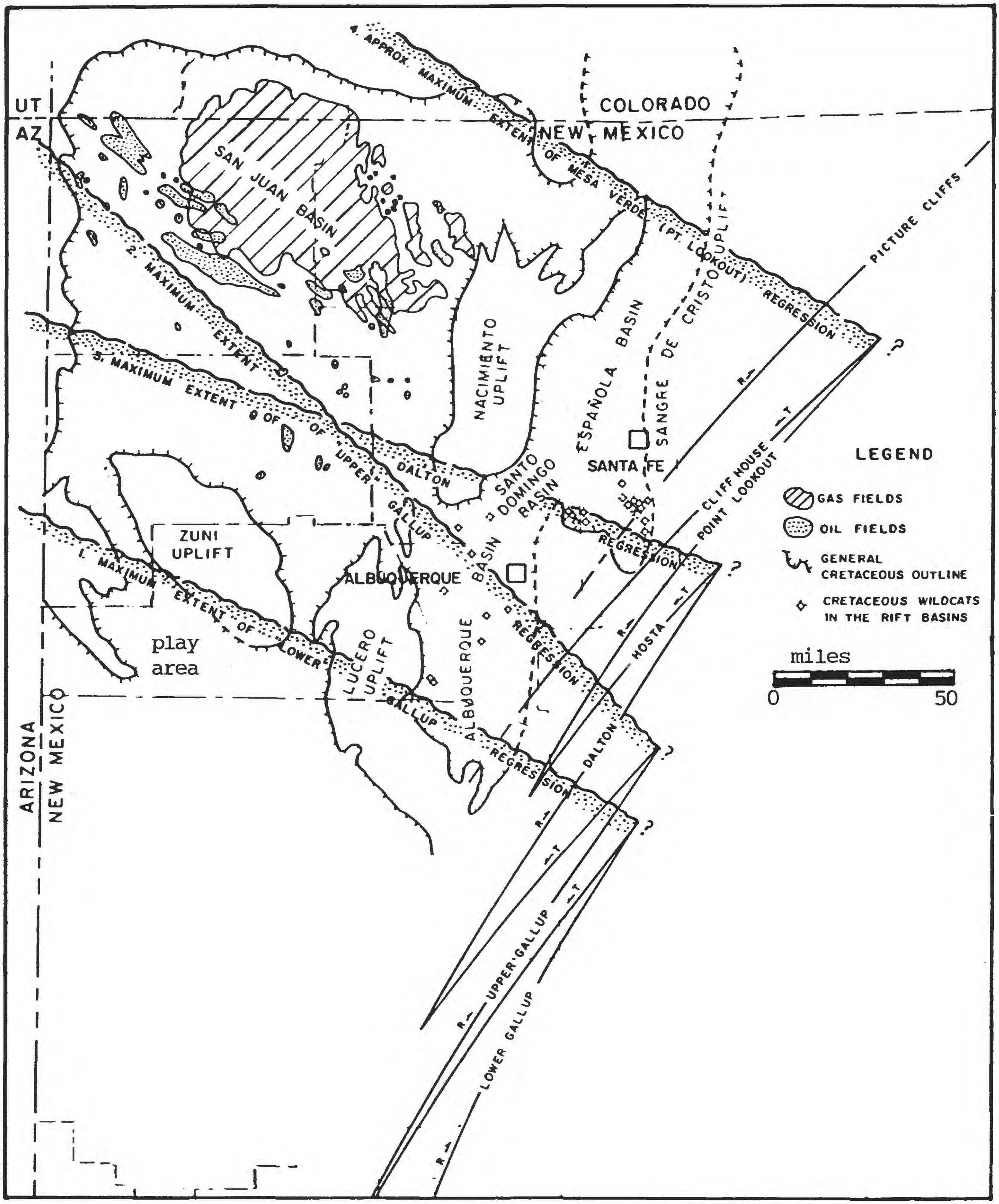

Figure 11--Map showing Cretaceous strand lines and maximum extent of regression in northwestern New Mexico. (From Black, 1983).

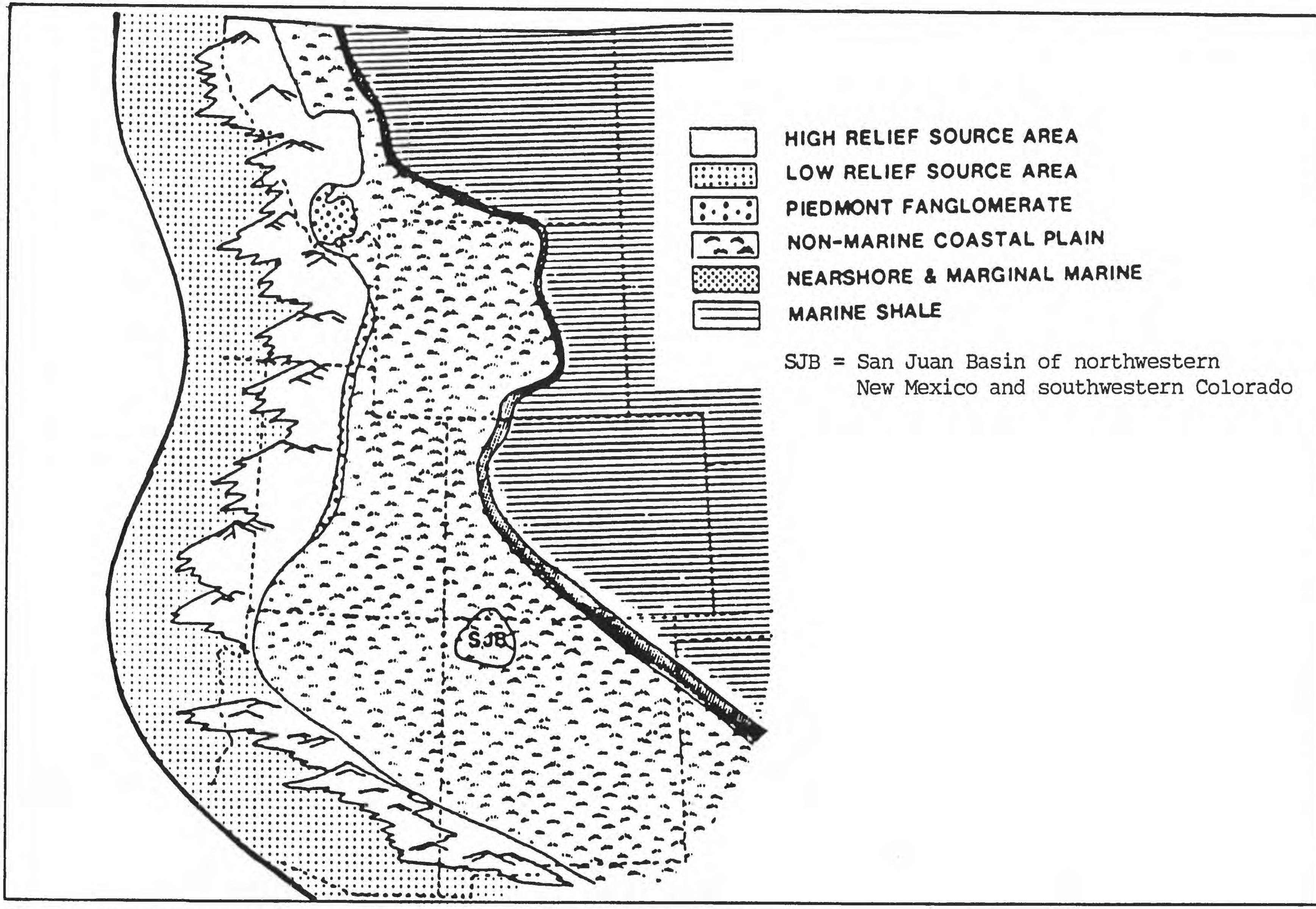

Figure 12--Paleogeography of the western margin of the western interior seaway during Late Cretaceous (Latest Campanian) time. (From Cumella, 1983).

TIME-STRATIGRAPHIC NOMENCLATURE CHART
(SAN JUAN BASIN)

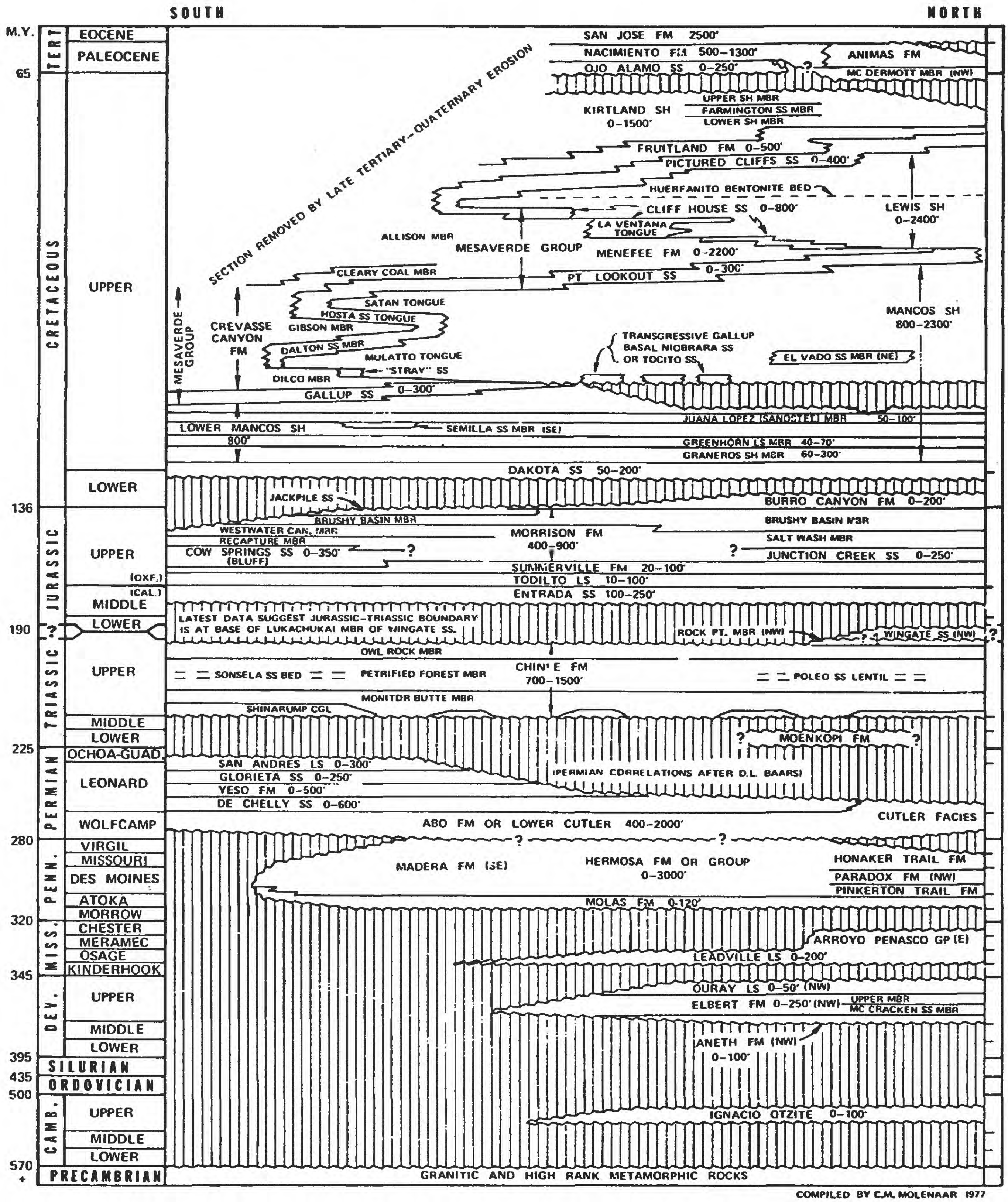

Figure 13a--Time-stratigraphic nomenclature chart, San Juan basin, New Mexico. (From Molenaar, 1978).

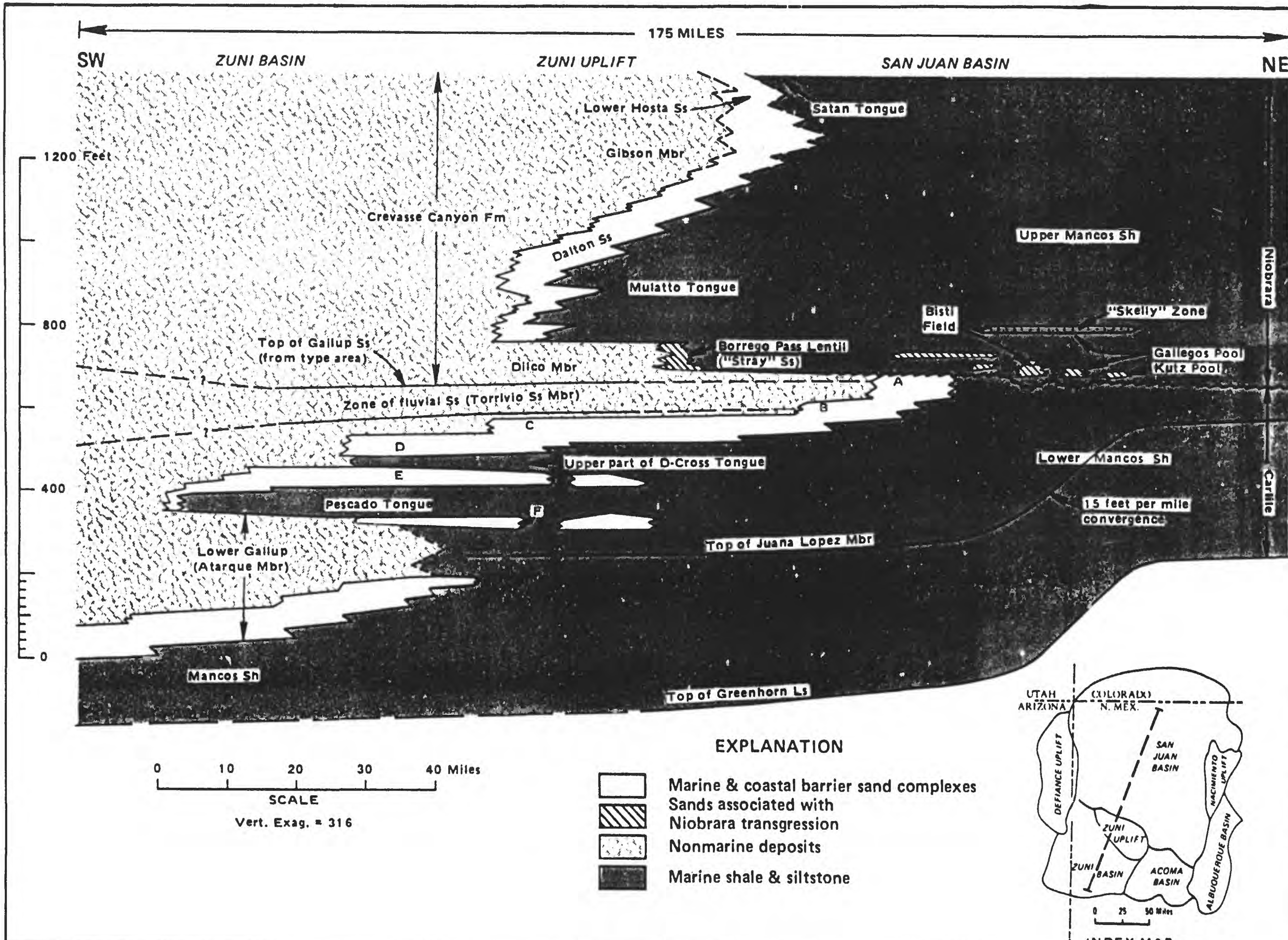

Figure 13b--Regional cross-section showing stratigraphic relationships of Gallup Sandstone through the Zuni basin and central San Juan basin. (From Molenaar, 1974).

Sears and others (1941), Dane (1960), Weimer (1960), Young (1960 and 1973a, b), Kauffman (1969 and 1977), McGookey (1972), O'Sullivan and others (1972), Molenaar (1973, 1974, 1977, and 1983a, b), Williams and Stelck (1975), Maxwell (1976), Cumella (1983), Hook (1983), Rice and Gautier (1983), Roybal and others (1987), and Kirk and others (1988).

Although major uplifts affected the Zuni area during the Late Paleozoic and Laramide orogeny, deformation was only mild relative to other areas surrounding the present-day Colorado Plateau. Northeast yielding (compression) of the Colorado Plateau (fig. 14) "microplate" during the Laramide orogeny (Woodward, 1973; Woodward and Callender, 1977), accompanied by clockwise rotation (Hamilton, 1981), rejuvenated and further established the northwest trend of the Zuni Mountains, a doubly plunging uplift, marking the northern limit of the play.

Cenozoic Era

The Cenozoic history of the present-day Colorado Plateau province involves primarily regional but differential uplift and erosion; in northwestern New Mexico there was local deposition of thick Paleogene continental sediments, and Neogene and Quaternary normal faulting and erosion (see Hunt, 1956; Smith and Eaton, 1978). In the play area depositon of pyroclastic debris plus small-scale (?) rifting and northwest-trending dike emplacement characterize the Oligocene (Vaniman and others, 1981; Laughlin and others, 1983). Several thousand feet of Cretaceous and Tertiary strata were removed from west-central New Mexico during and since the Miocene, although some non-volcanic continental deposits of Eocene age remain. During this same time interval, small-scale (?) rifting and extrusion of basalt also occurred. The Colorado Plateau is bounded by zones of extensional faulting that are currently growing at the expense of the plateau. Helmstaedt (1974), Elston (1976), Bird (1979),

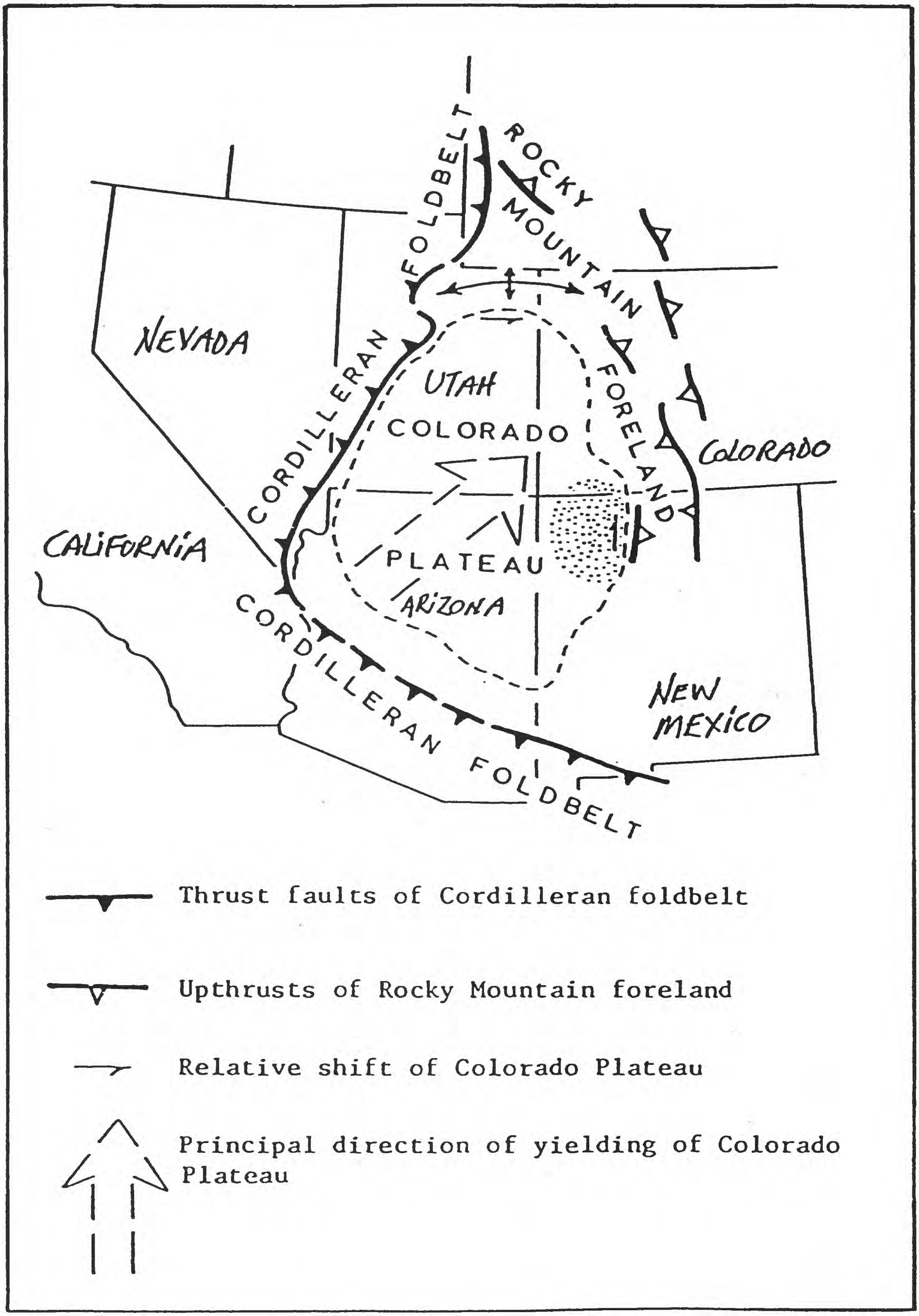

Figure 14-- Generalized tectonic map showing Cordilleran fold-belt, Colorado Plateau and Rocky Mountain foreland. San Juan basin stippled. (From Woodward and Callender, 1977).

and McGetchin and others (1979) have provided a comprehensive account of the volcanic history and uplift mechanisms of the Colorado Plateau as related to overplating, delamination, and general tectonic evolution.

A strong case can be made for the existence of a regional, northeast-trending lineament (Springer-Raton/Jemez lineament) passing through the play area. It is traceable from the Wheeler Peak area northeast of Taos, NM., to the Redondo Peak/Jemez Mountains volcanic area (west of Los Alamos, NM.) southwest to the Mt. Taylor Volcanic Field (northeast of Grants, NM.) into the White Mountains Volcanic Field of east-central Arizona. This 350-mile long lineament can be inferred from geothermal/geophysical anomaly maps, state geologic maps, and satellite-imaged maps, such as by Summers (1965), and Kelley and others (1982). The lineament parallels the oft-reactivated primary fracture pattern of the Precambrian crystalline basement which is well documented by many studies. It also corresponds to a Mid-Tertiary trend of high thermal anomalies. Lambert (1966), Landwehr (1967), Chapin and others (1978), Lipman (1980), and National Petroleum Council (1980) have located this large-scale trend (fig. 15, 16, and 17).

Late Paleozoic Orogrande Play in Eastern-most Basin and Range Physiographic Province of South-central New Mexico

Paleozoic Era

Precambrian crust (Mazatzal Province) consists of Early Proterozoic metamorphic craton intruded by Middle Proterozoic granite (Condie and Budding, 1979; Condie, 1981). Upper Cambrian through Middle Permian strata were intermittently deposited as platform cover in a shallow to occasionally-deep shelf environment in nonconformable contact with the Precambrian basement (see fig. 4 and 7). Cambrian seas generally transgressed northeastward across the southwestern edge of the North

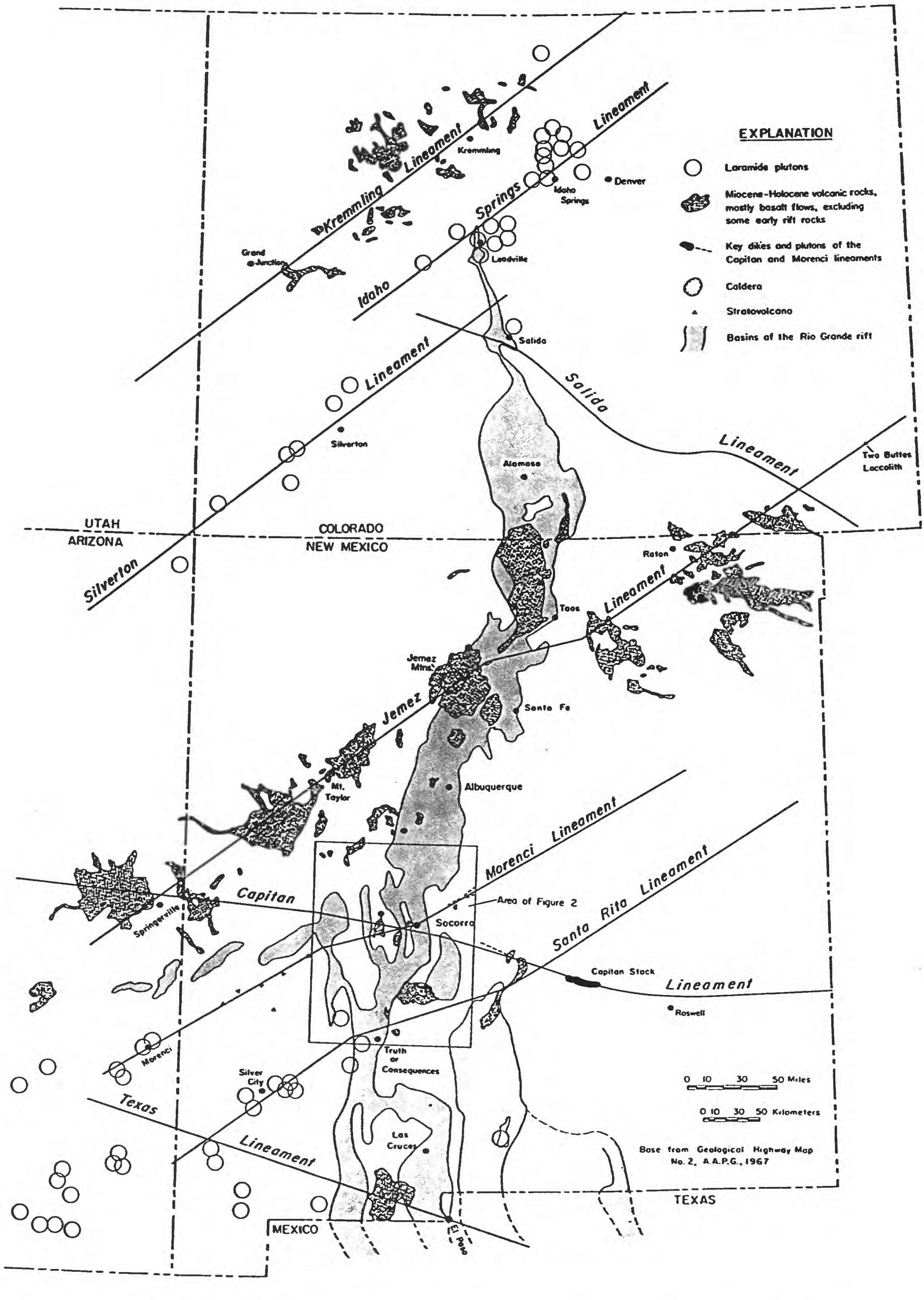

Figure 15--Generalized tectonic map of the Rio Grande Rift and major crustal lineaments. (From Chapin and others, 1978).

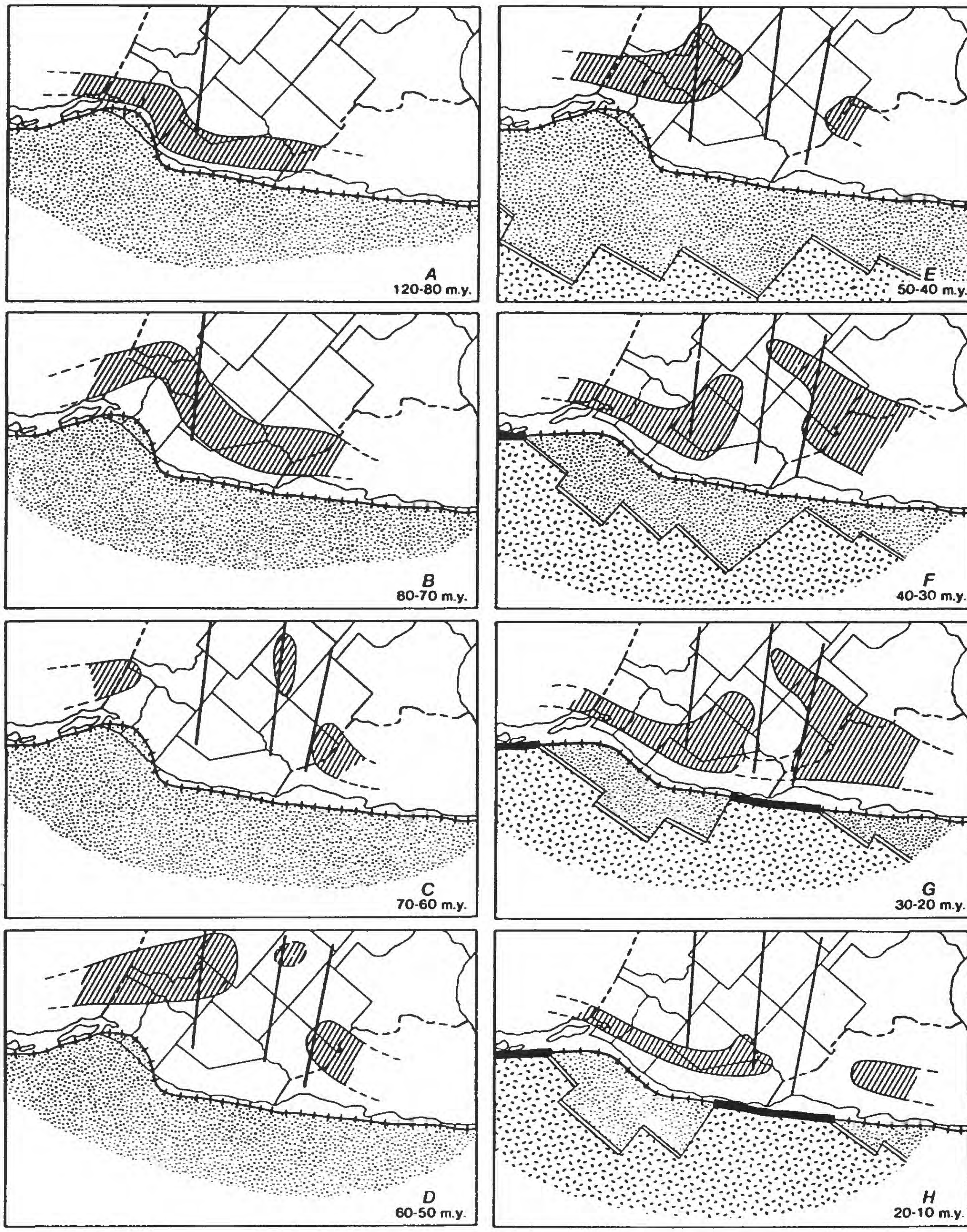

FIGURE 16—Generalized distribution in the western United States of predominantly andesitic volcanic suites, inferred to be related to subduction. Distributions are based on compilations (Lipman *et al.*, 1972; Snyder *et al.*, 1976; Stewart and Carlson, 1976; Armstrong *et al.*, 1977; Cross and Pilger, 1978) and on descriptions of local areas too numerous to cite individually. The base maps and diagrammatic plate geometry are from Atwater (1970) and Atwater and Molnar (1973). No attempt has been made to remove effects of late Cenozoic extensional and rotational deformation, even though such effects are probably large (Hamilton and Myers, 1966). Northeast-trending lines mark approximate traces of the Snake River–Yellowstone zone, the Colorado mineral belt, and the Springerville–Raton zone. (From Lipman, 1980).

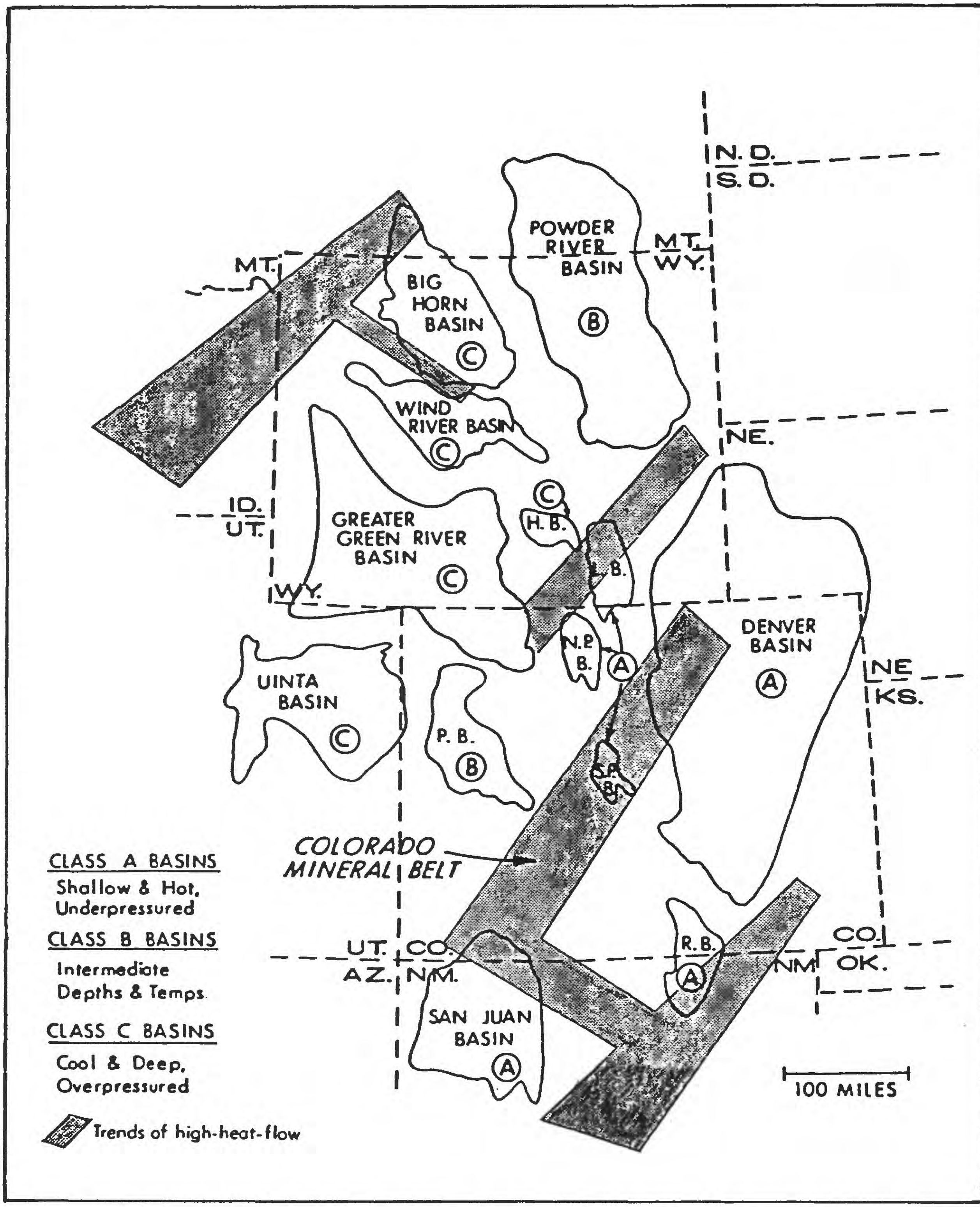

Figure 17--Generalized thermal trends in Rocky Mountain region showing shallow, hot basins, northern New Mexico. R.B.=Raton basin, P.B.=Piceance basin, L.B.=Laramie basin, S.P.B.=South Park basin, N.P.B.=North Park basin, and H.B.=Hanna basin. (From National Petroleum Council, 1980).

American Craton depositing tightly-cemented, glauconitic littoral sands. Fossiliferous carbonates of Early Ordovician age were conformably deposited in warm, tropical shallow seas south of the paleo-equator; they increase in thickness from north to south in the play. Silurian dolomite is 1,000 ft or more thick near El Paso and contains small bioherms (Kottlowski and Pray, 1967). Upper Ordovician and Lower Silurian carbonates reflect intertidal to supratidal environments. Carbonates accounted for over 2,000 ft of rock thickness before sea level fell and erosion reduced their present thickness. Conditions changed in Late Devonian time to a sediment-starved basin (fig. 18). Calcareous, argillaceous, and sandy sediments were laid down at this time; thicknesses range from a few ft in the north to 175 ft in the southwestern play area (Poole and others, 1967; Kottlowski, 1969a).

The Mississippian Period is characterized by deposition of fossiliferous intertidal carbonates mostly in the northern part of the play to subtidal starved-basin argillaceous and cherty carbonates in the southern part; thickness increases from a zero erosional edge in the north to 500-600 ft in the south (fig. 19, 20, and 21). Wilson (1970) believed the thin-bedded, silty and cherty carbonates and limey mudstones that are known in the Franklin, Hueco, and Sacramento Mountains, represent deep water conditions during the Mississippian. Regional arching (Penasco dome), a feature related to the Paleozoic TCA, exposed Precambrian rocks in central New Mexico. Thicker sedimentary sections in a possibly rapidly subsiding depocenter surrounded by "shelf" (indistinct shelf break according to some authors) lagoons in extreme south-central New Mexico, was the first indication of the incipient Orogrande basin principally of Pennsylvanian age (fig. 5, 6, and 7). Northward, Mississippian through Precambrian rocks are progressively overlapped by Pennsylvanian strata (see Meyer, 1966).

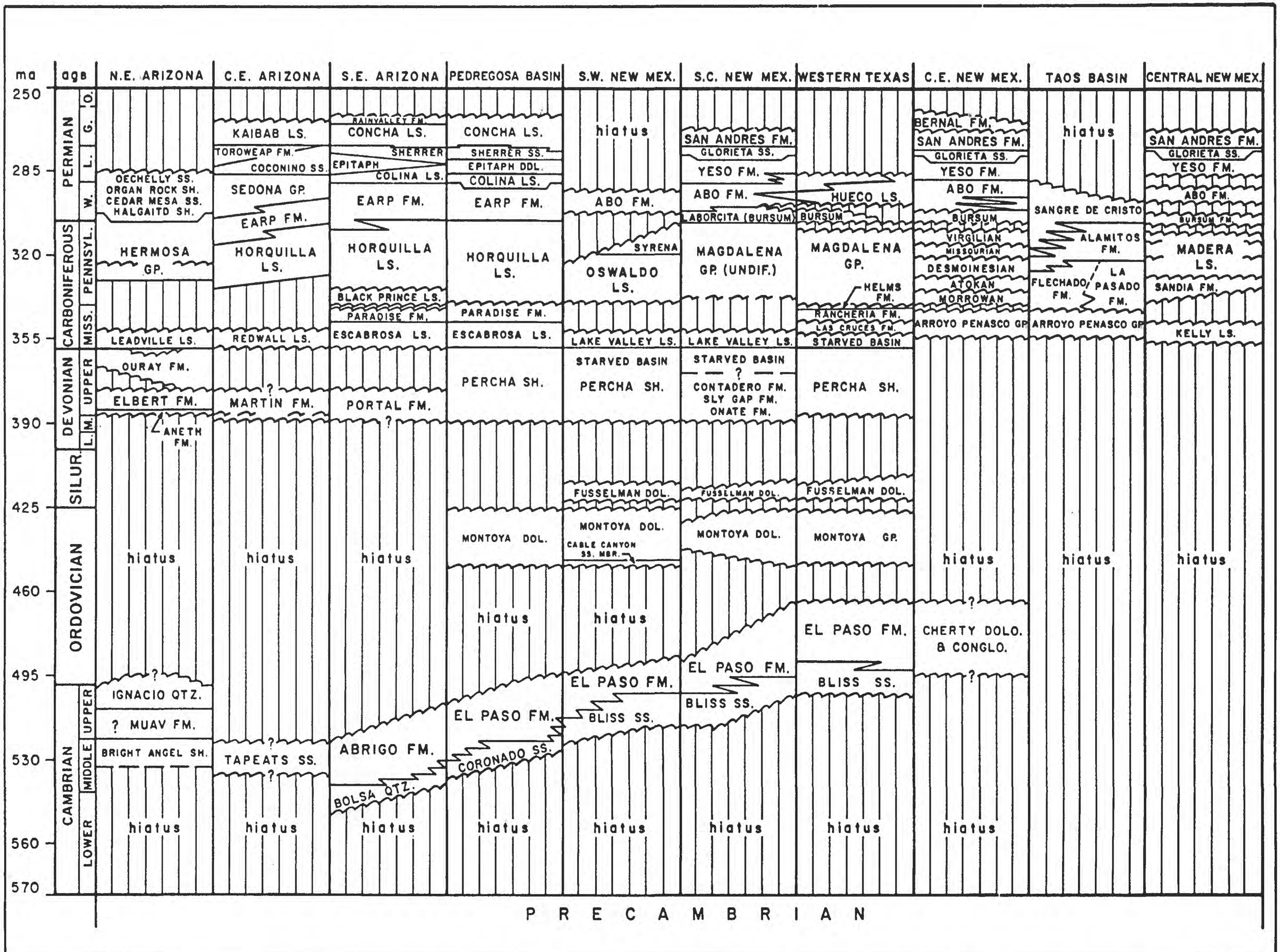

Figure 18--Correlations of Paleozoic strata in Arizona, New Mexico, and West Texas. (From Ross and Ross, 1986).

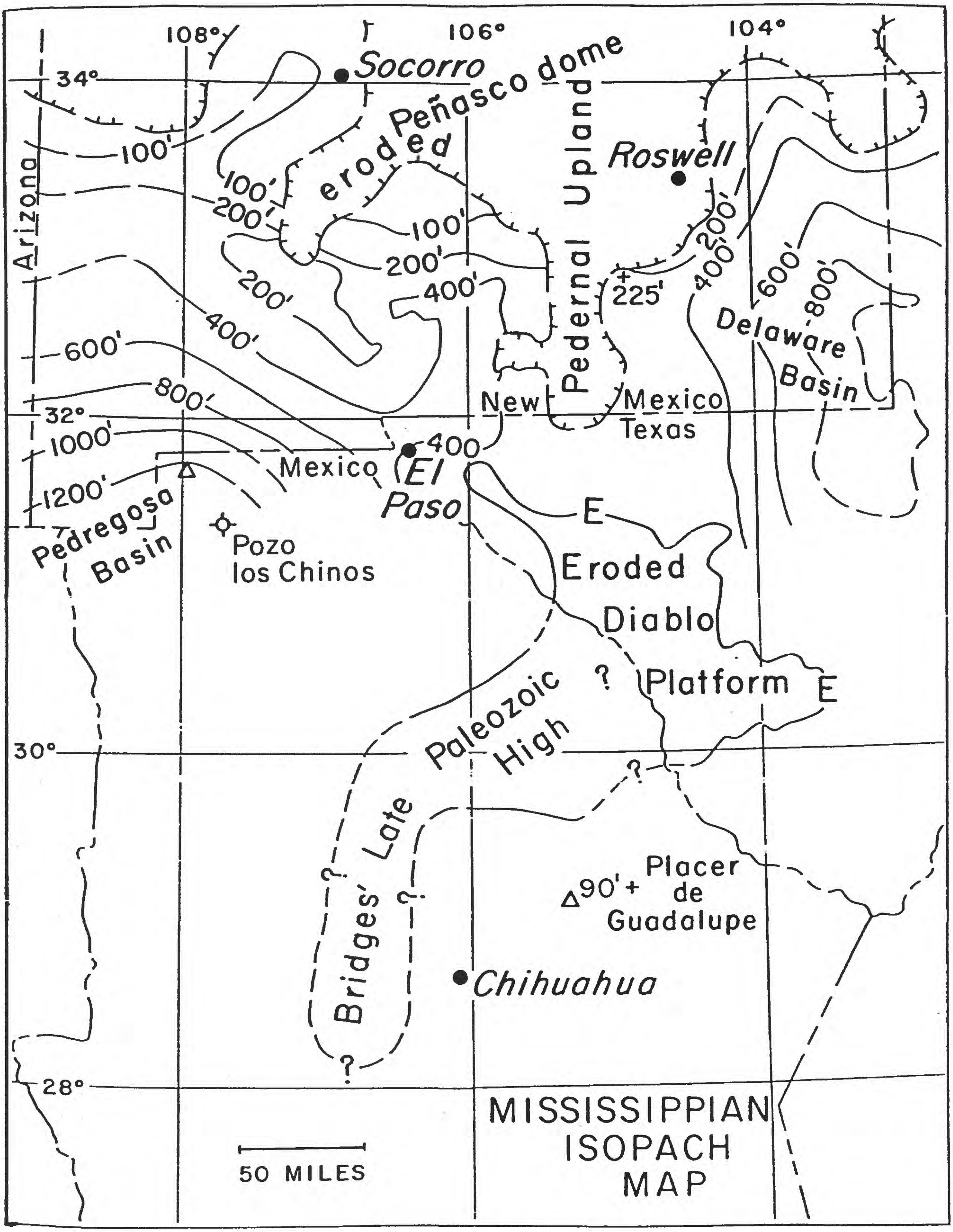

Figure 19--Generalized Mississippian isopach map of southern New Mexico showing Penasco dome. (From Kottlowski, 1970).

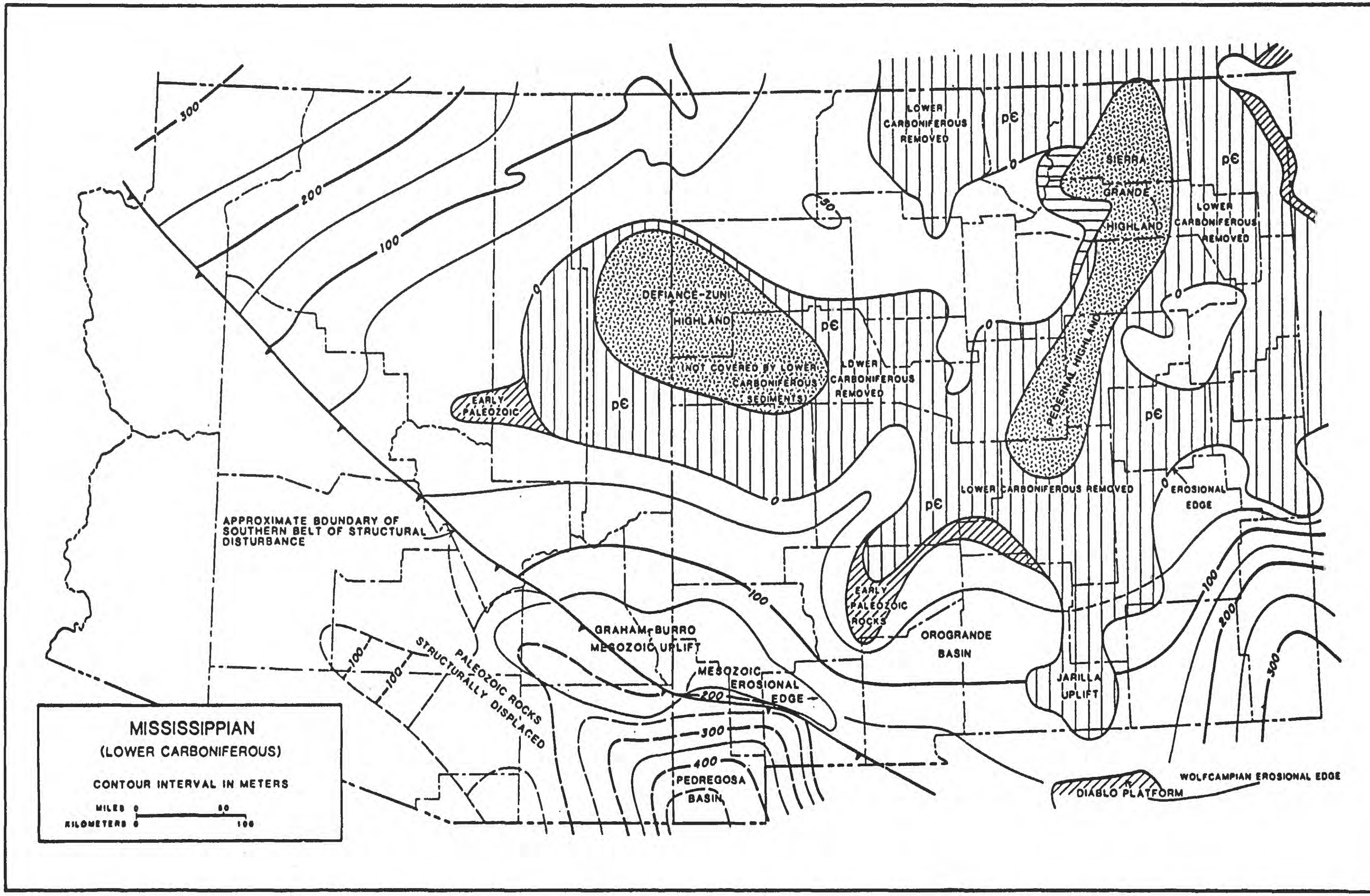

Figure 20--Generalized Mississippian isopach map of New Mexico and Arizona. (From Ross and Ross, 1986).

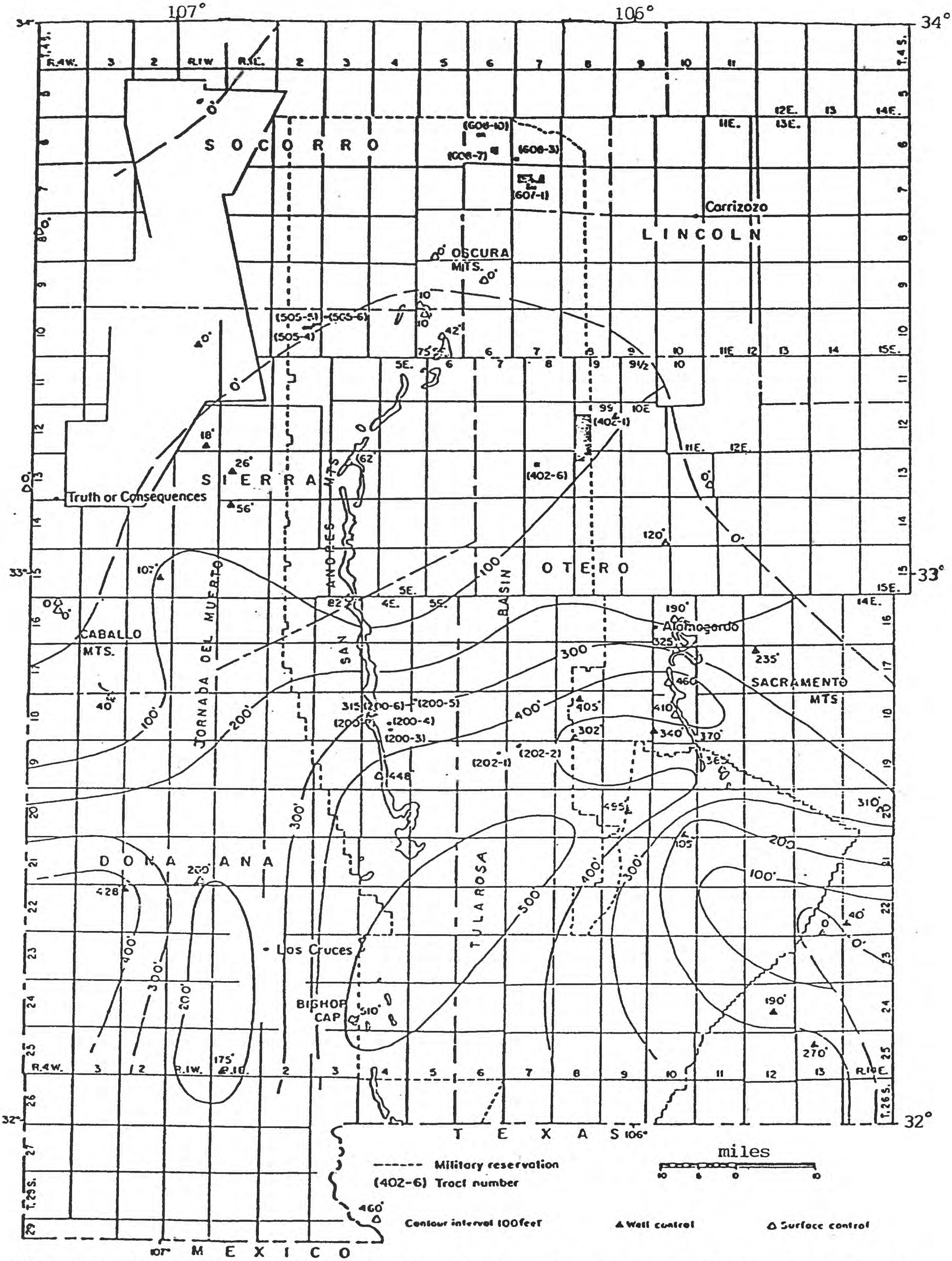

Figure 21--Detailed Mississippian isopach map of south-central New Mexico. (From Foster, 1978a).

Origin of the Orogrande basin, and adjacent Pedernal uplift, is attributable to a progressive, amagmatic collision (including subduction) of the North and South American tectonic plates affecting the southeastern margin of the craton (Ross, 1979; Kluth and Coney, 1981; Goldstein, 1984; Kluth, 1986; Handschy and others, 1987). The resulting Ouachita-Marathon fold and thrust belt is 200-250 miles south-southeast of this petroleum play (fig. 5 and 7). This collision of plates also fractured the North American craton into a principally northwest pattern according to Burchfiel (1979). Such fracturing may represent a readjustment of the prevailing northwest and northeast pattern of basement blocks - a pattern that later influenced Laramide structures and loci of volcanic activity (see fig. 15).

During the Pennsylvanian Period, gradual subsidence and a close source of clastics from the Pedernal uplift to the east (Kottlowski, 1960 and 1968) allowed the deposition of over 3,000 ft (fig. 22, 23, and 24) of alternating dark mudstone or shale, siliciclastic sandstone, limestone, gypsum, and biostromal-biohermal carbonates and reefs. The basin was open to the south but circulation was restricted enough to precipitate gypsum; clastic content of mostly arkose increases to the north (fig. 25). Up to 2,000 ft of Virgilian strata account for about two-thirds of the total Pennsylvanian section. Maximum sedimentation rate, according to Kluth (1986), was somewhat less than 0.005 cm per year.

Permian sediments, 1,000-3,000 ft thick in the Orogrande basin (McKee, 1967), were deposited in apparent angular discordance on Virgilian strata, at least in the eastern-central play area where they are thickest; this documents gradual uplift of the Pedernal positive area (fig. 26). In the northern and northeastern play area, a wedge of red beds (conglomerates, sandstones, and mudstones) of the Abo Formation was deposited as an

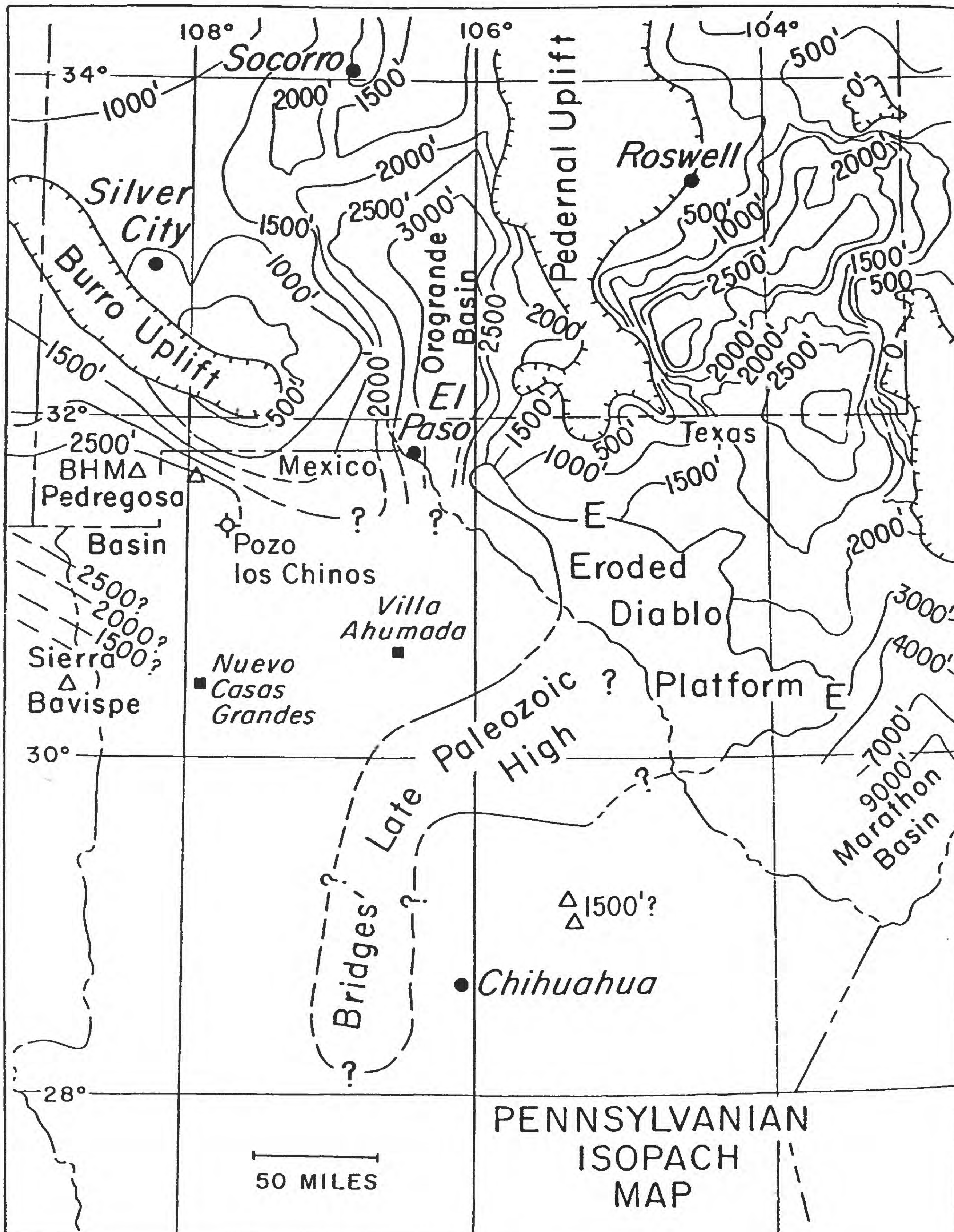

Figure 22--Generalized Pennsylvanian isopach map of southern New Mexico. (From Kottlowski, 1970).

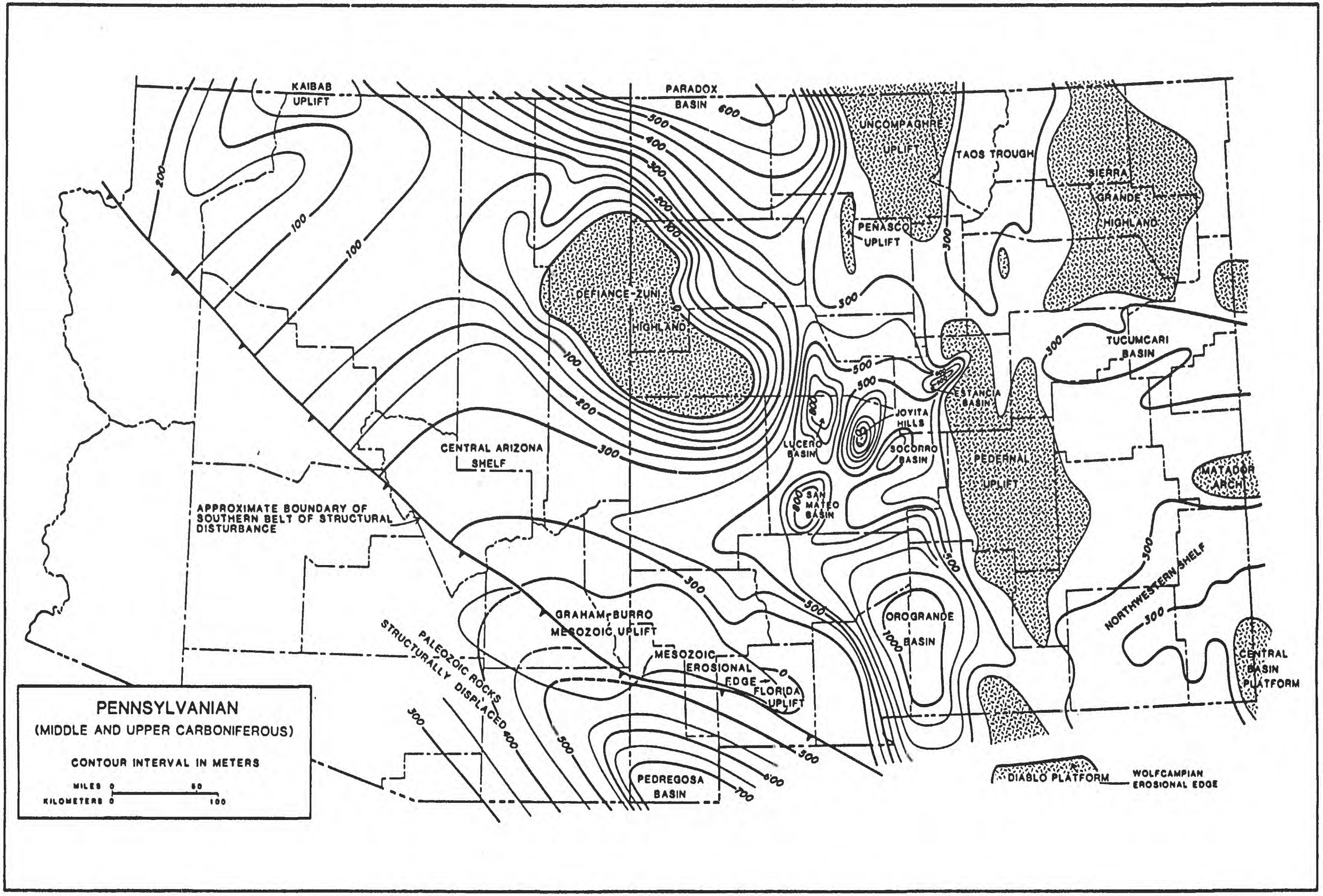

Figure 23--Generalized Pennsylvanian isopach map of New Mexico and Arizona. (From Ross and Ross, 1986).

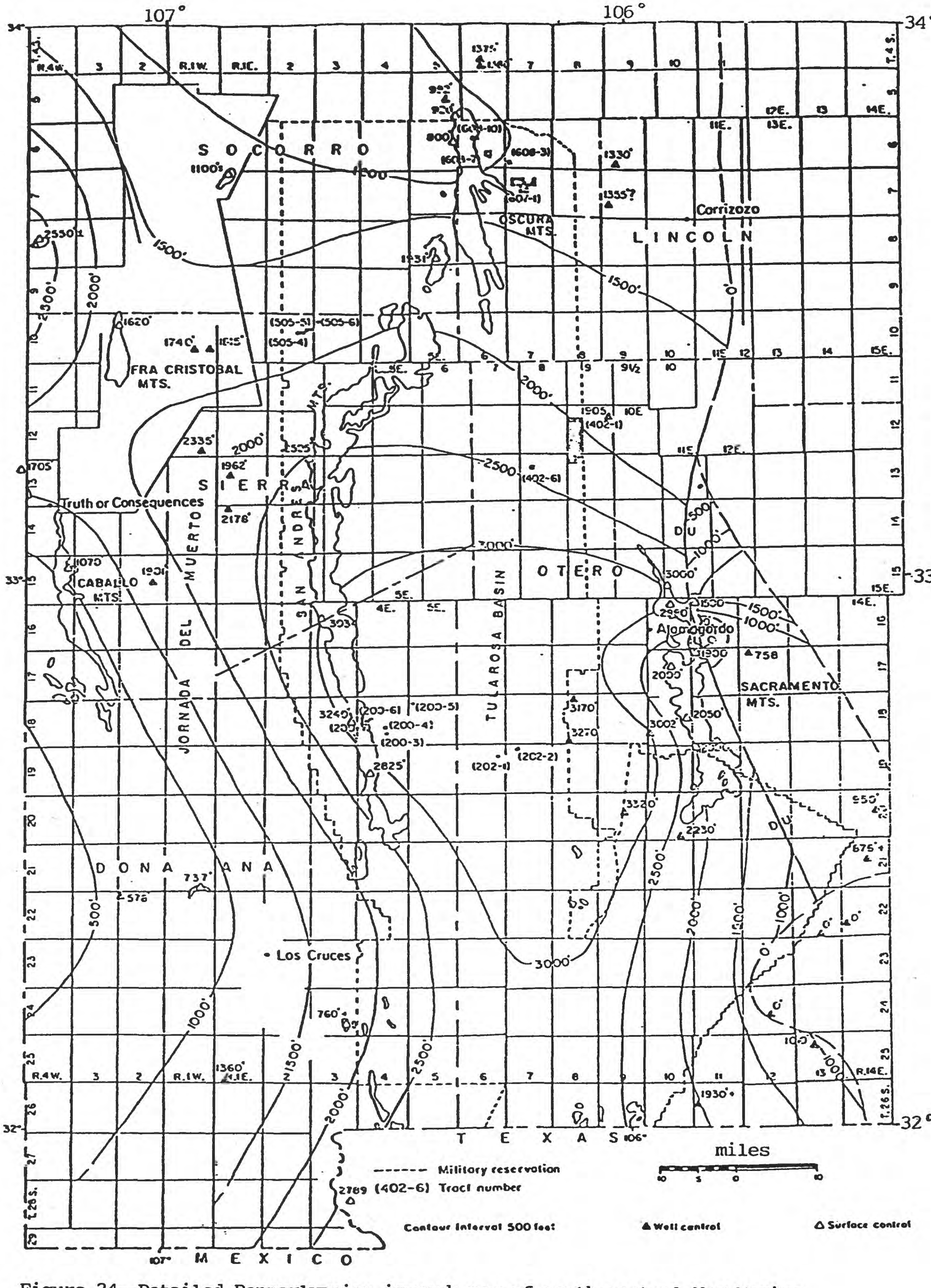

Figure 24--Detailed Pennsylvanian isopach map of south-central New Mexico. (From Foster, 1978a).

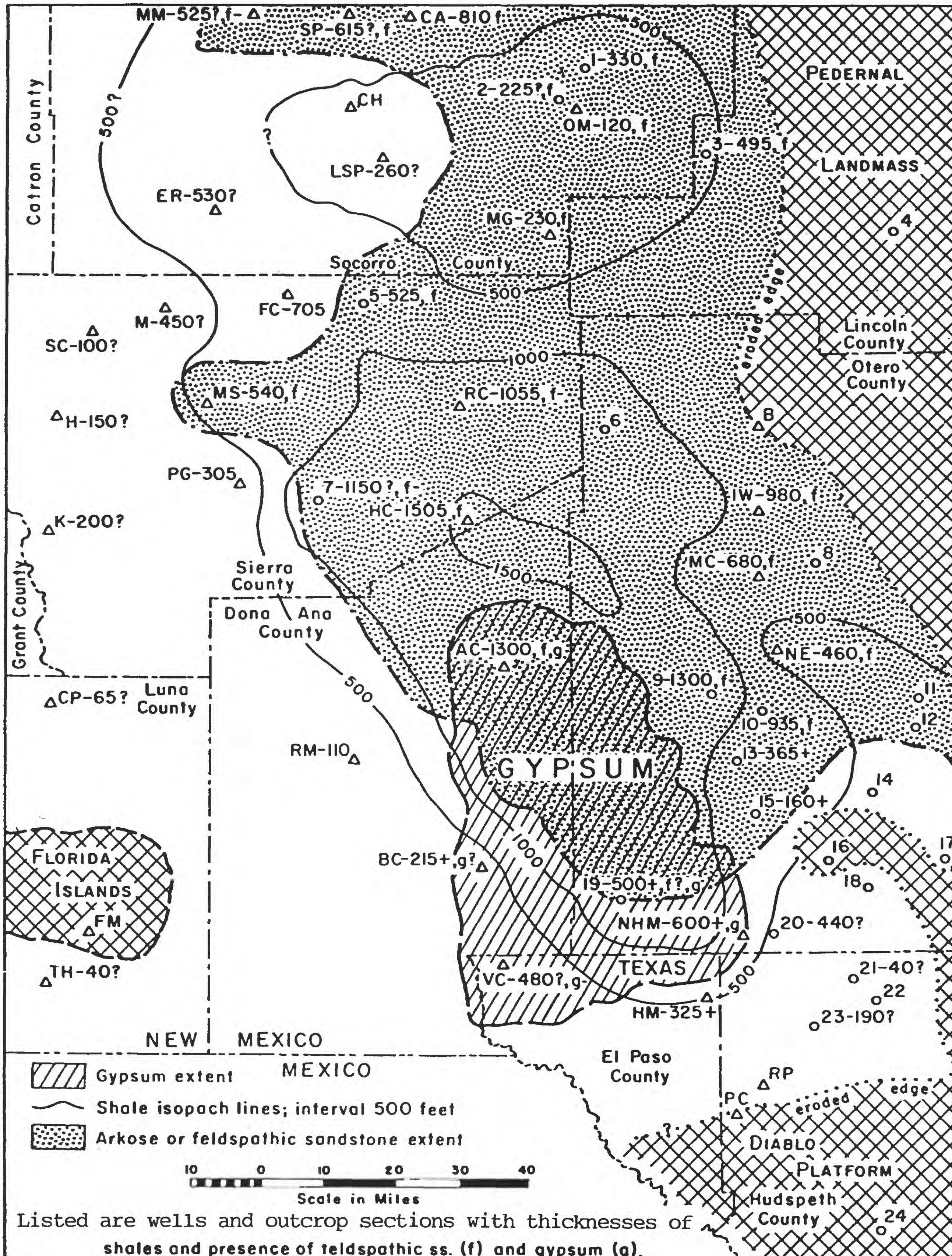

Figure 25--Gypsum-shale-arkose distribution map of Pennsylvanian rocks in south-central New Mexico. (From Kottlowski, 1963).

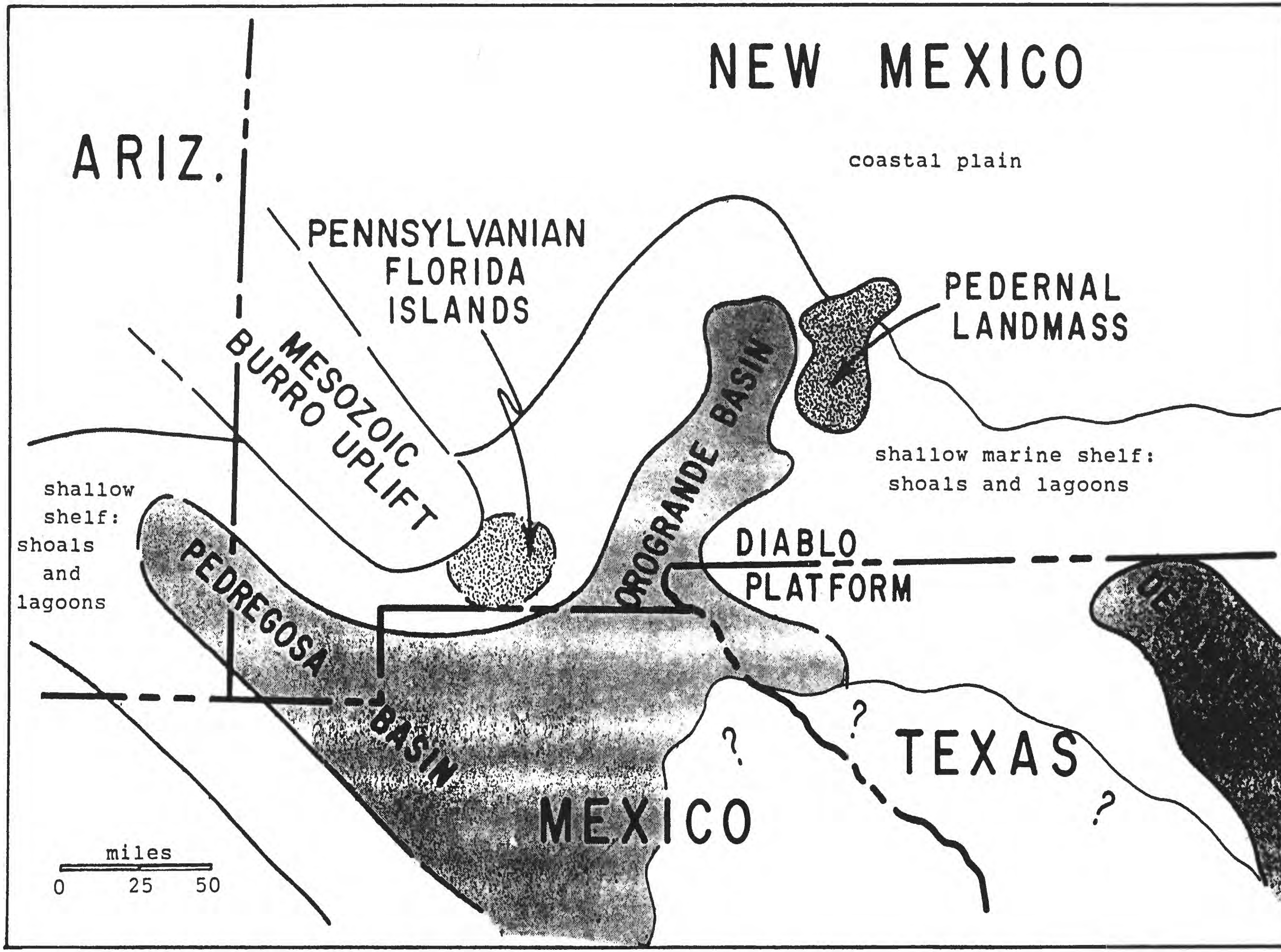

Figure 26--Wolfcampian paleogeographic map, southern New Mexico. (From Jordan, 1975).

alluvial-fluvial fan along coastal plains (fig. 27). Environments of deposition in the central to southern play are varied and include shallow sandy sea, sabkha, deltaic, tidal flat, and lagoonal settings. Roughly 1,000 ft of Wolfcampian strata were deposited in the far northern part of the play; the Wolfcampian red beds of the Abo cover the Bursum Limestone, thus indicating shoaling conditions (fig. 28). By late Wolfcamp, sea level rose and the Pedernal uplift and paleogeographic barrier to the east was finally inundated by shallow epeiric seas; basin deposits included gypsum, siltstone, sandstone, and light- and dark-gray carbonates (see Kottlowski, 1969b). About 1,600-2,000 ft of strata assigned to the Leonard stage are mapped in the south to southwestern play area.

North-south normal faulting (fig. 29) was a consequence of the subsidence of the Orogrande basin relative to the uplift of the Pedernal landmass. Movement on these faults, inherited from zones of weakness in the basement, was greatest from about mid-Pennsylvanian to mid-Permian time. This was also the time when the greatest number of structural traps may have formed. Intermittently reactivated Late Permian through Jurassic plus Laramide uplifts (Burro/Florida Islands southwest of Las Cruces, NM.) stripped away Upper Permian and some older strata; their total thicknesses, therefore, are unknown in many localities.

Mesozoic Era and Early Tertiary

During the Triassic Period, south-central New Mexico was a low source area where alluvial plains received terrestrial deposits of red sandstone, siltstone, and shale. Today these rocks crop out only in the north to northeastern part of the assessment province (see Kottlowski, 1969a). Erosion was locally the most significant geologic process during the Jurassic Period in the play; regionally, large-scale tectonism, such as opening (rifting) of the Gulf of Mexico, had indirect inland effects, e.g.

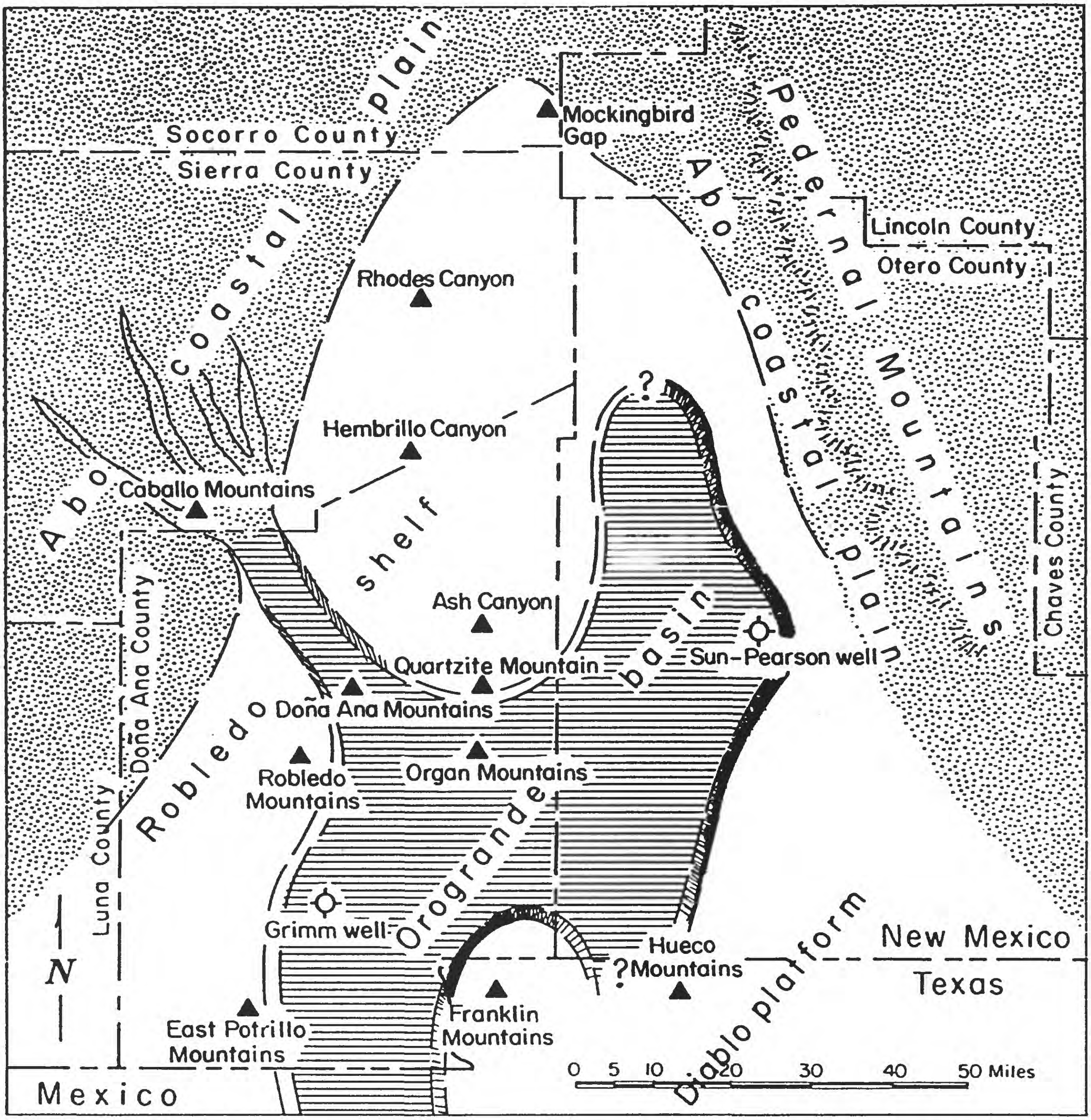

Figure 27--Wolfcampian paleogeography of the Orogrande basin and surrounding area. (From Seager and others, 1976).

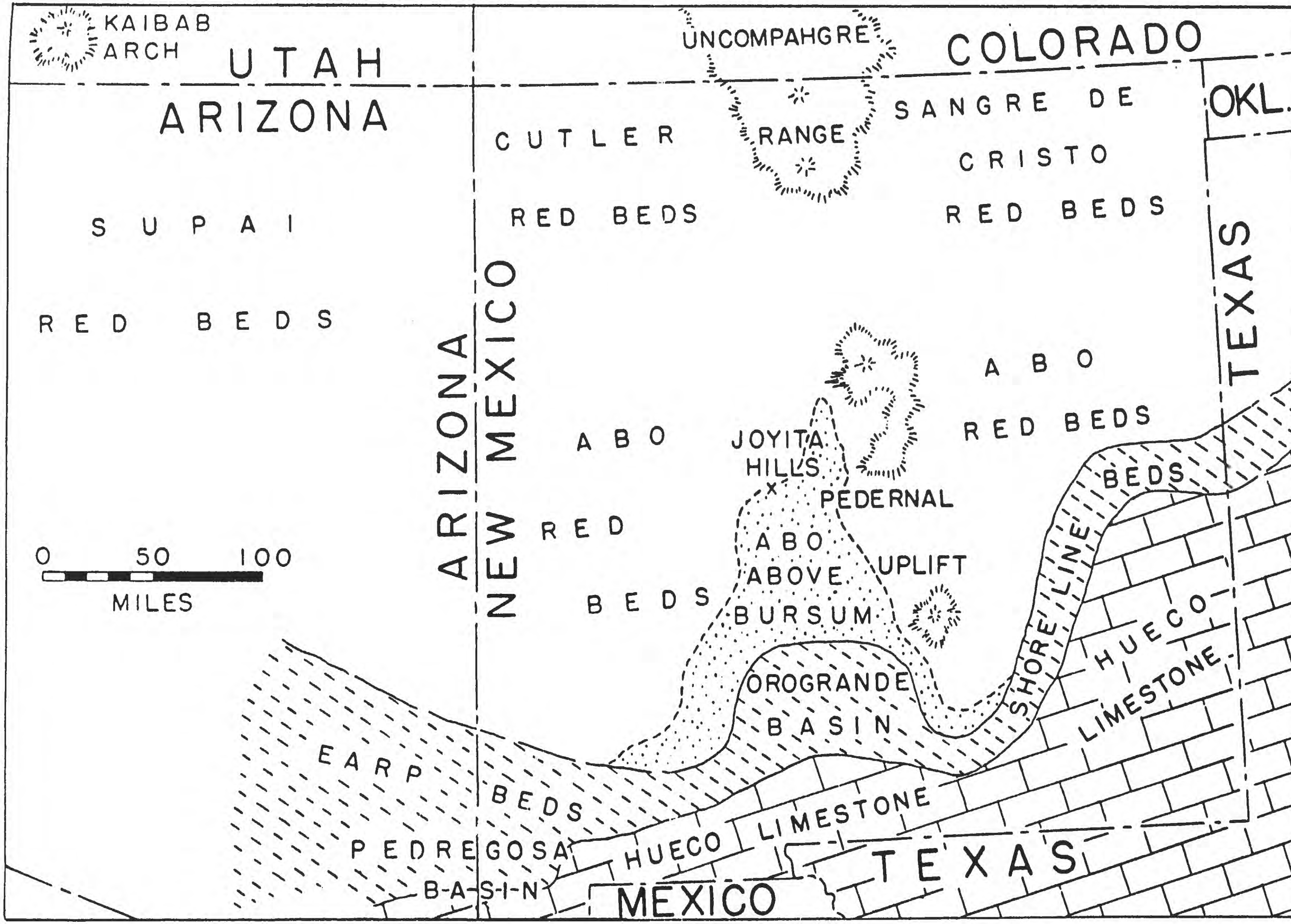

Figure 28--Wolfcampian paleogeologic map of New Mexico. (From Kottlowski, 1970).

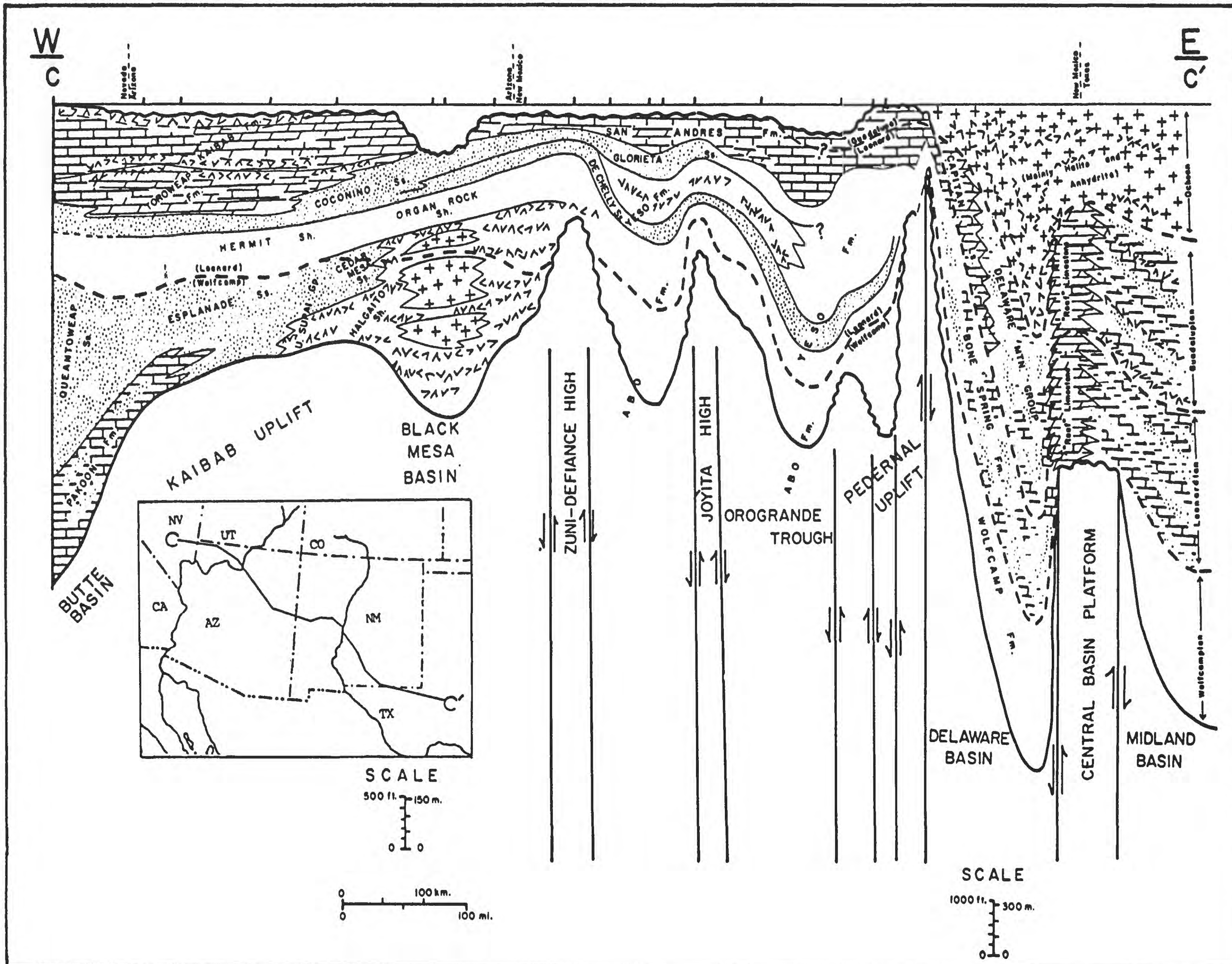

Figure 29--Permian cross-section, southern Nevada to West Texas. Note scale change. (From Peterson, 1980). Palinspastically restored in thrust belt of southern Nevada.

thermotectonic uplift (see fig. 9). Lower Cretaceous shales and limestones (0-?1,000 ft thick) in the Chihuahua trough of south-central New Mexico (fig. 11 and 30) are not well known; they occur in isolated outcrops and are usually undifferentiated to formation name. The Upper Cretaceous depositional regime is characterized by northeast-southwest and southeast to northwest oscillating shorelines (Hayes, 1970; Cumella, 1983). From beach-to-basin and oldest-to-youngest, sandstone, shale, and thin limestone or calcareous shales were deposited during each transgression and then reversed this sequence during regressions. As shown in figure 31, generally from north and northeast to south and southwest, environments of the Upper Cretaceous facies in the play change from marine shale and offshore sandbars to beach sands to paludal clastics and coals to fluvial and coastal plain sandstones. Long periods of subsequent erosion has removed much of the Upper Cretaceous section.

The Cordilleran Mountains were rising in southwestern New Mexico and southern Arizona during the Late Cretaceous (McGookey, 1972) and were a source for the thick clastic deposits of southwestern United States. The underlying cause for intense deformation in the present-day Basin and Range province was the low-angle oblique subduction (underthrusting) of the Farallon plate beneath the southwestern continental margin and craton (see fig. 11 and 16). Laramide deformation in the play was probably most intense during the Paleocene and Eocene, a time when the magmatic arc (fig. 5) was nearby in southwestern New Mexico (Woodward and Ingersoll, 1979). Within the play area, northeast Laramide compression locally resulted in northwest-trending thrust faults, northeast-trending right lateral faults intrusion of igneous rocks, and uplift of basement-cored crustal blocks by convergent wrenching (transpression) and tangential compression (Seager, 1983; Seager and Mack, 1986). See Kelley and McCleary (1960), Coney

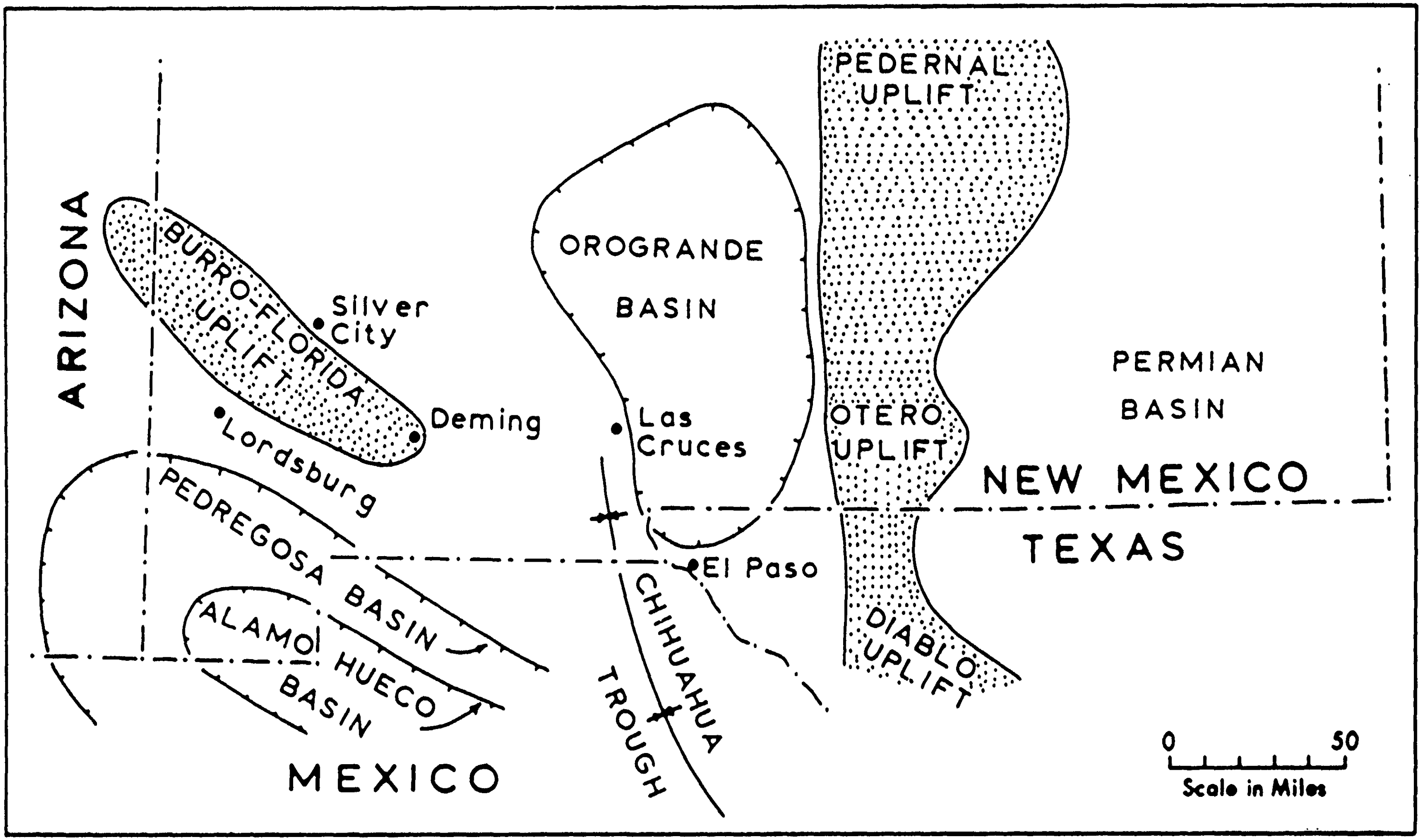

Figure 30--Generalized paleotectonic map of southern New Mexico showing position of Mesozoic Chihuahua trough relative to Paleozoic structures. (From Woodward and Duchene, 1982).

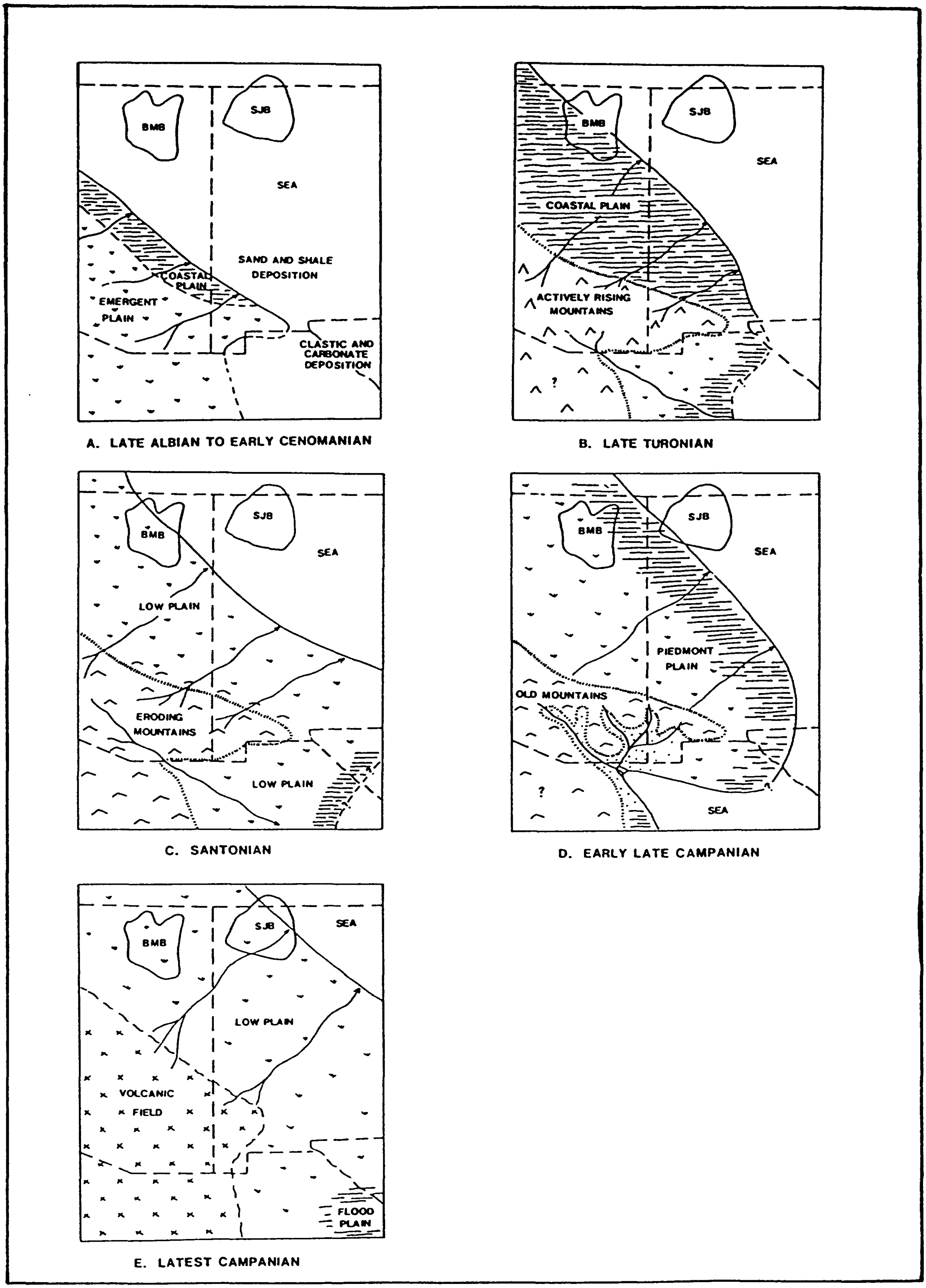

Figure 31--Paleogeographic maps of eastern Arizona and western New Mexico during Cretaceous time. (From Cumella, 1983).

(1972, 1976 and 1978), Horak (1975), Dickinson and Snyder (1978), Dickinson (1981), and Hamilton (1981) for a summary of the Laramide Orogeny in southwestern United States and in the general play area.

Cenozoic Era

Post-Laramide volcanism and extension in southwestern to south-central New Mexico are mainly related to deep-seated heat flow; eruption patterns show a westward-migration. From about mid-Eocene to mid-Miocene time, the play area was the site of deposition of volcaniclastic, pyroclastic, and flow rocks (rhyolites, andesites, and basalts) which covered most of the Laramide structures making these structures difficult to interpret. The Rio Grande Rift began opening in southern New Mexico in mid-Oligocene time as a result of clockwise rotation of the Colorado Plateau. Figure 16a shows that this was also the time when the North American plate met the East Pacific Rise (Pacific plate). Tectonic styles along the southwestern continental margin shifted from compression to transform motion at the San Andreas Fault plate boundary with ensuing extensional faulting of the Basin and Range. Rifting, uplift (about 3,500 ft), and local erosion have continued from the Miocene to the present-day (rifting began to diminish in the Quaternary) with thick deposits of Miocene, Pliocene, and Quaternary alluvium, including basalt of a deep-seated origin and volcaniclastics, filling the grabens. Due to extension during the Late Tertiary, the lighter upper crustal rocks thinned causing a vertical rise in the isotherms of the area (fig. 32). The Diablo platform (Otero Mesa) is presently undergoing rapid uplift according to leveling surveys by Reilinger and others (1980).

For a more complete account of the Tertiary volcanic and tectonic history, the reader is referred to Cook (1969), Christiansen and Lipman (1972), Lipman and others (1972), Chapin and Seager (1975), Seager (1975),

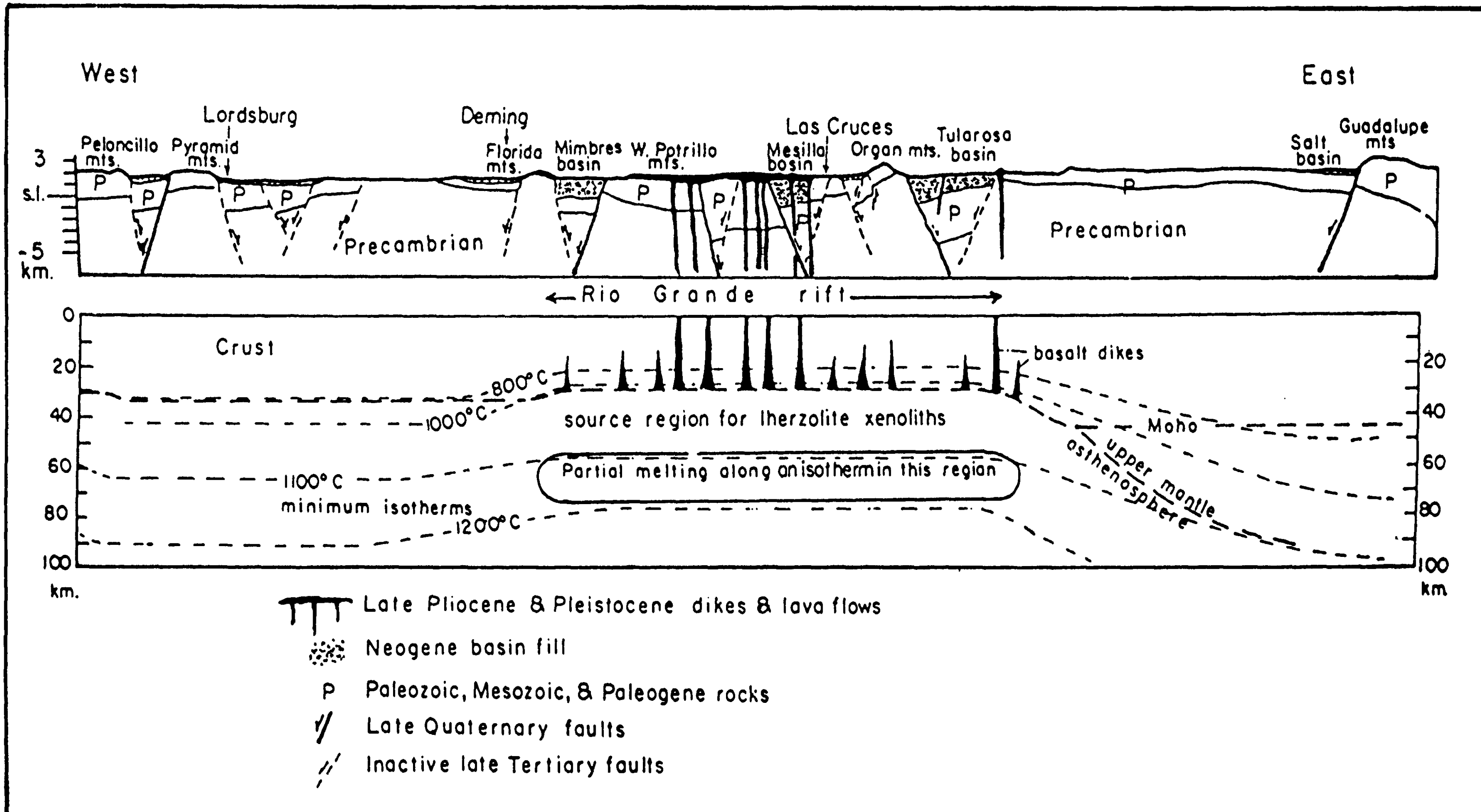

Figure 32--West-east hypothetical cross-section through southern Rio Grande Rift showing elevated isotherms in the crust and upper mantle. (From Seager and Morgan, 1979).

Elston (1976), Coney and Reynolds (1977), Coney (1978), Eaton (1979a, b), Elston and Bornhorst (1979), Riecker (1979), Stewart (1978), Seager and Morgan (1979), Eaton (1980), Lipman (1980), and Zoback and others (1981).

Physiography

Except for the southeastern-most 7-9 percent of its area, the play is within the southern Rio Grande Rift subprovince (fig. 33 and 34) which includes the north-trending Jornada del Muerto, Mesilla, Hueco, and Tularosa intra-rift basins (Chapin, 1971). The Tularosa Basin is the largest of these basin, i.e. about 120 miles long and 30 miles wide; it occupies the eastern half of the play (described by Sandeen, 1954) and is adjacent to the Rocky Mountain Front (Bayer, 1983) and Great Plains province. The Otero Mesa area of this play (southeastern sector) is part of the Texas foreland of the Great Plains physiographic province. Outcrops of the play include rocks from Proterozoic to Holocene in age. From 70 to 75 percent of the entire play is covered by a thick, complex mix of alluvium, eolian dunes, and volcanic pyroclastic and flow rocks of Mid-Tertiary through Quaternary age (calculated from Dane and Bachman, 1965). Basalt in the northern Tularosa basin (Carrizozo Malpais) is as young as a thousand years and less than 5 million years old in the Jornada del Muerto Basin (Luedke and Smith, 1978). Recent gypsum dunes cover 350-400 square miles of the central Tularosa Basin.

Structural Framework

Prominent geologic features surrounding and adjacent to the play include: a) the north-trending Pedernal uplift to the east (also called the Sacramento uplift, Otero uplift, and Diablo platform in its southern area), b) the Sierra Blanca Laramide intrusive complex to the northeast, c) the Estancia and Albuquerque basins to the north separated by the Chupadera platform, d) the west half of the Rio Grande Rift, i.e. a series of

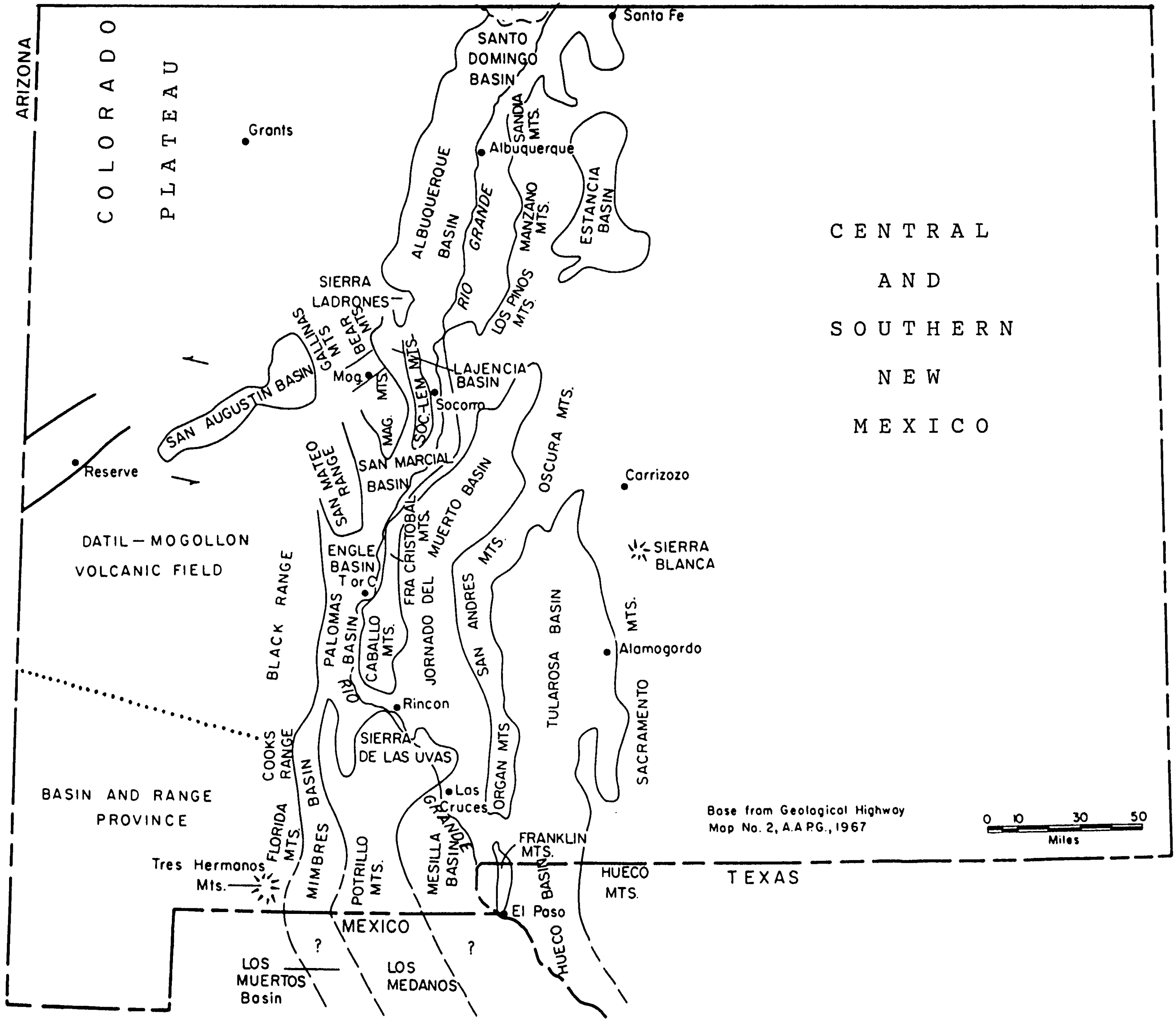

Figure 33--Generalized map of the Rio Grande Rift showing present-day basins and mountains. (From Chapin and Seager, 1975).

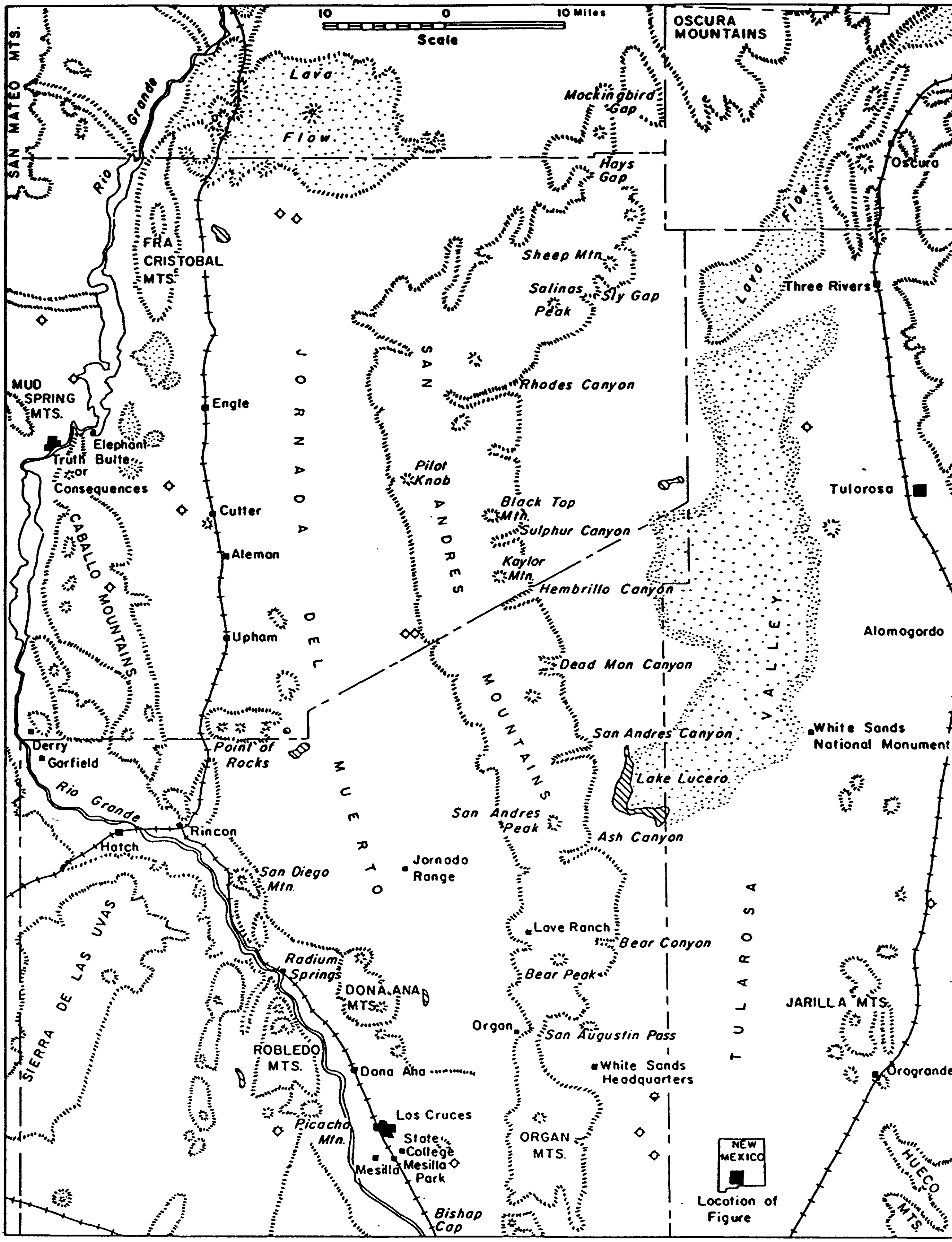

Figure 34--Index map of the San Andres Mountains. (From Kottlowski, 1975).

en echelon grabens, to the west, e) the Hueco Basin and Hueco Mountains uplift to the south, and f) the Salt (Brokeoff) Basin to the southeast. The Jornada del Muerto Basin occupies the western to northwestern part of the play between the San Andres Mountains and the Rio Grande River. This basin is a broad syncline according to Kelley and others (1982) and Lozinsky (1987), and is probably of Laramide origin (Kelley, 1955a; Chapin, 1971).

The play area has a highly-complex Phanerozoic history, experiencing tectonic deformation (e.g., normal, reverse, and strike-slip faulting) during the Paleozoic, Mesozoic, and Cenozoic eras. Following Precambrian deformation, each tectonic episode has left its structural imprint and unique geophysical signatures on the younger ones (Ramberg and Smithson, 1975). The overall north-south structural grain of the play reflects both Late Paleozoic and post-Laramide deformation. The mostly north-south central mountain axis (concave eastward) represents the Sierra Oscura, San Andres, Organ, and Franklin Mountains. This axis bisects the play and serves as a "spine" on which the play's regional stratigraphy can be "attached". These narrow ranges are fault-bounded blocks exposing Precambrian through Permian rocks. The San Andres Mountains are tilted west exposing Precambrian rocks on their east side; the Sierra Oscura Mountains to the north are tilted eastward and expose Precambrian rocks on their west side. A series of mostly northwest-trending, transverse, normal faults cut these two ranges.

Structural contours on the Precambrian basement in the play reveal a total relief of 6,000-7,000 ft (Bayley and Muehlberger, 1968; King, 1969; Landes, 1970). Cone (1965) and Woodward and others (1975) have shown at least 10,000 ft of Precambrian relief in the Jornada del Muerto Basin. Detailed work by Foster (1978a), however, reveals the Tularosa Basin has a basement relief of about 15,000 ft and the Jornada del Muerto Basin has a relief of about 13,000-14,000 ft. Eroded Precambrian exposures in the eastern San Andres Mountains are used as the highest reference points (i.e., about 6,000 ft). Wells have penetrated the Precambrian surface at about +1,000 to +4,500 ft elevation southeast of Tularosa, NM., on the Otero Mesa (King and Harder, 1985). Clark (1984) has shown in an east-west cross-section, through the southwestern play into northwestern Texas, that the top elevations of the Precambrian basement in the structural basins are about 16,500 ft below sea level. Figure 35 illustrates in simplified cross-section the north-south, vertical fault system in the Tularosa and Jornada del Muerto basins.

Lower and Middle Paleozoic formations wedge-out from south to north in the northern play area (Kelley and Furlow, 1965). A subcrop map would show progressively older wedge-edges from northeastern Sierra and northwestern Otero counties into southeastern Socorro and southwestern Lincoln counties. Pre-Permian strata in the Tularosa basin wedge-out toward the Diablo platform (fig. 36) and dip westward about 4 degrees. Petroleum migrating updip could be trapped by faults against adjacent blocks, e.g. the Pedernal uplifted block, an feature active in the Pennsylvanian and reactivated in Mid-Tertiary time. The Organ and San Andres block-faulted mountains are tilted westward with Paleozoic strata dipping into the Jornada del Muerto Basin (fig. 37).

The Pedernal paleogeographic landmass of Thompson (1942) between the play and the Delaware basin is probably the southern extension of the Uncompahgre uplift (part of the Ancestral Rockies) to the north in north-central New Mexico and southwestern Colorado (see fig. 6 and 7). In south-central New Mexico it is a normal-faulted Pennsylvanian uplift, symmetrical in plan view but steeper to the east, with a Precambrian core

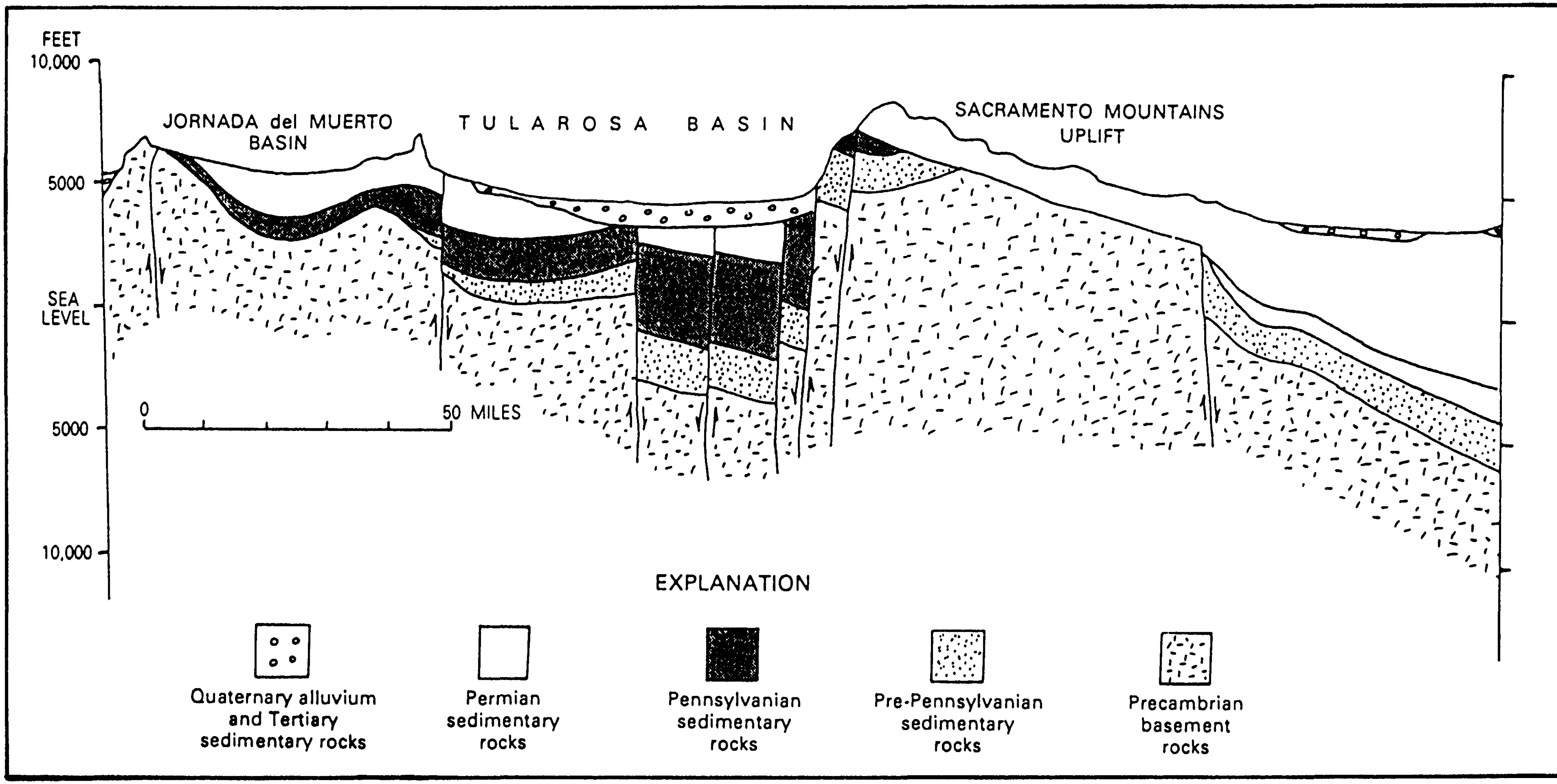

Figure 35--Generalized west-east cross-section through the Jornada del Muerto and Tularosa Basins and Sacramento Mountains. (From Ryder, 1983).

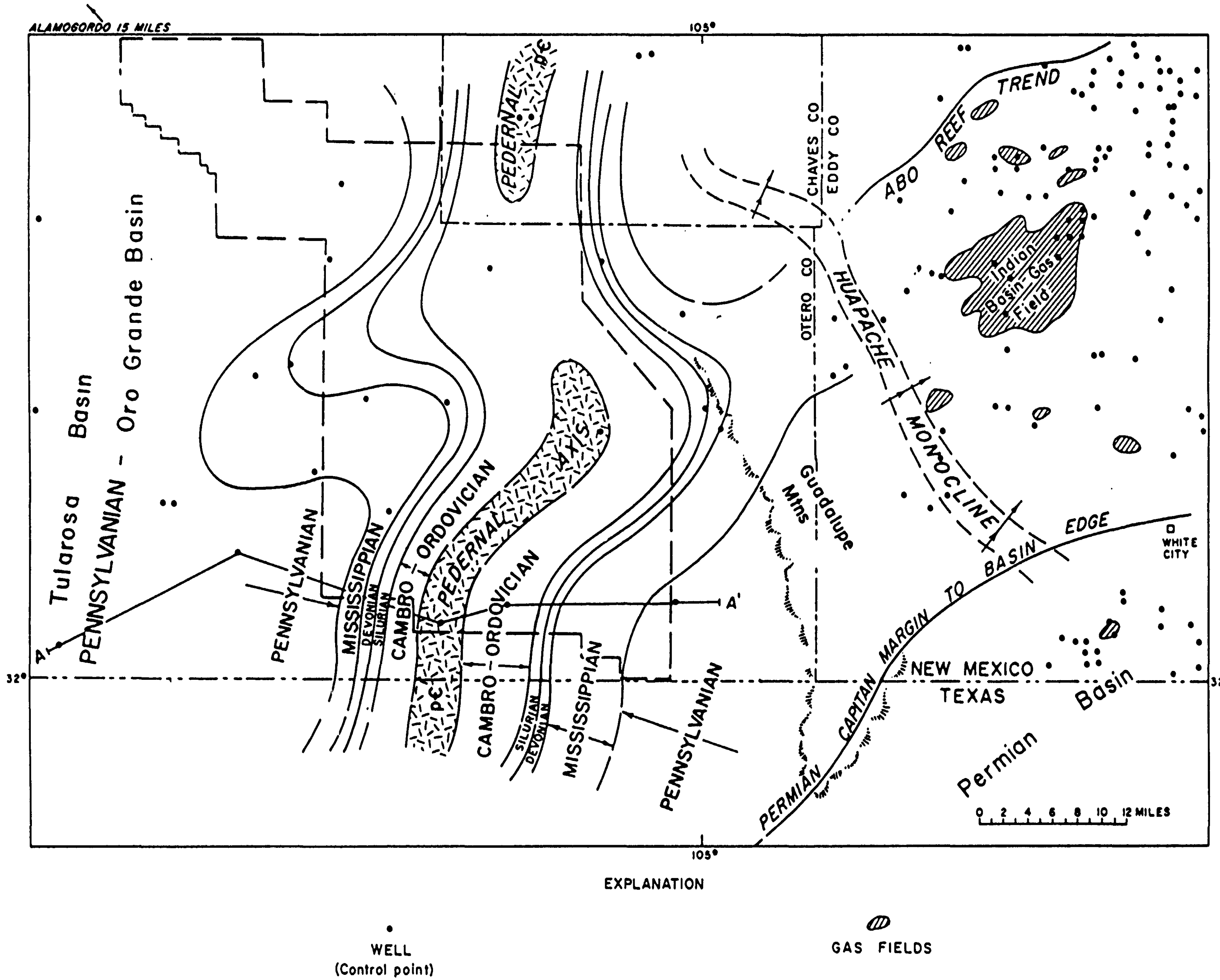

Figure 36-- **Pre-Permian subcrop map of Otero platform, showing locations of Pennsylvanian Oro Grande basin and Permian Basin.** (From Black, 1976).

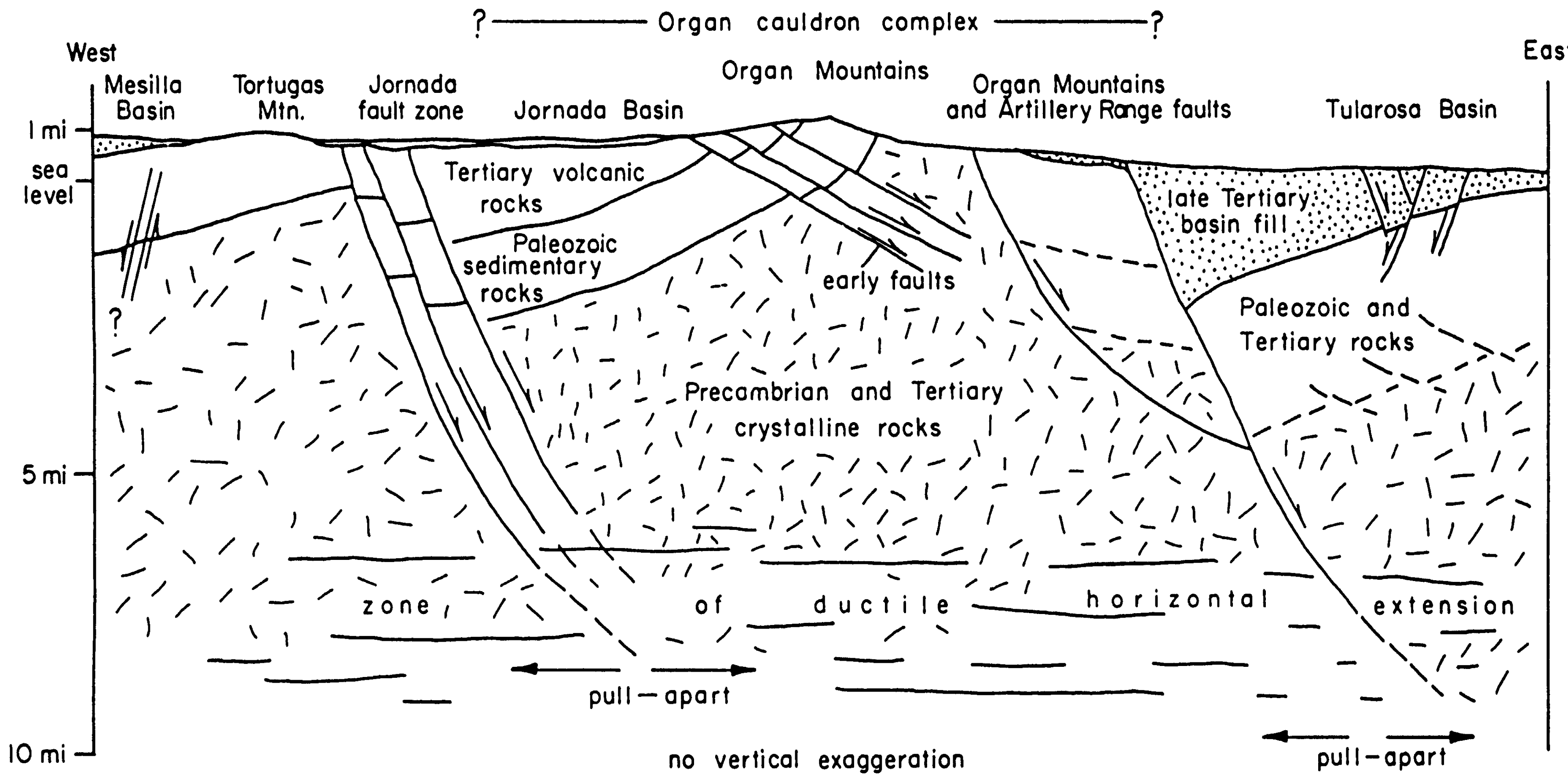

FIGURE 37– DIAGRAMMATIC EAST-WEST SECTION FROM WESTERN TULAROSA BASIN THROUGH THE ORGAN MOUNTAINS TO THE MESILLA BASIN. Major fault blocks, antithetic fault system and inferred downbending of bolson fill in western Tularosa Basin, and possible pull-apart zones at depth are shown. (From Seager, 1981).

covered by Lower and Middle Permian strata (fig. 29). Drape folds (fig. 38) occur over concealed, high-angle normal faults cutting Early Permian rocks (Pray, 1961 and 1977). A north-to northwest-trending anticlinorium in the southern Sacramento Mountains (Otero platform) has been characterized by Black (1976). The angular unconformity between Pennsylvanian and Permian strata in this area indicates these local structures were created during the Late Pennsylvanian; later deformation (northwest-trending folds) in Laramide time is also documented. These folds possess symmetrical, gently-dipping, and commonly doubly-plunging attributes.

The northwest-trending Chihuahua tectonic belt (Cordilleran overthrust of Laramide origin) may extend through the extreme southwestern corner of this play (e.g., see Dickinson and Snyder, 1978; Woodward and Duchene, 1981 and 1982; and, Seager and Mack, 1986), but it may have only an indirect relationship to the play's petroleum potential. On the other hand, Laramide overthrusts in the Mesilla basin may trap Paleozoic oil and gas but insufficient subsurface data exists to evaluate this concept. The Deming Axis/Texas Lineament (fig. 39) is a megashear zone and series of uplifts which occupies essentially the same geographic position as the Chihuahua tectonic belt (fig. 40) but owes its origin to Precambrian through Paleozoic and even Laramide tectonics (e.g., see Turner, 1962; Muehlberger, 1965; Moody, 1966; Sales, 1968; Fischer and Judson, 1975; Lovejoy, 1975; Woodward 1976; Muehlberger, 1980; Baars and Stevenson, 1982). Laramide thrust sheets moved to the northeast; dexteral shearing or wrench faulting are manifested by northeast trends (fig. 41).

Plutons of Laramide origin -- probably early Tertiary but possibly Oligocene age according to some workers -- have intruded the Dona Ana Mountains, the Organ Mountains, the northern Hueco Mountains, the Jarilla Mountains, the Cornudas Mountains, the southern and northern San Andres

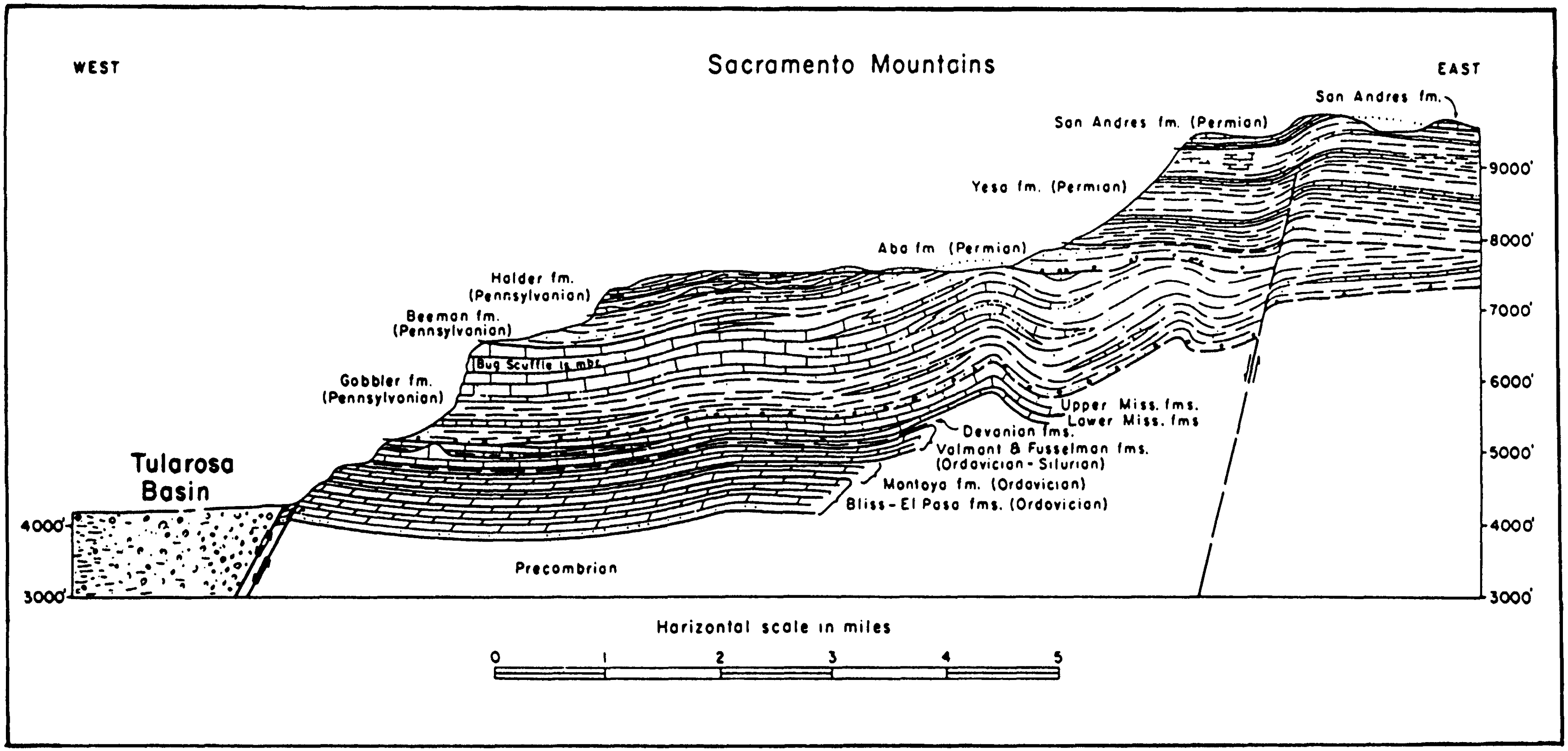

Figure 38--Diagrammatic cross-section of the central part of the Sacramento Mountains Escarpment. (From Pray, 1961).

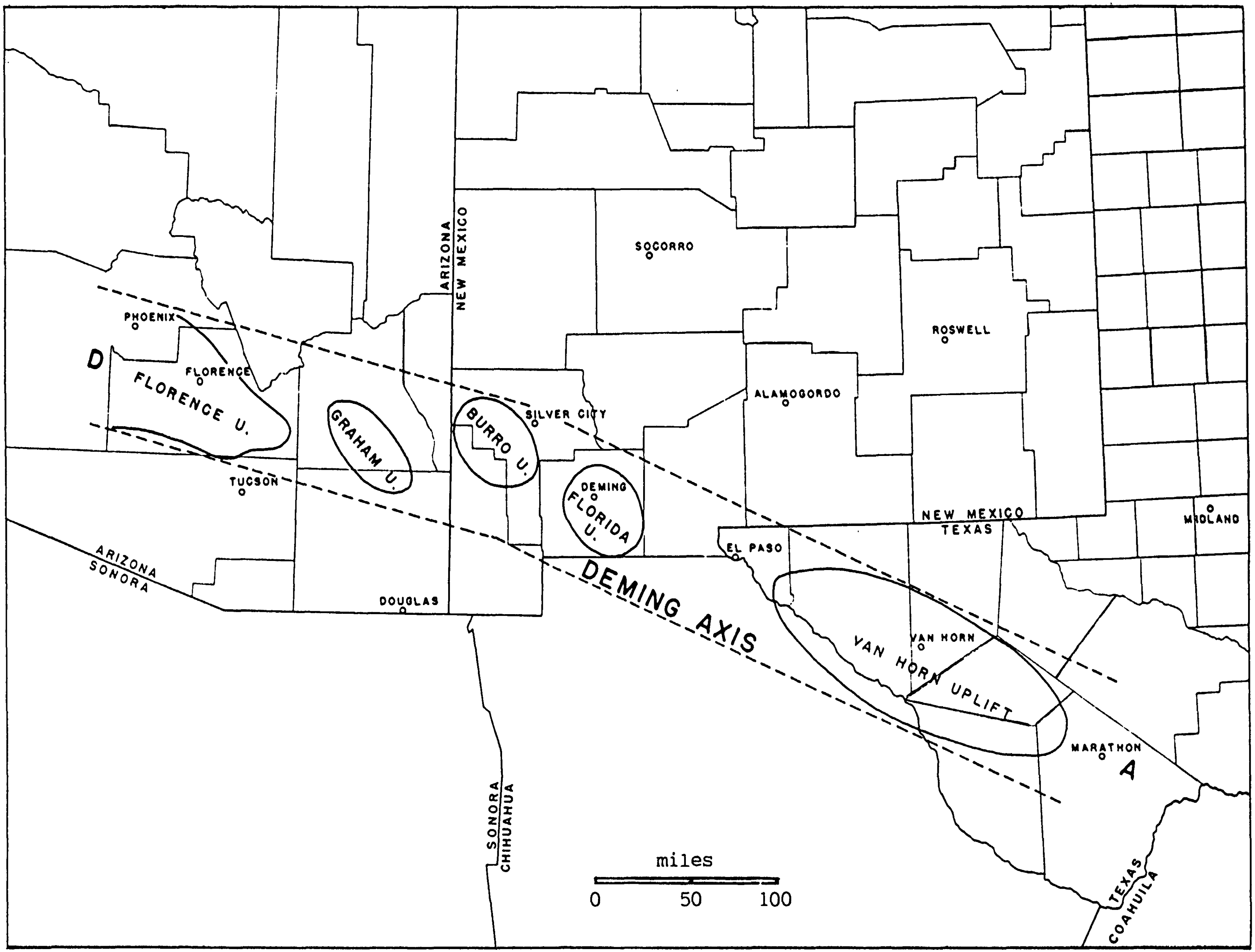

Figure 39--Map showing Deming axis (? Texas lineament) and trend of Laramide uplifts. (From Turner, 1962).

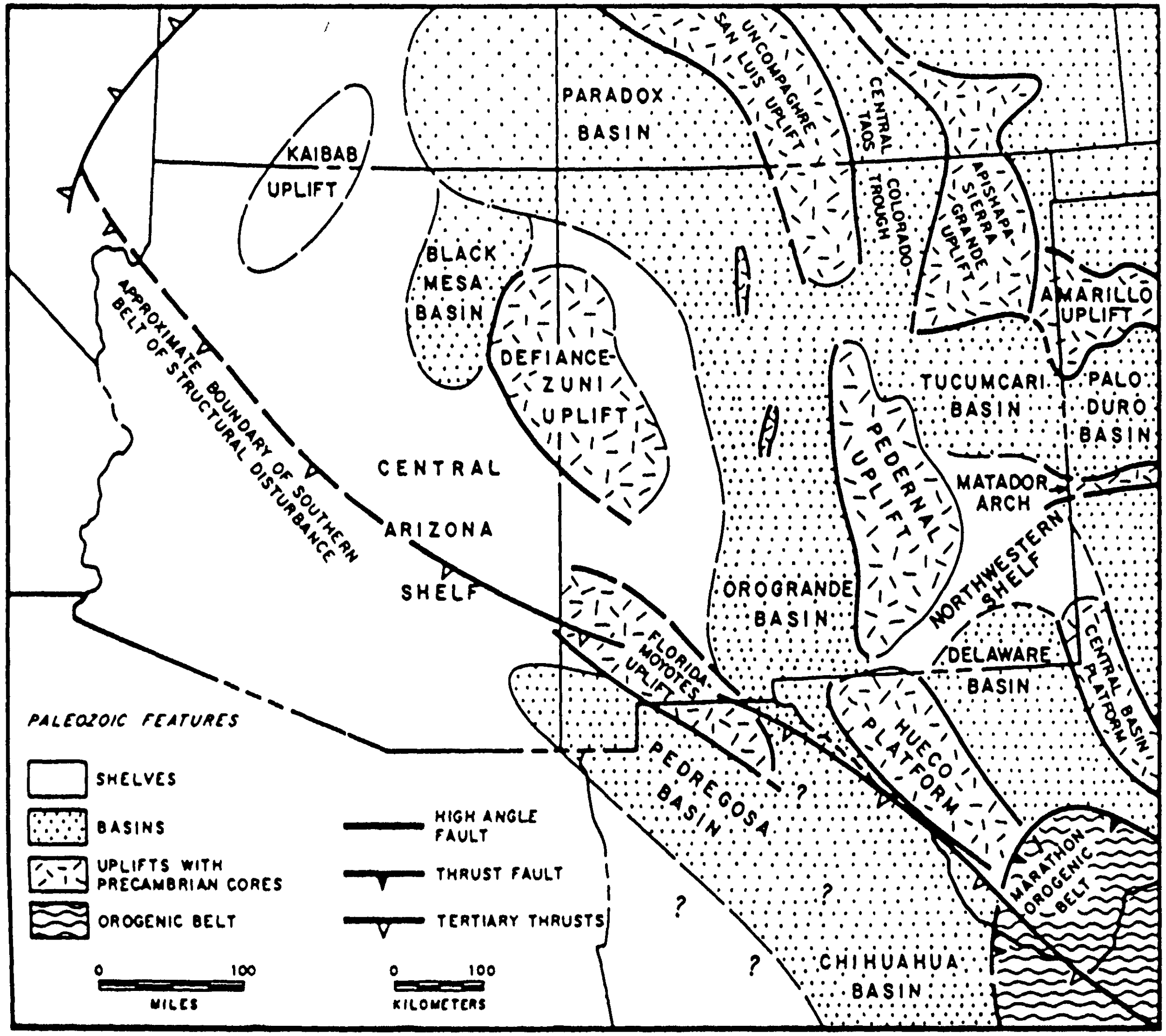

Figure 40--Generalized tectonic map of New Mexico and Arizona showing area of Tertiary thrusts at southernmost side of the Orogrande basin. (From Ross and Ross, 1986).

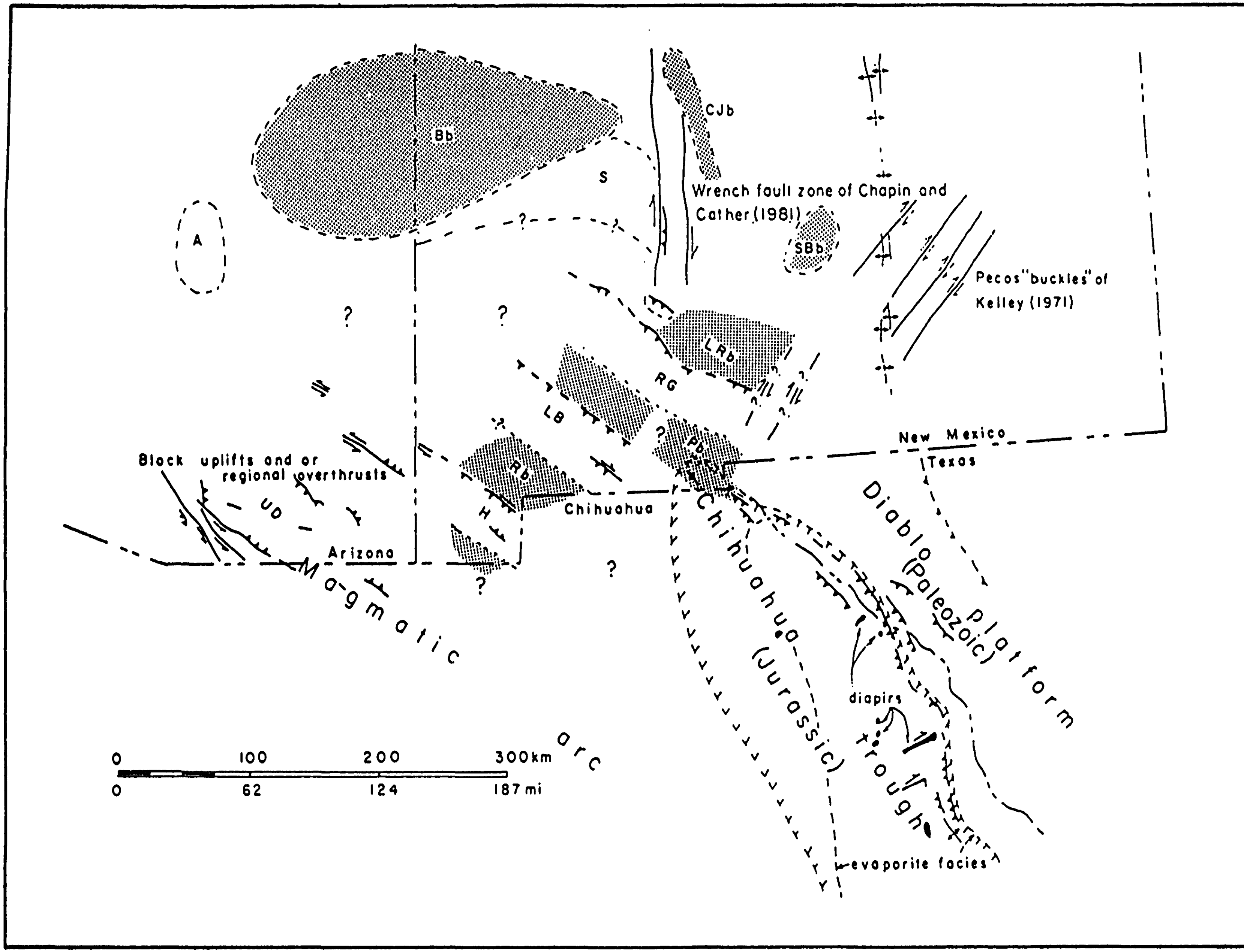

Figure 41–Map showing major Laramide structural features in western Texas, northern Chihuahua, southern New Mexico, and southeastern Arizona. Uplifts: A, Apache uplift; S, Sierra uplift; RG, Rio Grande uplift; LB, Laramide Burro uplift; H, Hidalgo uplift, UD, uplift of Davis (1979). Basins: Bb, Baca basin; CJb, Carthage–La Joya basin; SBb, Sierra Blanca basin; LRb, Love Ranch basin; Pb, Potrillo basin; Rb, Ringbone basin. (From Seager and Mack, 1986).

Mountains, and the Oscura-Carrizozo-Coyote area (Dane and Bachman, 1965). See Kelley and others (1982) for satellite photomap and other generalized tectonic, geologic (with stratigraphic columns and cross-sections), and physiographic maps.

Geophysical Studies

Geophysical information is exceptionally critical to an interpretation of the subsurface where drilling and outcrop data are sparse. However, a systematic review of geophysical data is beyond the scope of this play analysis. Some of the general gravity, seismic, and magnetic literature for such a review includes the following: Decker and others (1975), Decker and Smithson (1975), Padovani and Carter (1977), Aiken and others (1978), Healey and others (1978), Ramberg and others (1978), Cook and others (1979), Thompson and Zoback (1979), Hildenbrand and others (1982), Zietz (1982), Cordell (1983), Keller and Cordell (1983), Keller and others (1984), Jachens and others (1985), and Simpson and others (1986). Thompson and Burke (1974) have summarized the present geophysical framework of the Basin and Range province thusly: "The regional geophysical data put many useful constraints on speculations about the fundamental tectonic processes of the Basin and Range province. Among these data the heat flow is central; the volcanism, thin crust, low mantle velocity, accentuated low velocity zone, generally high elevation, subdued magnetic anomalies, high electrical conductivity, and great breadth of the seismically active zone can logically be associated with high temperatures and high heat flow."

PETROLEUM PLAY IDENTIFICATION

Cretaceous Coalbed Methane Play

Location, Size, and Land Status

The coalbed methane play is within the stable craton near the outer edge of the southeastern quadrant in the Colorado Plateau physiographic province (Fenneman, 1928; Hunt, 1956; Thornbury, 1965; Grose, 1972; Baars, 1983; and, Bayer, 1983). Specifically, it is on the Mogollon Slope of west-central New Mexico (Kelley, 1955b) in western Cibola (formerly named Valencia) County (fig. 2). The area evaluated is between the Gallup sag to the west-northwest and the Acoma sag to the east. North of the play is the Zuni Mountains positive area - an asymmetric, basement-cored northwest-trending anticline; these mountains more-or-less mark the southern terminous of the San Juan basin. Landes (1970) and Molenaar (1974, 1977) considered the play area to be part of the Zuni basin, whereas Chapin and Cather (1981) and Cather and Johnson (1984) referred to it as part of the Baca basin of Early Tertiary age.

The play size is between 500 and 550 square miles; boundaries lie approximately within 107° 55′ to 108° 35′ long. and 34° 40′ to 34° 55′ lat. The area is within North Plains structural valley. Basalt that covers the valley is called the Zuni-Bandera Lava Field. Land classification types include private (44 percent), Bureau of Land Management (25 percent), Ramah Indian Reservation (18 percent), and state-owned (13 percent).

Basis of Play

Upper Cretaceous outcrops of predominately Dakota Sandstone, Mancos Shale, Gallup Sandstone, and Mesaverde Group border the play on the east (Cebollita Mesa, also spelled Cebolleta), west, and southwest and have composite thicknesses up to 2,500 ft (McGookey, 1972; Seyfert and Sirkin, 1973); 1,000-2,000 ft is a reasonable estimate for the play area. The Dakota sandstone and Mancos Shale probably exist beneath the basalt, but it is not known with any certainty how thick the carbonaceous-rich Mesaverde Group might be.

Beneath the Cretaceous rocks the stratigraphic section is relatively thin and consists of up to 3,500-4,000 ft of Permian, Triassic, and Jurassic strata resting unconformably on Precambrian basement. These pre-Cretaceous rocks are exposed north of the play on the south flank of the Zuni uplift area. The total thickness of the stratigraphic section in the play area is unknown due to its concealment beneath basalt and a lack of borehole information, but it is estimated to be 4,500-6,000 ft.

Relatively shallow coalbed methane has probably been thermogenically generated within the nonmarine Upper Cretaceous strata which contain coal lenses and stringers and other beds with disseminated but abundantly-carbonaceous material. Although some upward migration of non-associated gas may have occurred, for this assessment the reservoir rocks are considered to be the same units as the source rocks. Methane is adsorbed on surfaces and within the coal microstructure (cleat systems). Several 12-inch and possibly thicker coal lenses are inferred to be present in the middle to lower part of the Dakota Sandstone deposited in a delta plain environment. Also, the Gallup Sandstone and the Dilco Member of the Crevasse Canyon Formation consist of carbonaceous shale with intercalated coaly units. (The Moreno Hill Formation coal seams described by Roybal and Campbell, 1982, in the Fence Lake area are stratigraphically above the Atarque Sandstone and below the Crevasse Canyon Formation). A total of 50-75 ft of coal plus carbonaceous clastics of Late Cretaceous age are most likely present in these three stratigraphic units. Although 200-300 ft of the entire Cretaceous section may contain significant amounts of organic matter of the terrestrial humic type III in clastic units, the play emphasizes the Dakota, Gallup, and Crevasse Canyon coaly reservoirs. A stratigraphic column and cross-section of Upper Cretaceous coal-bearing strata in the Zuni basin are shown in figure 42(a,b).

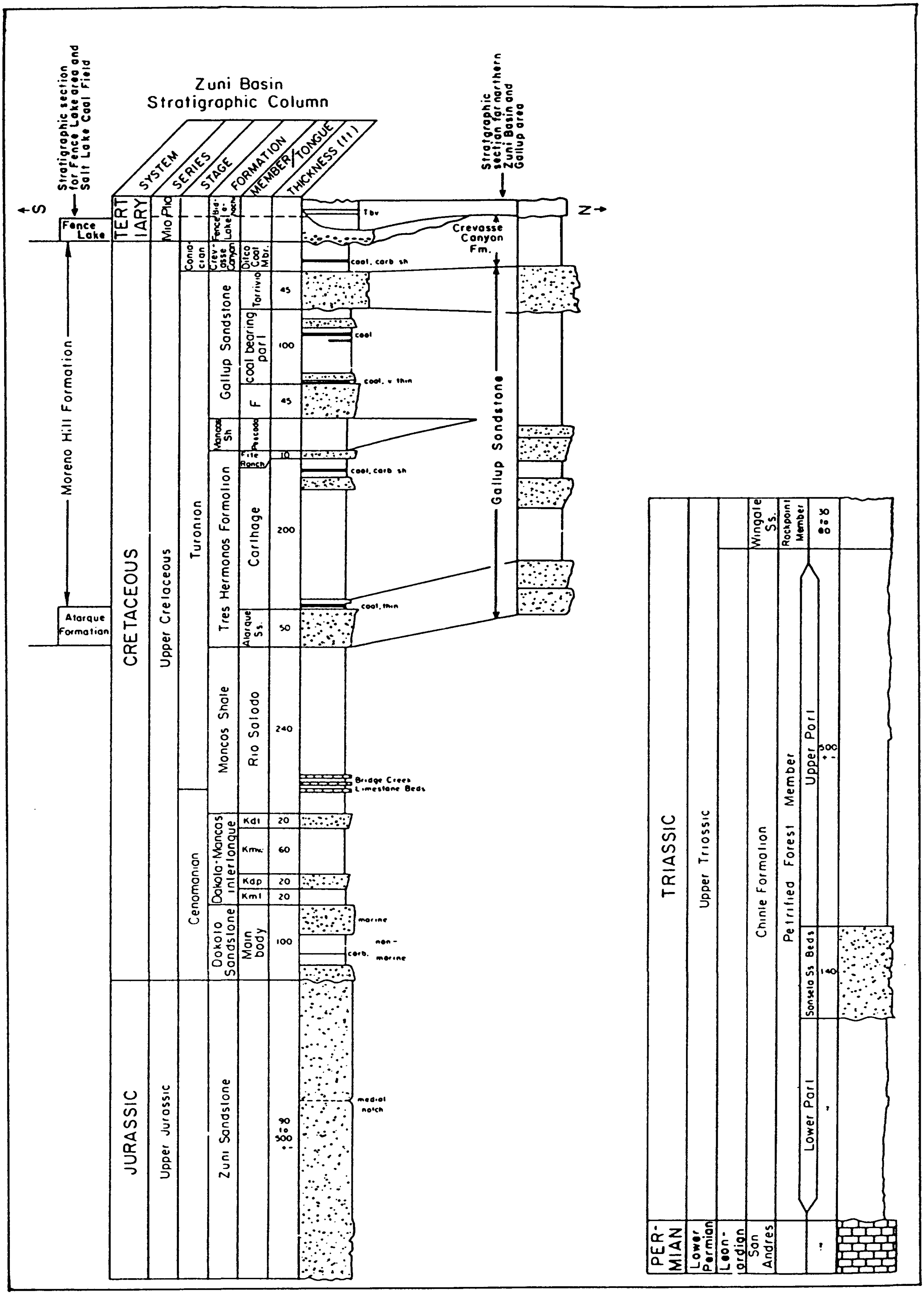

Figure 42a--Composite stratigraphic column of the Zuni basin. (From Roybal and others, 1987).

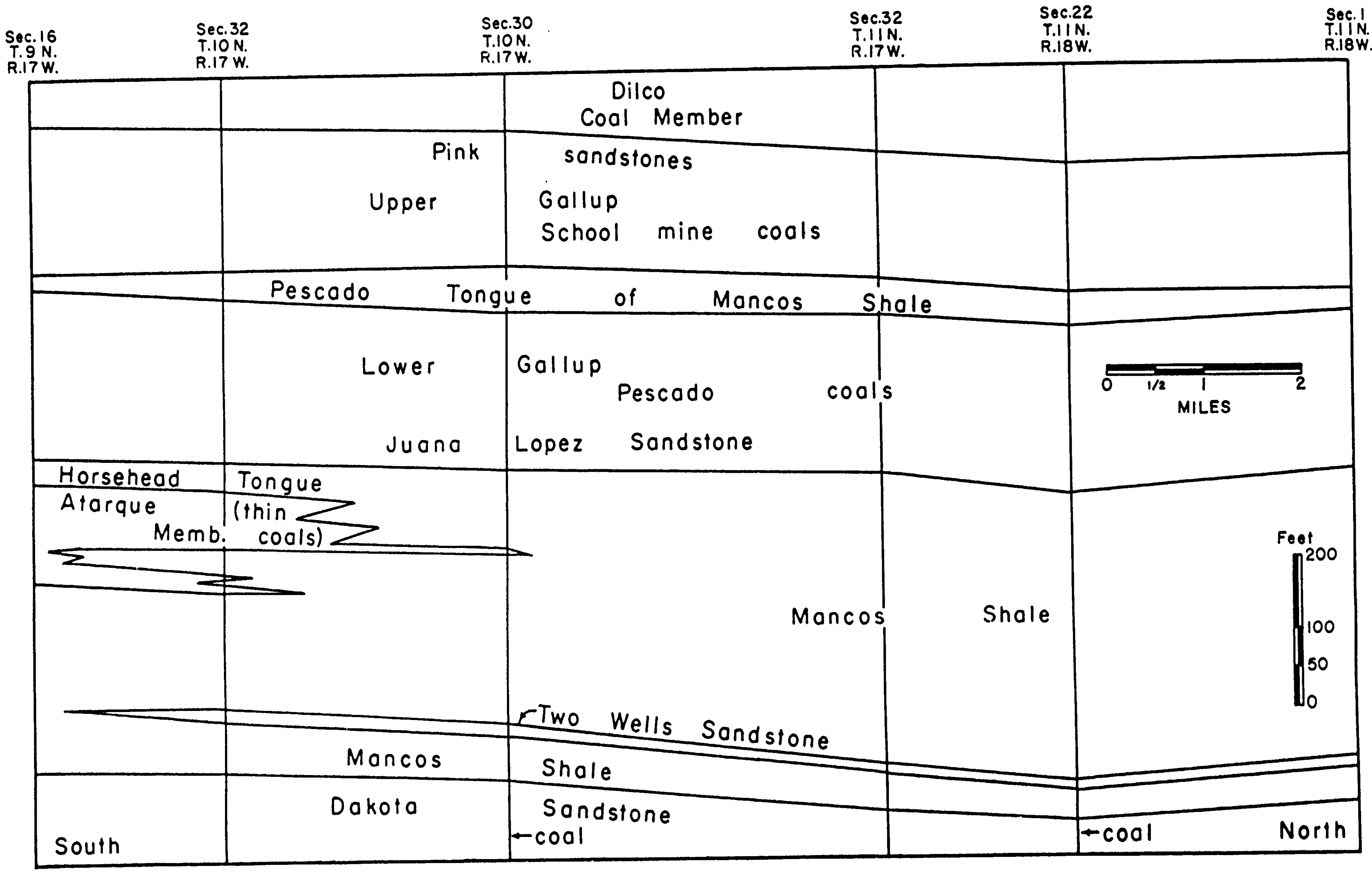

Figure 42b--Cross-section of Upper Cretaceous strata showing stratigraphic relationships of coal beds in the Zuni basin. (From Shomaker and others, 1971). Location of section is 15-30 miles northwest of play.

Hydrocarbon Occurrence

The San Juan basin north of this play is a prolific coalbed methane producer with an estimated in-place gas resource of 2-31 trillion cubic feet (TCF) (Shirley, 1986), and 50 TCF according to Kelso and others (1988); see fig. 43. There the Dakota Sandstone is a major non-associated gas producer (Deischl, 1973; Arnold and others, 1976; Kottlowski, 1977; Parker and others, 1977). Fassett (1983) calculated the Dakota Sandstone in the San Juan basin has produced about 3.63 TCF of dry gas and 44.3 billion cubic feet (BCF) of "casinghead" (condensate) gas through 1982. Cumulative production through 1985 has been 4.00 TCF. Production is mainly from the central, deeper, and hence more mature part of the San Juan basin. Fassett (1983) also determined that through 1982 the Gallup Sandstone produced over 67 BCF of dry gas in the basin. Other productive formations higher in the stratigraphic section are not present in this play area.

Geothermal Maturity

The coalbed methane play is an area of high present-day heat flow -- the key ingredient responsible for generating the in-situ gas resource from sub-bituminous and lesser amounts of high-volatile bituminous-C coal. See Fieldner and others (1936) and Shomaker and others (1971) for analyses of northwestern New Mexico coals. Geothermal data from surrounding outcrops indicate the maturation level (based on depth of burial) since the Late Cretaceous has barely reached the threshold for oil generation (fig. 44). Quaternary basalt less than 5 my old, and possibly as young as 1,000 years (Nicols, 1946; Luedke and Smith, 1984), covers the entire play area.

Maximum generation of gas is assumed to be contemporaneous with the intrusion and extrusion of basalt during the last five million years, but more probably during the last 1-2 million years. Although the Cretaceous rocks are immature (R_o = 0.48-0.60 percent), i.e. slightly below the

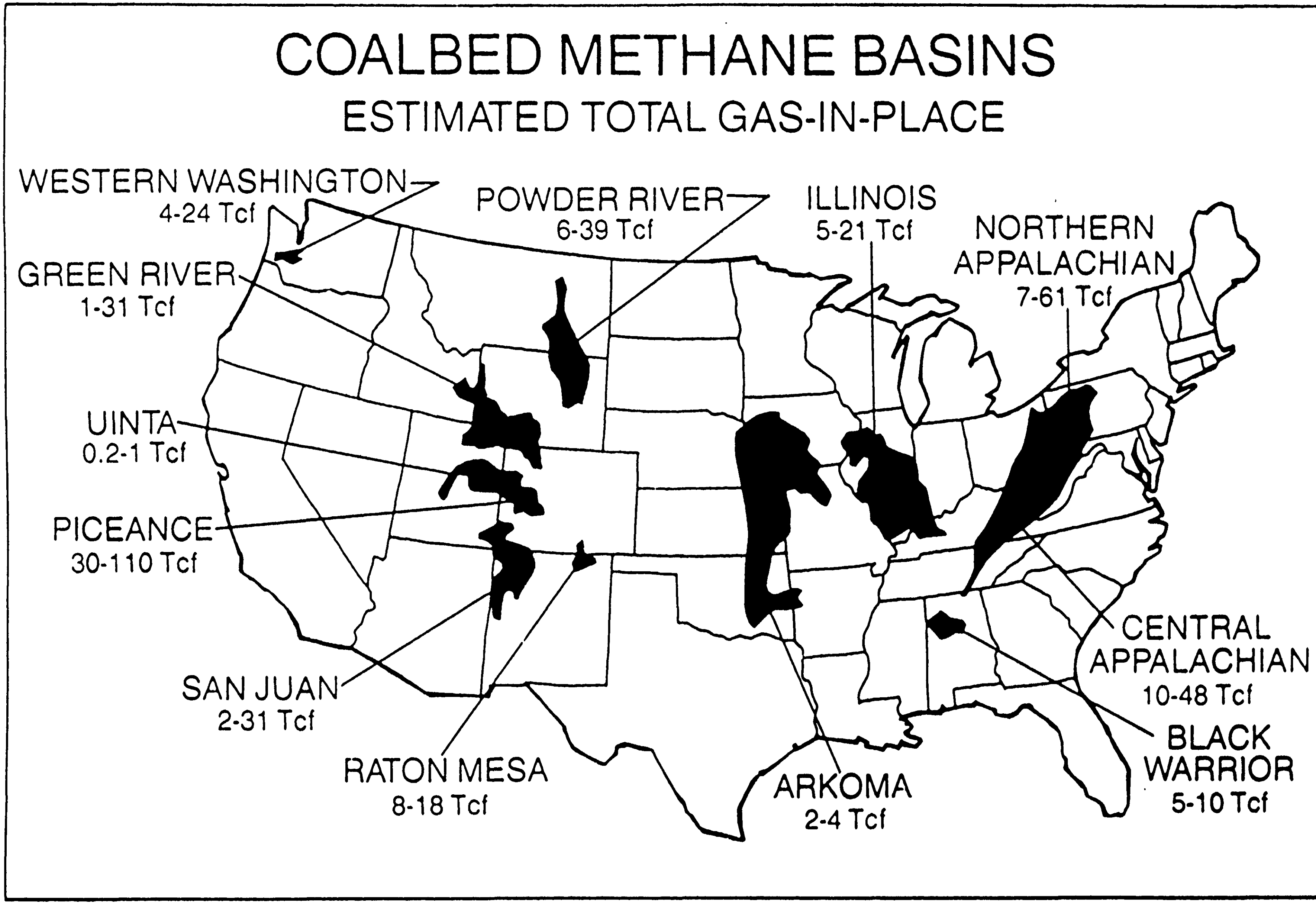

Figure 43--Estimated in-place, undiscovered coalbed methane of the San Juan basin. (From Shirley, 1986).

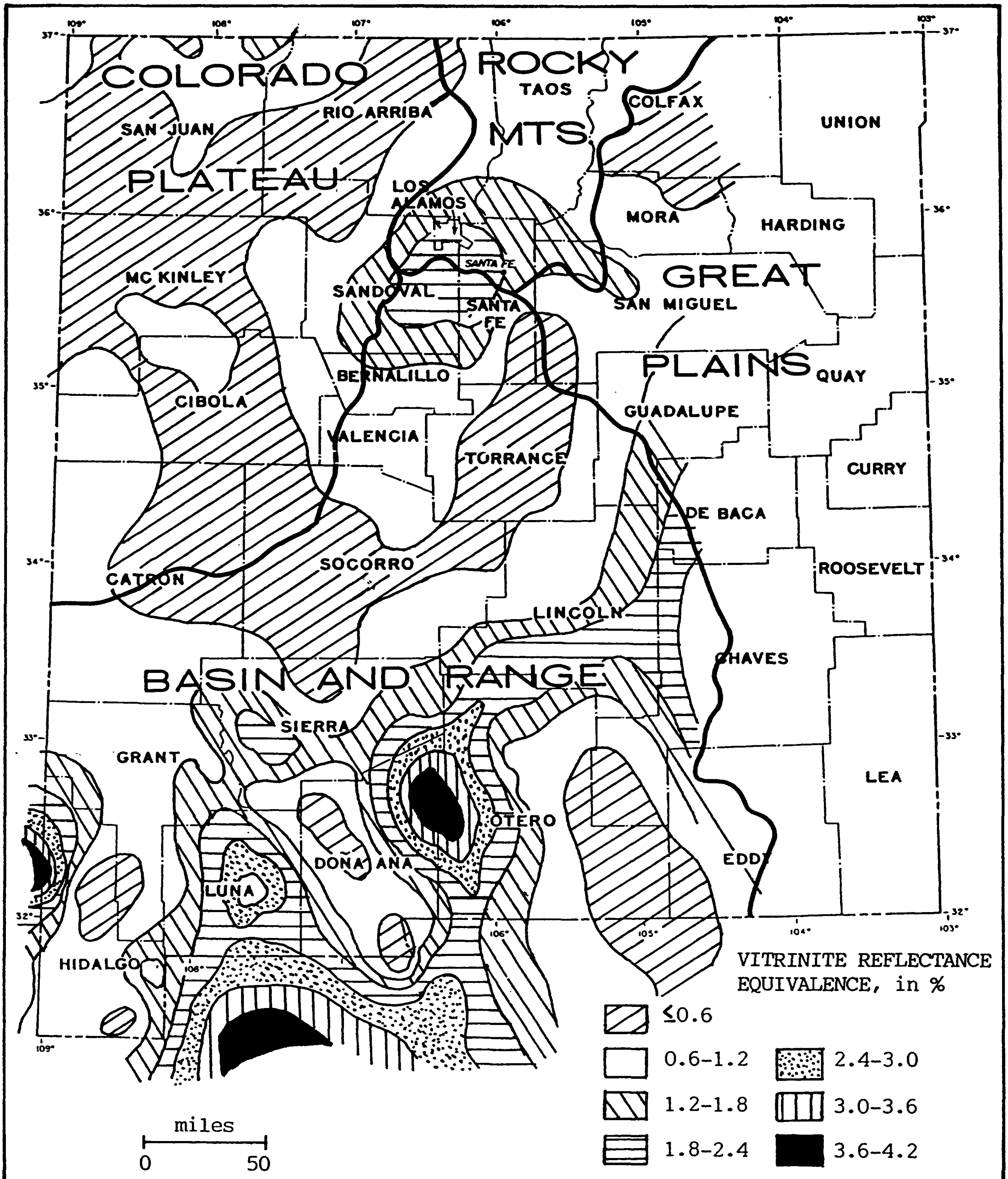

Figure 44--Preliminary surface thermal maturity map of Paleozoic and Mesozoic strata in western New Mexico. Higher values near plutons and lower values over alluvial basins have not been reconciled.

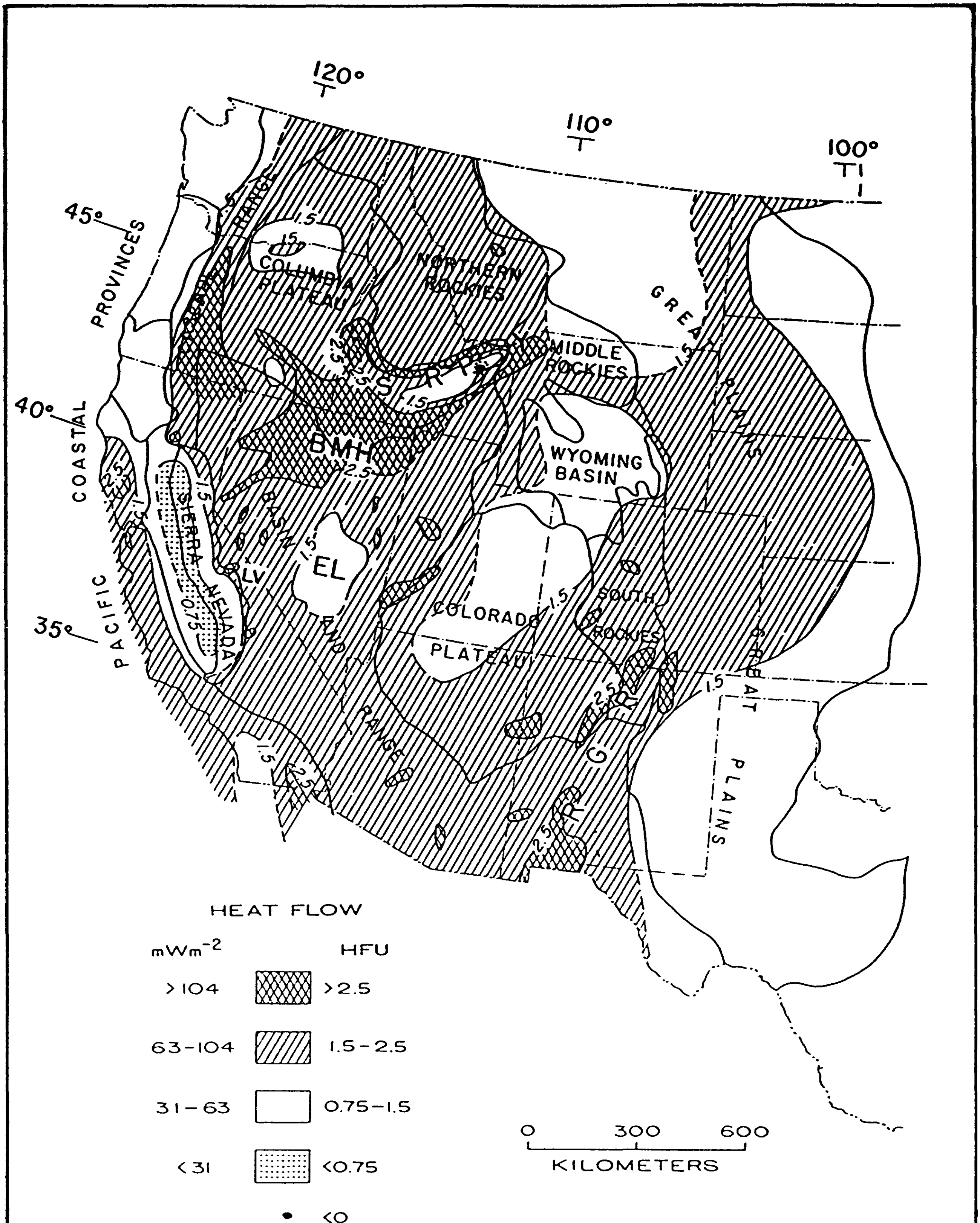

Figure 45-- Map of the western United States showing heat-flow contours (in heat-flow units, HFU, 1 HFU = 41.8 mWm^{-2}), heat-flow provinces, and major physiographic divisions (SRP: Snake River Plain; BMH: Battle Mountain High; EL; Eureka Low; RGR: Rio Grande Rift Zone; Y: Yellowstone; LV: Long Valley). (From Sass and others, 1981).

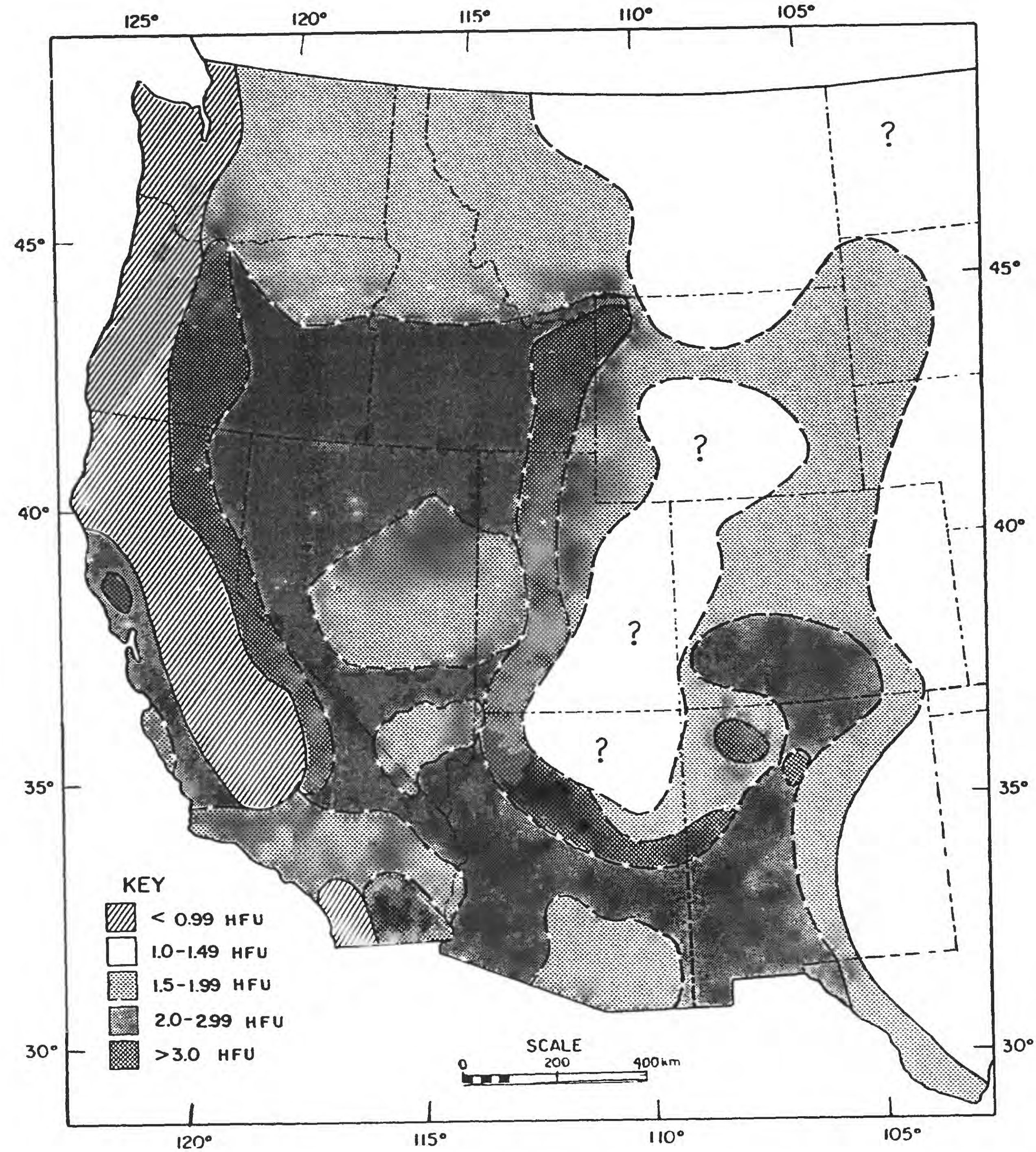

Figure 46--Energy-flux map of the Western United States. Contours are in heat-flow units. (From Blackwell, 1978).

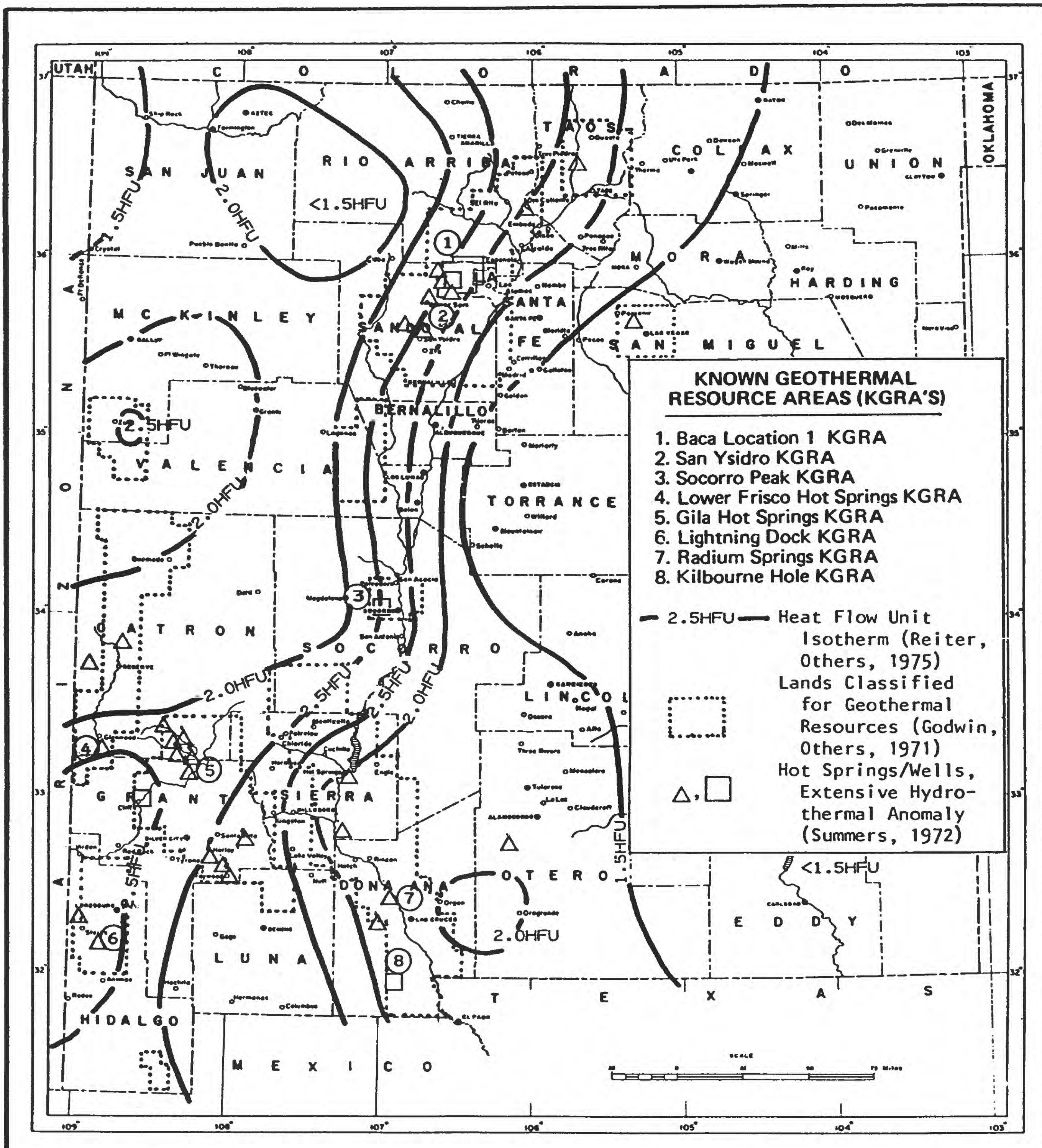

Figure 47--Index map of New Mexico showing geothermal resource areas and heat flow unit isotherms. (From Grant, 1978).

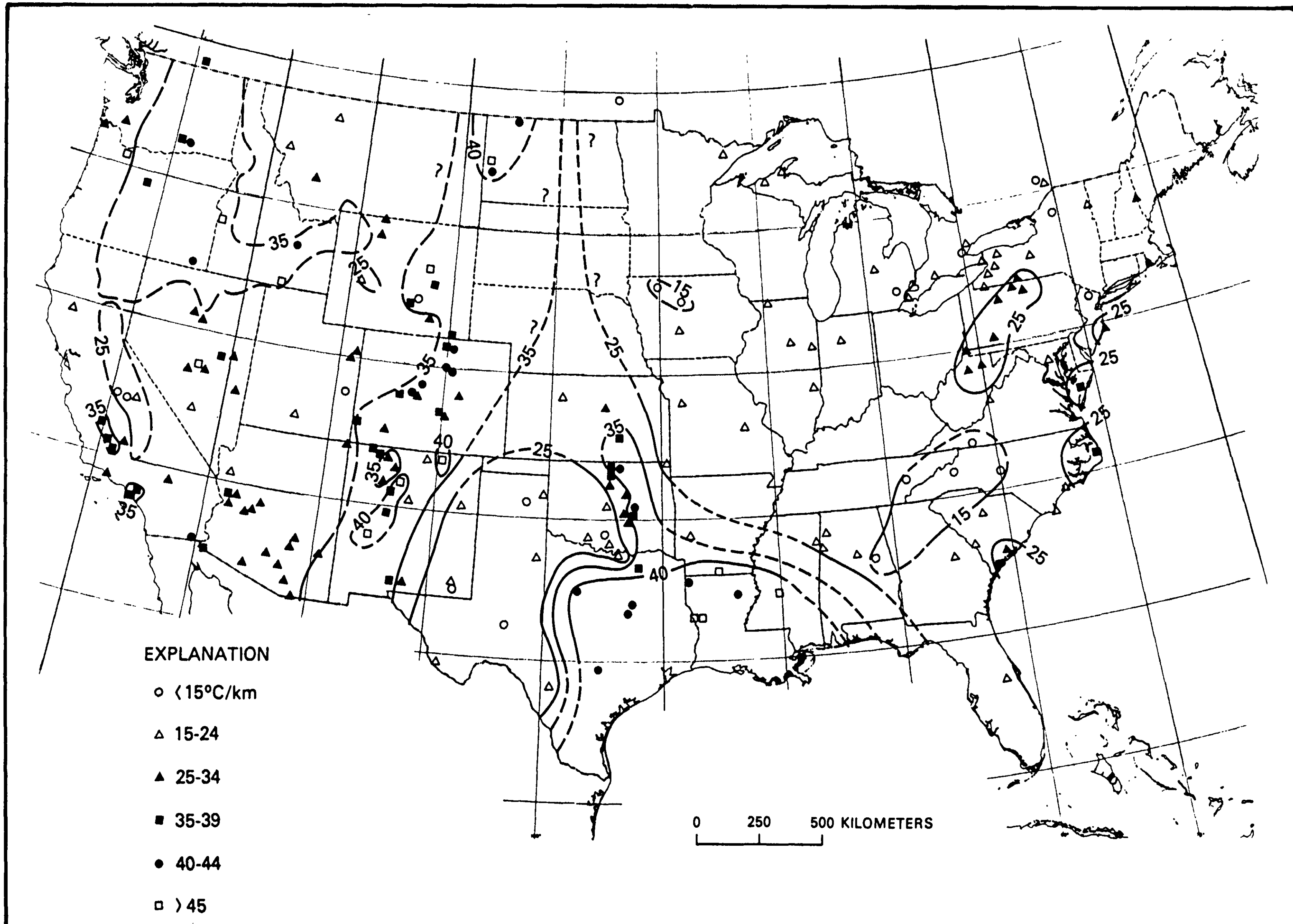

Figure 48--Temperature gradient map of the conterminous United States. (From Nathenson and others, 1983).

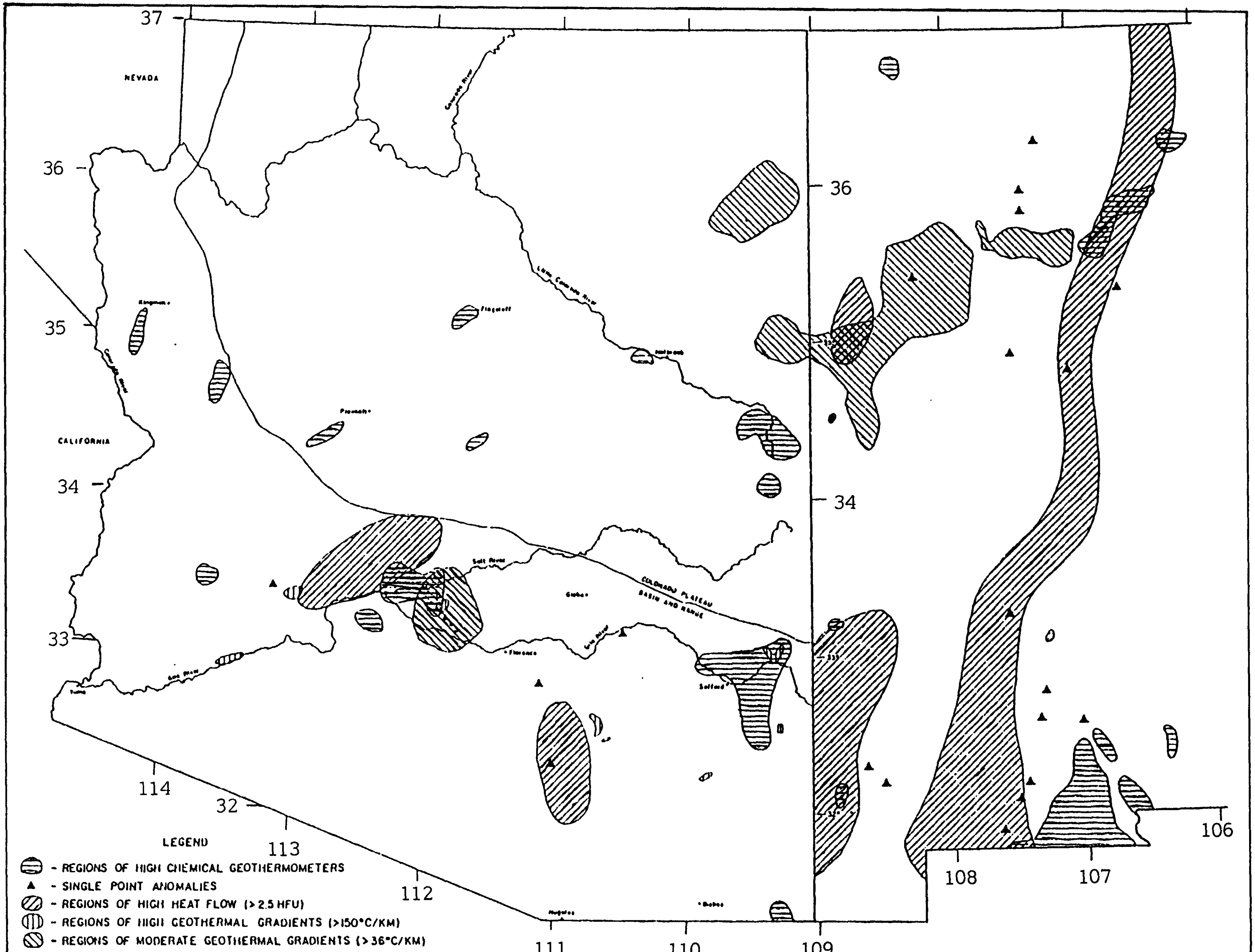

Figure 49--Map of Arizona and western New Mexico showing thermal anomalies and geothermal gradients. (From Swanberg and others, 1977).

threshold for heavy oil generation, present-day heat flow is relatively high (fig. 45-49). These rocks are therefore conceivably generating methane at present. Heat flow units (HFU) in and surrounding the play generally occur in the range between 2.35 and 3.0 HFUs (Reiter and others, 1975; Grim, 1977; Lachenbruch and Sass, 1977; Edwards and others, 1978; Grant (1978), Grim and Berry, 1979; Reiter and Shearer, 1979; Ikelman and Theberge, 1980; Sass and others, 1981; Kron and Stix, 1982; and, Eggleston and Reiter, 1984). For reference, the mean surface heat flow of the Colorado Plateau is 1.62 HFU according to Crough and Thompson (1976), 1.3 HFU according to Keller and others (1979), and about 1.56 HFU in the non-volcanic areas of the province according to Reiter and Mansure (1983).

Geothermal gradients are mapped as being 2.0°F/100 ft. (36.5°C/km) by DeFord and Kehle (1976) and Swanberg and others (1977). Nathenson and others (1983) indicate higher values of 2.2-2.5°F/100 ft. (40-45°C/km). A few miles west of the play in New Mexico the highest value, according to Kron and Stix (1982), is 3.7°F/100 ft. (67°C/km). The origin of the basalt is deep-seated from the lower crust or upper mantle. For this reason, the extrusive process could locally maintain relatively high temperatures, especially along a network of fractures or conduits within the valley.

A wide array of thermal phenomena and anomalous thermal trends surround the play area. A known geothermal area is documented due west of the play in New Mexico (Arnold and Hill, 1981). In 1982 Phillips Petroleum Company drilled eleven geothermal wells near the Arizona-New Mexico border to exploit this energy resource. Abundant volcaniclastic and flow rocks, plus a volcanic maare (tuff ring of Aubele and others, 1976) at Salt Lake, NM., are two types of volcanic features south to southwest of the play, respectively. Mafic intrusions are scattered occurrences immediately south of the play. Although there is no direct comparison to known source rocks in the San Juan basin, this play does have similarities to that basin's petroliferous reservoirs of Upper Cretaceous age. San Juan basin source rocks produce large volumes of oil and particularly gas, in part due to deeper burial and, therefore, a more favorable geothermal maturity.

Source Rocks, Reservoir Rocks, Traps and Seals

The primary source beds are the coals with secondary coaly clastic units of the Dakota Sandstone. The entire lower part of the Upper Cretaceous section in the play contains approximately 75 ft of coal and very carbonaceous clastics, i.e. conglomerate, sandstone, siltstone, and shale containing black powdery coalified material. These beds serve as both source and reservoir rocks for methane. The coal and disseminated coal-like material found in the known coalbed methane reservoir beds of northwest New Mexico include high-volatile bituminous "C" and sub-bituminous types. A small increase in temperature of about 10-20^{o}C, is capable of converting sub-bituminous coal to high-volatile coal with a large release of methane. Several tongues of the Mancos Shale probably act as effective seals; however, the mechanism for trapping is adsorption within the coal and conventional gas-trap structures and seals are thus unnecessary.

Three coal fields within the Mesaverde Group surround this play (fig. 50): the Gallup-Zuni field to the west and northwest, the Salt Lake field to the southwest, and the Datil Mountain field to the east and southeast (See Ellis, 1936; Trumbull, 1960; Kottlowski and Beaumont, 1965; Bieberman and Weber, 1974; Kottlowski and others, 1974; U.S. Geological Survey, 1977; Tabet and Frost, 1978; Logsdon, 1982; Roybal and Campbell, 1982; McLellan and others, 1983; and, Cavaroc and Flores, 1984).

Local Structure

The fracture pattern in the Zuni uplift is northwest and northeast (Kelley and Clinton, 1960). Precambrian basement rises from about +2,000

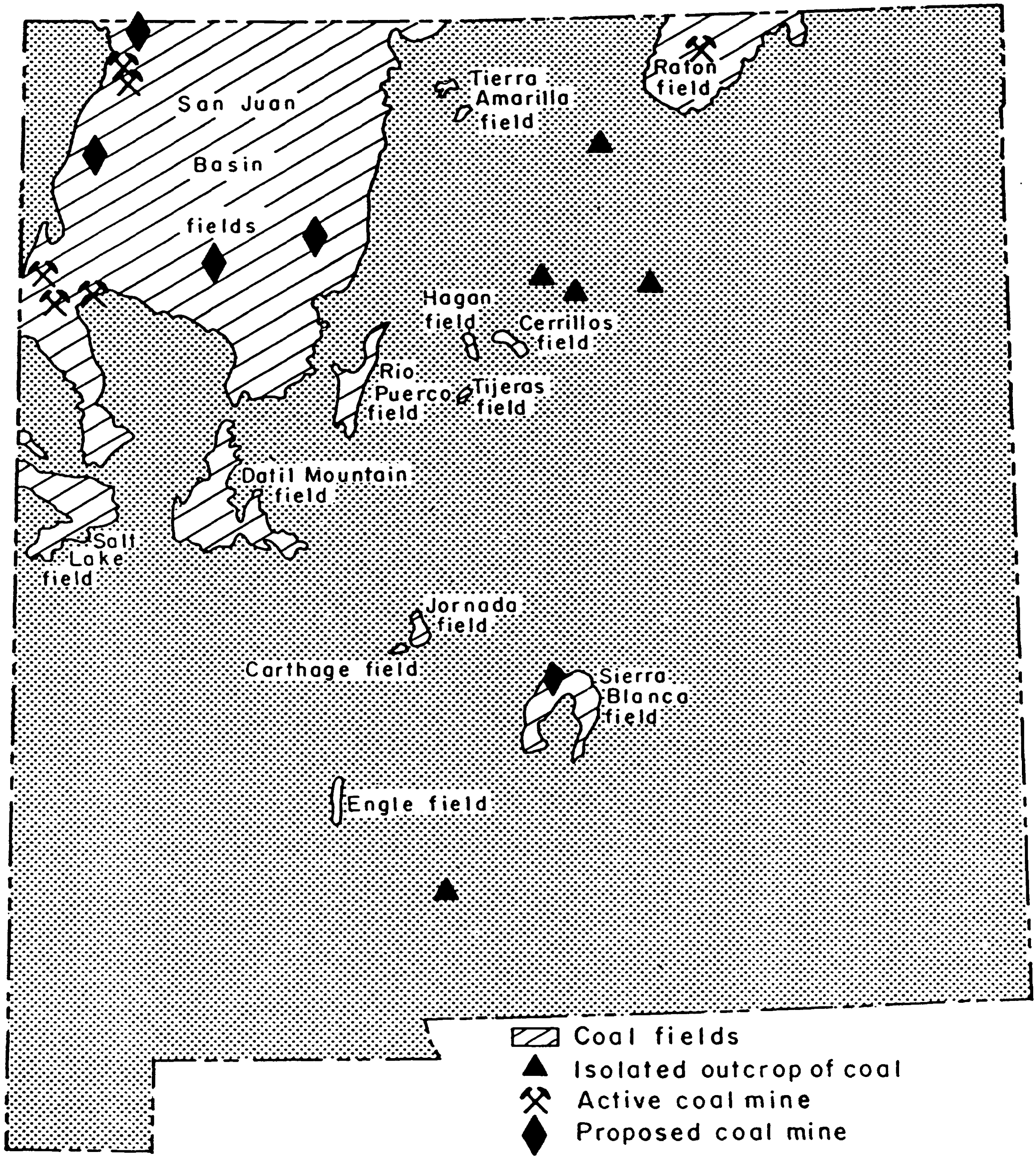

Figure 50--Location of coal fields of New Mexico. (From Arnold and Hill, 1981).

ft to about +4,000 ft northward within the play area (Hunt, 1956; Cone, 1965; Bayley and Muehlberger, 1968; King, 1969; and, Kleinkopf, 1972). The exposed core of the Zuni anticline is Precambrian granite dated at about 1.5 billion years (Condie, 1981). Although local fold structures undoubtedly exist, the strata superjacent to the Precambrian in the play are for the most part undeformed except for dipping 1-2 degrees south to southwesterly away from the Zuni Mountains as determined by structural contours of the Dakota Sandstone (Thaden and Zech, 1984). Faults in the play may be hidden below the basalt but some Recent, normal, en echelon faults have been mapped in the Cretaceous rocks along the eastern edge and in Cebollita Mesa; Cather and Johnson (1984) illustrate a northeast-trending fracture zone (Hickman fracture zone) in the same area (fig. 51). Other normal faults are common in the eastern Zuni Mountains. Most of these faults parallel the north-northeast axis of North Plains Valley and a few are inferred to have a small right-lateral component (Maxwell, 1986).

The North Plains Valley, containing voluminous basalt, is probably an asymmetrical (deeper to the east), small-scale (?) rift basin or rotated block (north side up and south side down) of (?) Miocene or younger age. The basalt on top Cebollita Mesa to the east is (?) Miocene or (?) Pliocene (Dane and Bachman, 1965) indicating that some extrusions may have occurred contemporaneously with graben development or block rotation. As much as 1,500 ft of displacement, increasing southward, is suspected on the east side of the graben. Further filling of North Plains Valley with olivine tholeiitic and alkalic olivine basalts occurred during Holocene time (Laughlin and others, 1972). Enough mafic rock is present within the valley to manifest a northeast-trending positive gravity anomaly (Bouguer and isostatic residual) over the North Plains valley (Aiken and others, 1978; Keller and Cordell, 1983; Jachens and others, 1985). Similar

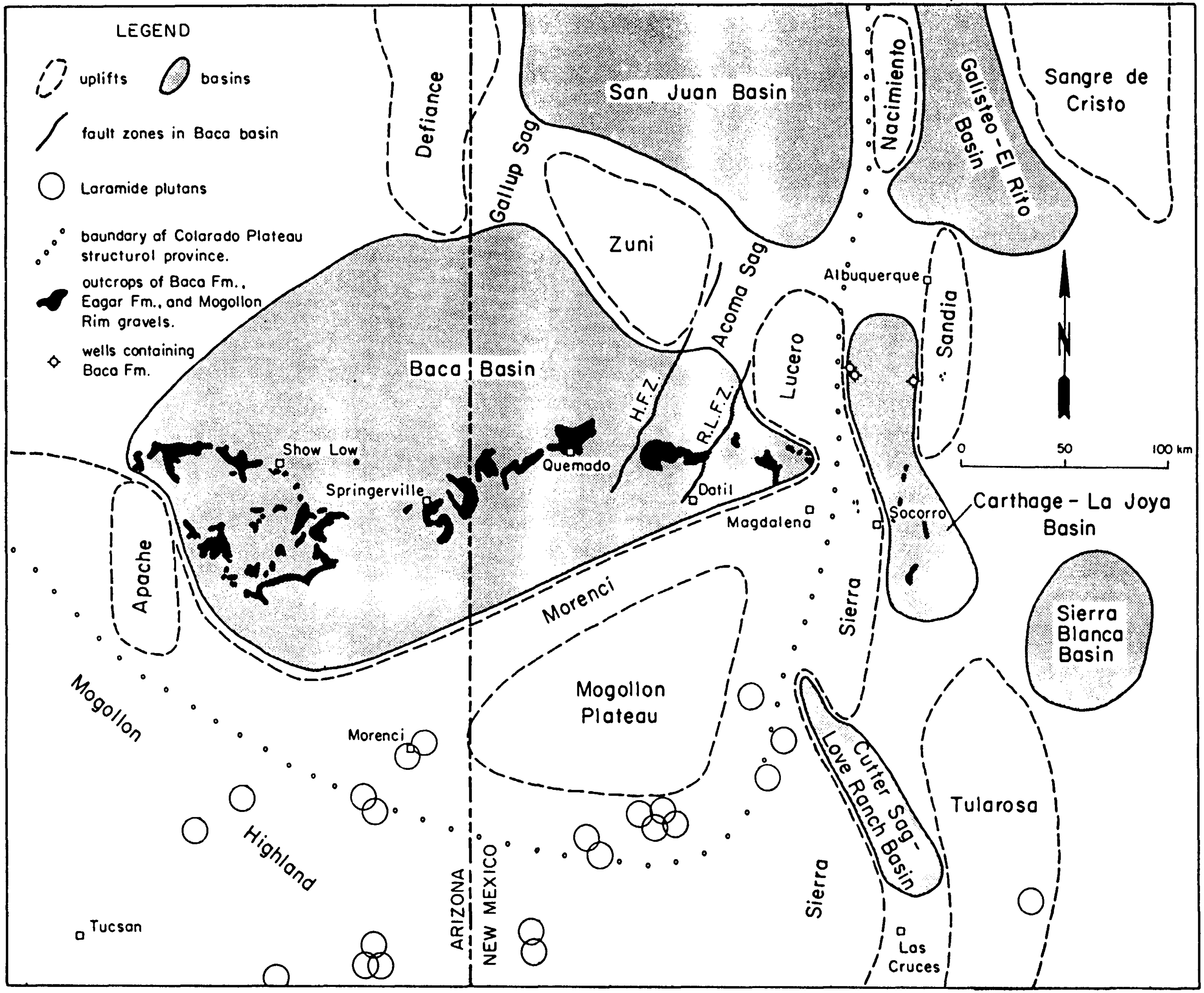

Figure 51--Map showing Eocene uplifts and basins in western New Mexico and eastern Arizona. RLFZ=Red Lake fault zone and HFZ=Hickman fault zone. (From Cather and Johnson, 1984).

trends are seen on aeromagnetic maps (e.g., Zietz, 1982; Cordell, 1983), but these are less well defined.

The axis of the (?) rift zone appears to parallel and perhaps be related to the Rio Grande Rift in eastern Valencia County. The Rio Grande Rift, a major intraplate boundary, began opening in central New Mexico during Oligocene time in response to clockwise rotation of the Colorado Plateau. To analyze whether the fault structures of this play are inherited from zones of weakness in the Precambrian basement, or whether they are unique products of Cenozoic tectonics, or both, is tangential to this report. Trapping of coalbed methane, however, for all practical intent is independent of local structure in the geologic framework of this play.

Depth of Occurrence

In the play, maximum depths for reservoirs of the Dakota Sandstone range from 200-1,000 ft near the north edge, 750-1250 ft in the southwest corner, and up to 1,500-2,000 ft elsewhere. The Cretaceous section rises and thins towards the Zuni Mountains where some small and isolated outcrops of Permian and probably Triassic age are found as "windows" in the basalt.

Potential of Coalbed Methane Resource

The methane content of other high-volatile C coal in New Mexico is about 72 CFG/short ton. Twenty-five to 50 ft of coal plus coal-equivalent thickness is assumed in this assessment. Because the subsurface thermal regime of west-central New Mexico is not completely understood, the inferred extent of producible Upper Cretaceous reservoirs may actually be 5-10 miles east and west of the currently outlined play. Sparcity of heat flow data, however, limits the play boundary to the area capped by basalt. Shirley (1986) noted that some single coalbed methane wells in the San Juan basin, producing from the Upper Cretaceous Fruitland Formation about 3,000 ft deep, have already produced over 1 billion cubic feet each in the last

30 years and are still active. Given certain basic geologic conditions, such as permeability, the amount of gas as a total resource can also be estimated quantitatively using PC computer software (Downey, 1987).

Exploration Status

The area of this play, plus the area 10-15 miles outward from this play, is the least drilled area of the northwestern quadrant of New Mexico. About ten boreholes (Petroleum Information, Corp., 1984) account for all drilling in a 2,300 square mile area.

Pertinent Literature on Coalbed Methane Research and Resource Methodology

Coalbed methane is an important unconventional petroleum resource in the United States that has received considerable emphasis and subsequent research since the early- to mid-1970's. This emphasis has included coal sampling procedures, laboratory analyses of gas content and desorption, and the methodology of resource assessment with quantitative examples. For the interested reader, some of the pertinent literature concerning San Juan basin natural gas and coalbed methane, plus other resource models and methodology, is listed here: Kottlowski and Beaumont (1965), Juntgen and Karweil (1966), Cervik (1969), Fassett and Hinds (1971), Shomaker and others (1971), Kim (1974), Kottlowski and others (1974), Ruppel and others (1974), Averitt (1975), McCulloch and others (1975), McCulloch and Diamond (1976), Irani and others (1977), Kim (1977), McCulloch (1977), Murray and others (1977), Shomaker and Whyte (1977), Tabet (1977), Weimer (1977), Curl (1978), Fender and Murray (1978), Kim (1978), Barron and others (1980), Kelso and others (1980), Lent (1980), Murray (1980), Tremain (1980), Walker (1980), Boreck and others (1981), Diamond and Levine (1981), Murray (1981), Tremain and others (1981), TRW Energy Engineering Division (1981), Williams and Smith (1981), Choate and Rightmire (1982), Diamond (1982), Merry and Larsen (1982), Aitken (1983), Choate (1983), Wood and others (1983), Choate and others (1984), Eddy (1984), Meissner (1984), Meissner and others (1984), Rightmire (1984), Tremain (1984), Ward (1984), Jones and others (1985), Stricker and Anderson (1985), Choate and others (1986), Molnia and others (1986), Shirley (1986), Fassett (1988), and Kelso and others (1988).

Late Paleozoic Orogrande Basin Play

Location, Size, and Land Status

The Orogrande basin is a large play, entirely within New Mexico, covering 9,975-10,250 square miles mostly in the Rio Grande Rift province of south-central New Mexico (fig. 2). However, 11-12 percent of the play area (about 1,150 square miles) has very low potential because the reservoirs of Mississippian through Permian age which have potential elswehere in the play, are either exposed at the surface or have been eroded away, such as in the San Andres Mountains (fig. 34). Approximate bounding longitudes are 105°30′ to 107°00′ east to west and latitudes 32°00′ to 34°00′ south to north. Parts of five counties are within the area outlined: Otero, Dona Ana, Sierra, Lincoln, and Socorro. White Sands National Monument, San Andres National Wildlife Reserve, White Sands Missile Range, and Fort Bliss Military Reservation occupy the central to south-central portion of the area.

Land classification types and their estimated areas within the assessed area include: military (48 percent), Bureau of Land Management, i.e. public (30 percent), private (7 percent), state (7 percent), national monument (2 percent), wildlife reserves (2 percent), grant lands (2 percent), and miscellaneous (2 percent). Land status has been estimated from numerous Bureau of Land Management maps published in 1981 and 1982.

Basis of Play

Foster and Grant (1974) have outlined favorable exploration areas and reservoir zones in New Mexico. Kottlowski's (1977) rendition of their map (fig. 52) indicates areas of "good", "medium", and "fair" potential (classes #2, #3, and #4, respectively) for various sectors in the play in strata of Pennsylvanian age, excluding the uplifted, mountainous, north-south sector from roughly east-central Socorro County through the San Andres Mountains to the Organ Mountains and southeastern-most Dona Ana County, New Mexico, and northwestern-most Hudspeth County, Texas. About half of New Mexico was considered by these authors to have no, or very low, petroleum potential, and about 15 percent (San Juan and Delaware basins) was rated high potential, i.e. class #1. Ordovician, Silurian, Mississippian, and Permian strata also have favorable attributes in the assessed province, but their areas of potential are much less evenly distributed than for the Pennsylvanian System.

In the Orogrande basin, there is a close association within the Pennsylvanian section of alternating, or possibly reciprocal cyclic (Wilson, 1967 and 1972a, b; LeMone, 1985; Bowsher, 1986), porous, and permeable calcarenites, quartz sandstones, carbonate coquinas, algal reefs, carbonaceous shales, and dark fetid and petroliferous limestones. Foster (1978a) stated, "It can be assumed that oil and gas were present in the area prior to the Laramide development of the Basin-and-Range structural province. Under the conditions that existed into Cretaceous time, it would be unique to have a sequence of source and reservoir rocks of the thickness and extent present in south central New Mexico and not to have substantial deposits of oil and gas." Furthermore, Thompson and others (1978) have ranked the Magdalena Group of Pennsylvanian age in the Orogrande basin the highest priority of thirteen exploration targets of south-central and southwestern New Mexico with respect to their potential as source and reservoir rocks.

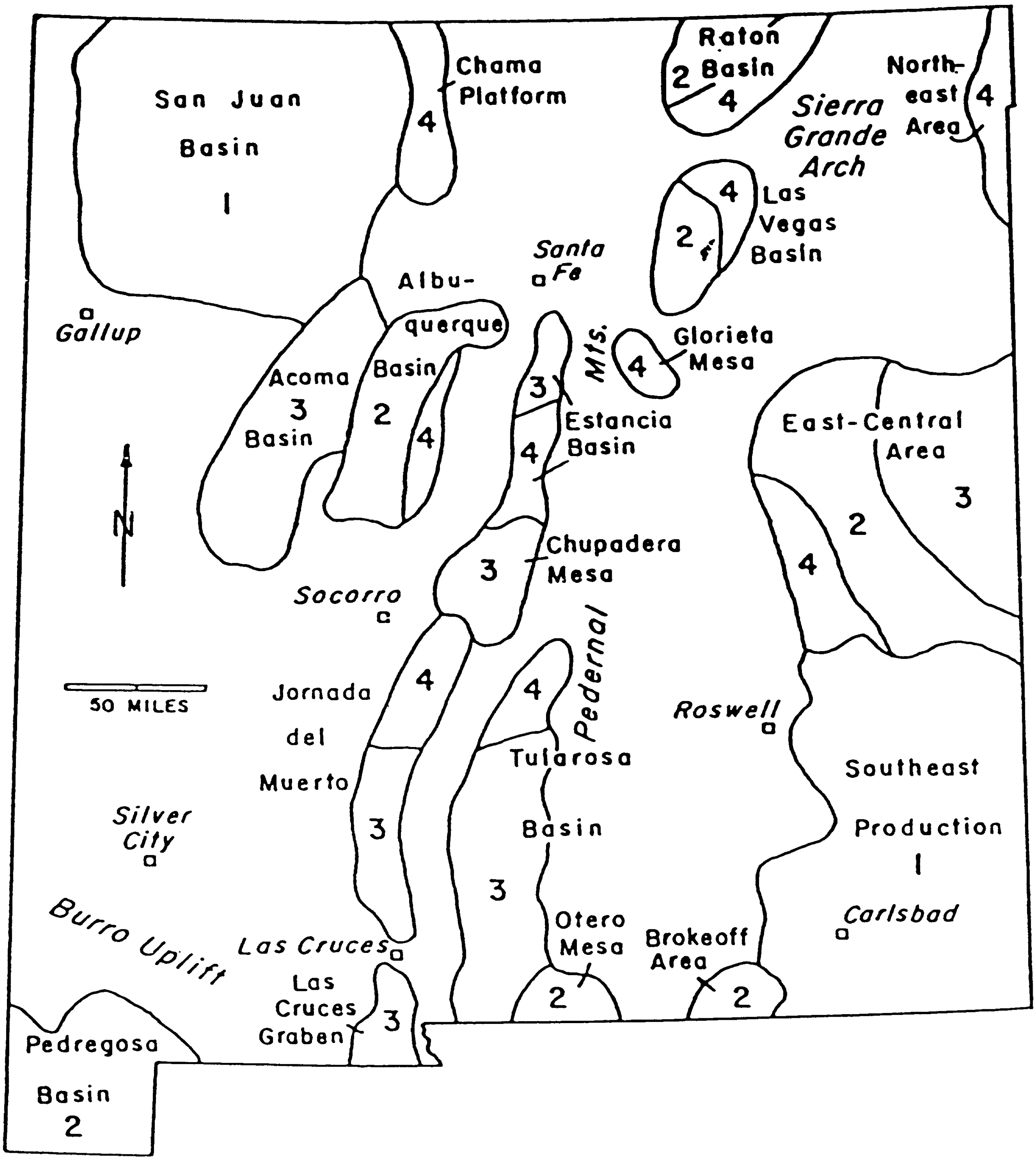

Figure 52--Petroleum potential map of New Mexico. Areas of #1 are petroleum provinces and areas #2-4 have exploration potential with #2 being highest. (From Kottlowski, 1977).

Pennsylvanian strata deposited in the shallow (probably 200 ft maximum depth), gradually-subsiding Orogrande basin are up to 3,250 ft thick (Kottlowski, 1965) in the center of the present-day, asymmetric Tularosa Basin (fig. 24). These strata thin in all directions to about 1,000-1,500 ft at the edge of the play (Kottlowski, 1962; Foster, 1978a; Connolly and Stanton, 1986; Peterson and Smith, 1986; and Ross and Ross, 1986), except in the southeastern part (Otero platform) where they are very thin to absent. For this latter area, fetid, oolitic and biostromal carbonates of Permian age, occurring as shallow and fractured reservoirs, have the greatest petroleum potential.

The total thickness of Paleozoic strata is from about 4,000 to 8,500 ft in the play (fig. 53). Foster and Grant (1974) have estimated the maximum thicknesses of the sedimentary sections, Precambrian to Recent, in several areas of the play. Their values are 25,000 ft for the Las Cruces (Potrillo or Mesilla) Basin, 14,000 ft for the Tularosa Basin, 7,500 ft for Otero Mesa, and 10,000 ft for the Jornado Del Muerto Basin.

To supplement the regional stratigraphic picture as presented in figure 18, appendices A and B are included for the reader who desires an understanding of local stratigraphic relationships and nuances.

<u>Geothermal Maturity</u>

The plutonic and volcanic history and heat flow of south-central New Mexico are intimately linked to the subduction of the oceanic Farallon plate beneath the southwestern margin of the North American plate. The origin, composition, and timing of emplacement and extrusion of mid-to-late Tertiary igneous rocks, plus the tectonic relaxation which allowed magma to rise, are related to the direction of movement, subduction rate, subduction angle, and thermal stability of the descending slab.

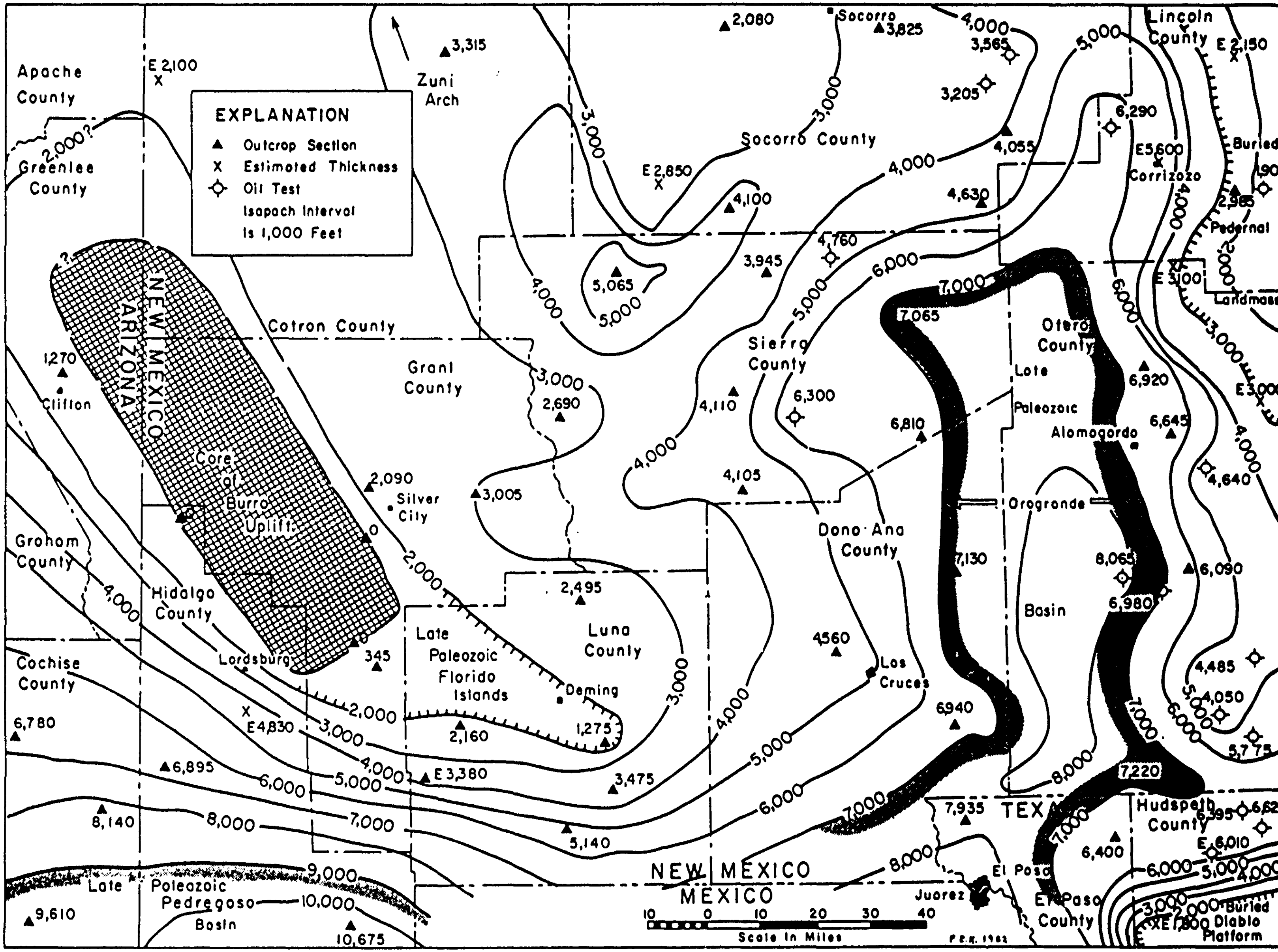

Figure 53--ISOPACH MAP OF PALEOZOIC STRATA IN SOUTHWESTERN AND SOUTH-CENTRAL NEW MEXICO (From Kottlowski, 1963).

The depth of burial of potential reservoirs plus the relatively high geothermal maturity of rocks uplifted to the surface indicate that parts of the play are gas-prone. A preliminary thermal maturity analysis of Paleozoic and Mesozoic outcrop samples by the author, using vitrinite reflectance and conodont alteration indices (fig. 44), shows a relatively hot, arcuate trend (concave eastward) of mature to super-mature rocks with respect to the oil window. Computer-contoured data, from formerly deeply -buried Paleozoic strata, show an interpolation of high values over the Tularosa Basin, when in fact the Cenozoic alluvium is an area of no data. Maturity values along the Sacramento Mountains escarpment are consistently about 1.2 vitrinite reflectance equivalents (VR_o). The western and northern thirds of the play are relatively cool with values of 0.6 to 1.2 VR_o. Upper Paleozoic strata buried within the deeper parts of the Tertiary basins will have higher thermal maturities, and hence be prone to generating greater amounts of associated gas (condensate or "wet gas"), and non-associated thermal ("dry") gas than heavy oil given the same type of kerogen, presumedly mostly type II..

Present-day geothermal gradients, according to DeFord and Kehle (1976), are between 1.0-1.4 ^{o}F/100 ft. (18.2-25.7 ^{o}C/km) in the southeastern play, and 1.2-1.9 ^{o}F/100 ft. (21.9-34.8 ^{o}C/km) in the northwest. Nathenson and others (1983) have shown a fairly uniform increase in the temperature gradient from about 1.37 to 2.20 ^{o}F/100 ft. (25-40 ^{o}C/km) from the southeastern to the northwestern corners of the play, respectively (fig. 48). Gradient data (Kron and Stix, 1982) in units of ^{o}F/100 ft. (^{o}C/km) show these ranges: 1.20-1.58 (22.0-28.8) in the north; 1.55-2.09 (28.6-38.0) in the northwest; 1.45-1.75 (26.5-31.9) in the west-central part; 1.66-2.21 (30.54-40.1) in the south-central part; 1.48-1.71 (26.9-31.2) in the southwest (one highly anomalous value is 73.0 ^{o}C/km);

1.20 (22.0) in the southeast; and, 1.65 (30.4) in the northeast.

Present-day heat flow and areas of known geothermal resource areas (KGRA) have been mapped by Warren and others (1969), Thompson and Burke (1974), Reiter and others (1975), Sass and others (1976), Grim (1977), Blackwell (1978), Grant (1978), Reiter and others (1978), Edwards and others (1978), Grim and Berry (1979), Reiter and others (1979), Swanberg (1979), Guffanti and Nathenson (1980), Ikelman and Theberge (1980), Swanberg and Morgan (1980), and Sass and others (1981). Their data generally show an increase in heat flow from east to west, i.e. from 1.5 to 2.5 heat flow units (HFUs) from the Sacramento Mountains to the Rio Grande River (fig. 45-47). In the southwestern sector of the play HFUs exceed 2.5; here the area is classified as a major geothermal area and KGRA. Grim (1977) included a 3.10 HFU value in the volcanic-plutonic area of the Organ Mountains. Ranges of HFUs in specific regions of the play include: 1.44-1.56 in the north; 2.20 in the northwest; 1.60-1.96 in the west-central part; 1.75-2.48 in the south-central part; 1.47-3.31 in the southwest; 2.0 in the southeast; and, 1.77 in the northeast.

Source and Reservoir Rocks

Thick, abundant, Pennsylvanian brown-to-black carbonaceous shales (e.g., the Panther Seep Formation) are potential source rocks (Kottlowski and others, 1956; LeMone, 1985). Figure 25 shows these strata are up to 1,500 ft thick. Secondary source rocks are inferred to be the dark, basinal Devonian shales up to 170 ft thick, such as the "Percha Shale" as described by Sorauf (1984) in the southern play area; equivalent units are the Onate, Sly Gap, Contadero, Thoroughgood, and Rhodes Canyon Formations. Additionally, Mississippian and Permian shales and carbonates may eventually prove to be good source rocks. The porous dolomite and other carbonates of the Permian San Andres and Yeso Formations are of particular note for their bituminous content (Foster, 1978a).

Reservoir rocks are almost ubiquitous, but specifically include Permian and Pennsylvanian bioherms and siliciclastic strata, Mississippian bioherms, and lastly, carbonates of Ordovician and Silurian ages to a lesser extent. Algal banks and bioherms (see Wray, 1962; Wilson, 1977) normally 75-100 ft thick in the Magdalena Group and Panther Seep Formation are potential reservoirs; they occur in the exposed parts of the Sacramento, San Andres, Franklin, and Hueco Mountains (Seewald, 1975). Virgilian algal reefs up to 200 ft thick and possibly a mile wide have been described in the Sacramento Mountains by Plumley and Graves (1953) and Bowsher (1986). Mississippian and Permian bioherms up to 350 ft thick, plus petroliferous Permian carbonates, have also been documented in the stratigraphic section, but they may have less porosity than the Pennsylvanian ones.

LeMone (1985) concluded the following relative to the Hueco Mountains: "The Pennsylvanian Magdalena Group has outstanding Morrow sand development as well as chaetetid biostromes and phylloid algal mounds which could develop into excellent reservoir rocks. Stromatolitic algae in this unit can act as both reservoir or source rock." In describing the Pennsylvanian Panther Seep Formation, Kottlowski (1975) has written, "Besides the southern thickening of the formation in the San Andres Mountains, the proportion of coarse clastic rocks decreases southward, reef-like limestone and associated grayish-black carbonaceous shale occur chiefly in the central part of Rhodes Canyon to Hembrillo Canyon, and gypsum beds with argillaceous calcilutite are the characteristic feature of the strata of San Andres Canyon. The biohermal-like limestone masses near Hembrillo Canyon may encircle the deeper part of the Orogrande basin, connecting as a reef-zone eastward with the Virgilian reefs in the Sacramento Mountains and arched south-southwest, south, and then southeastward to join the Virgilian reefs in the northern Hueco Mountains." Toomey and others (1977) have described in detail the Late Pennsylvanian carbonate-mound buildups (phylloid algae) classified as boundstone, packstone, and wackestone, which are exposed in the eastern play area. Mazzullo and Cys (1979) have similarly described Wolfcampian bioherms. Foster (1978a) also suggested that Virgilian reefs may ring the present-day Tularosa Basin, and noted there is excellent pay zone potential in the lower and middle Pennsylvanian deltaic facies of the northeastern part of the play area.

Thicknesses and General Facies

Mississippian strata generally thicken southward from an erosional edge in southeastern-most Socorro County to 500 ft in the Franklin Mountains (Armstrong, 1962; Armstrong and others, 1979; Armstrong and Mamet, 1979). Significant erosion, however, has also reduced thicknesses on the Pedernal uplands/Otero platform (fig. 19-21). Mississippian strata are argillaceous, nodular, cherty crinoidal to biohermal calcarenites and calcirudites plus calcareous siltstone and calcareous shale. Pennsylvanian strata are inferred to be thickest about 20-30 miles west of Alamagordo, NM.; they show rapid facies changes due to the terrigenous influx from the east. Pennsylvanian rocks include coarse arkosic sandstone, chert pebble conglomerate, red siltstone, dark shale, and cherty calcarenites and calcilutites. Thicknesses of Permian strata range from 2,500-3,000 ft in the south-central play area to 4,300-6,000 ft in the north to northeast. Permian rocks are also diverse lithologically; they include red beds, arkose, limestone conglomerate, siltstone, sandstone, cherty limestone, shaley carbonates, mudstone, marl, and evaporites. See Jordan (1971) for a detailed stratigraphic analysis.

Ranges of average thicknesses of the combined Mississippian, Pennsylvanian, and Permian strata include about 6,500 ft in the southern

San Andres Mountains, 3,500 ft in the Franklin Mountains, 5,800 ft in the Hueco Mountains, 4,000 ft in the Sierra Diablo Mountains, 5,750 ft in the Sacramento Mountains, 6,275 ft in the northern San Andres Mountains, and 4,650 ft in the Carthage area. Excluding the addition of Cenozoic rock thicknesses, which can range from zero to 12,000 ft in the deepest part of the rift basins, the total stratigraphic section in the same locations as noted above are: 7,600-9,225 ft in the southern San Andres Mountains, 7,800-8,100 ft in the Franklin Mountains, 6,000-10,600 ft in the Hueco Mountains, 8,265-12,900 ft in the Sierra Diablo Mountains, 4,925-7,825 ft in the Sacramento Mountains, 7,000-7,250 ft in the northern San Andres Mountains, and 3,675-8,300 ft in the Carthage area.

Traps and Seals

Individual traps are not identified in this synopsis, but abundant traps in Mississippian through Permian strata are present; traps are of the general types which include wedge-on-wedge (see cross-sections of Kelley and Furlow, 1965, Meyer, 1966, and Lane, 1974), stratigraphic pinchout, unconformity, biohermal, fault, and anticline. Common limestone-dolomite facies and porosity changes also enhance the potential of stratigraphically trapping hydrocarbons. Given that unconformities occur within every Paleozoic system, and together with the generally east-west stratigraphic thinning and thickening in Upper Paleozoic strata (see fig. 59-63), numerous opportunities are available for trapping of hydrocarbons.

Structural complexity increases from east to west, i.e. from the Tularosa Basin to the Jornada del Muerto Basin. This complexity has both positive and negative consequences for the trapping of petroleum. Folding and faulting can create traps, however, late faulting can also rupture traps destroying any accumulations, i.e. after migration. Extensive faulting has increased the probability of high-pressure freshwater flushing

(Bridges, 1984; DeJong, 1985), particularly in the Jornada del Muerto Basin. Potential Pennsylvanian reservoirs along the eastern edge of the Tularosa Basin may have been flushed by invasion of meteoric (fresh) water; however, other older reservoirs have produced highly saline water (McLean, 1975). Howard and others (1978) and Seager (1980) reported on the extensive array of "late faulting" (Quaternary pull-apart faults) found in the eastern part of this play. King and Harder (1985), however, stated, "In summary, despite flushing of some reservoirs, the stratigraphic section of the Tularosa Basin is favorable for oil and gas exploration because source beds and reservoir beds are abundantly present." Foster (1978a) suggested that due to the multiple episodes of faulting, younger oil may have migrated into older reservoirs or commingled with older oil.

Permian shales, such as present in the Yeso Formation, may act as seals for older reservoirs on the Otero platform. The question of whether effective seals are present, however, especially for gas, is unresolved.

Depth of Occurrence

Pennsylvanian strata occur: 1) as outcrops exposed at 5,000-6,000 ft elevation in the mountainous areas where their potential is greatly diminished, and 2) as highly potential reservoirs roughly -2,500 ft in the bolsons. Most hydrocarbon shows have been detected in the interval between 2,430- and 8,600-foot top-depths (distance below kelley bushing). Gas shows, however, at 19,240 ft indicate there may be potential for thermal gas from this depth to 25,000 ft in the southwestern-most part of the play. Mississippian strata are generally 1,000-3,000 ft deeper than the Pennsylvanian strata; Permian strata are generally 2,000-3,000 ft shallower.

Oil and Gas Shows of the Orogrande Basin

Significant shows of oil and gas have been discovered in the play. For information on specific exploration wells, see Albright and others

(1955), Kottlowski and others (1956), Cooley (1958), Kottlowski and others (1969), McCaslin (1974), Black (1975), Thompson and Bieberman (1975), Foster (1978a, b), Thompson and others, 1978, Pearson (1980), Tovar (1981), Thompson (1982), Woodward and Duchene (1982), Broadhead (1983), Brady (1984), Howland (1985), King and Harder (1985), Lozinsky (1987). Hydrocarbon shows in Pennsylvanian strata were notable in the following wells:

1) Exxon #1 Beard, sec. 5, T14S, R1E, 76 MCFGPD test at 7,200-7,430 foot top-depths;
2) Landreth #1 Federal, sec. 23, T4S, R6E, drilled on Oscura anticline east of San Antonio with oil and gas shows at 2,499-2,505 and 2,902-2,918 foot top-depths;
3) Grimm and others #1 Mobil, sec. 32, T25S, R1E, gas show at 19,015-19,240 foot top-depths;
4) Summit #1 Mims, sec. 2, T13S, R4W, gas shows at 5,708-5,800 foot top-depths;
5) Hodges #1 Houston, sec. 23, T14S, R10E, 16 MCFGPD test (98 percent methane) at 2,433-2,444 foot top-depths;
6) Southern Production #1 Cloudcroft, sec.5, T17S, R12E, oil and gas cut mud at 2,464-2,492 foot top-depths;
7) Houston #1 Lewelling, sec. 12, T12S, R9E, 430 MCFGPD test, 25/64" choke on July 6, 1974, at 8,000-8,016 foot top-depths and 12 MCFGPD at 8,572-8,598 foot top-depths, 82.3 percent methane and 15.9 percent carbon dioxide, testing of the higher interval 14 days after initial test yielded 168.3 MCFGPD; and
8) Snowden and Clary #1 State, sec. 36, T23S, R2E, oil and gas shows at 2,540-2,560 foot top-depths.

Wells with significant hydrocarbon shows in Permian strata are as follows:

1) Snowden and Clary #1 state, sec. 36, T23S, R2E, oil and gas at 553-573 foot top-depths, oil at 1,025-1,035 and 1,161 foot-top depths, and oil and gas at 1,492-1,518 foot top-depths;

2) Lockhart #1 Federal, sec. 28, T4S, R6E, oil show at 1,120-1,125 foot top depths;

3) Southern Tularsoa Basin #1, sec. 34, T13S, R8E, oil show at 1,638 foot top-depth;

4) Duggar #1 Federal, sec. 30, T6S, R10E, oil show at 476-489 foot top-depths;

5) Smith #1 Walker, sec. 21, T15S, R11E, gas show at 355 foot top-depth and oil show at 400 foot top-depth;

6) Turner #1 Evans, sec. 22, T24S, R12E, gas shows at 353, 410, and 1,086 foot top-depths;

7) Houston #1 Lewelling, sec. 12, T12S, R9E, 13-18 MCFGPD test at 5,140-5,170 foot top-depths; and,

8) Picacho #1 Armstrong, sec. 15, T23S, R1W, gas shows at 2,435 and 2,620 foot top-depths.

Exploration Status and Brief Comparison to Delaware Basin

Because of the extensive Cenozoic cover and en echelon extensional faulting, outcrops are "jumbled" and fragmentary thus requiring much interpolation of subsurface stratigraphic and structural relationships by the explorationist.

In 1924 the first major oil was discovered in southern New Mexico. It was found in shallow Permian reservoirs at Artesia in Eddy County. Nearly half of the area of this play is military land which is condemned with respect to leasing and exploratory drilling for petroleum; the play is thus immaturely explored and considered a frontier area. About 65 wells have been drilled in the play; they have an average depth of about 4,250 ft. Drilling density is about 155 square miles per borehole considering the entire play. This figure is reduced to about 145 square miles per well if the lowest priority areas are eliminated from consideration, e.g. the plutons and outcrops of uplifted Pennsylvanian and older strata. The deepest well (Grimm and others #1 Mobil), which is also the only well drilled deeper than 10,000 ft, was drilled and abandoned in 1973. Penetration was to 21,759 ft where it bottomed in Upper Ordovician rocks in the Las Cruces (Potrillo or Mesilla) Basin in the southwestern corner of the play (sec. 32, T25S, R1E).

The nearest production of petroleum is east of this play in the Late Paleozoic basins of southeastern New Mexico and western Texas. Eight giant-sized oil and gas fields have been found in the Delaware basin of New Mexico and produce primarily from Permian carbonate reservoirs with anticlines and reefs as traps. The gas-prone northwestern shelf of the Delaware basin looks stratigraphically similar (Upper Paleozoic analog) to the Orogrande basin. The Permian Basin petroleum province of New Mexico and West Texas contains an estimated ultimate in-place resource (discovered plus undiscovered) of more than 100 billion barrels of oil and 130 trillion cubic feet of natural gas (Dolton and others, 1979, p. 1, 14); about 71 percent of the cumulative production has come from reservoirs of Permian age. These Permian reservoirs produce oil and associated/dissolved gas from depths of 1,000 to 10,000 ft; non-associated Permian gas is produced from depths of 500 to 7,000 ft (Dolton and others, 1979, p. 15).

During the Late Paleozoic, the Delaware and Orogrande basins were connected by common seaways; this relation should justify continued exploration in south-central New Mexico. These basins exhibit many of the same structural features and geologic history, and contain similar Upper Paleozoic reservoirs (Seewald, 1969; Horak, 1975; and, Pearson, 1980) where every Paleozoic system economically produces hydrocarbons (Dolton and others, 1979). One major difference, however, is the much greater water depth of the Delaware basin (? aulocogen, Walper, 1977, 1980) during the Late Paleozoic Era, and consequently its greater accumulation and preservation of organic matter in a basin with over 25,000 ft of Paleozoic sediments. Over 70 percent of production from the Delaware basin is from Permian rocks, most of which is from Upper Permian strata. The Permian thickness in southeastern New Mexico is about 15,000 ft (McKee, 1967).

The Delaware basin was not significantly affected by the Laramide orogeny and subsequent Mid-Tertiary extensional deformation. The Delaware basin also has more effective seals for traps. Hydrocarbon generation in the Delaware basin occurred at three times: 1) during the Middle Ordovician through Mississippian, 2) in Middle Pennsylvanian time, and 3) in Early and Middle Permian time (Hills, 1984). If generation has occurred in Pennsylvanian strata in the Orogrande basin play, it is likely to have been during the Permian, Late Cretaceous, and/or Middle Tertiary to Holocene. These intervals are based on achieving thermal maturity through deepest burial and proximity to heating processes or events. Several papers, such as Greenwood (1970), Bachman (1975), Horak (1975), Greenwood and Kottlowski (1975), and Greenwood and others (1977), have addressed both the issues of parallelism and dissimilarity among the southern New Mexico basins.

With sufficient subsurface exploration through modern geophysical methods and drilling, the potential of the Orogrande basin should be realized. The time required, however, to make commercial petroleum discoveries in the play could be protractive. This is due to the basin's low exploration intensity in an atmosphere of high risk-taking where so much of the land is military and hence non-leasable.

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APPENDIX A: COMPOSITE STRATIGRAPHIC SECTIONS AND CROSS-SECTIONS

The large size and geologic diversity of this play preclude detailed descriptions of all potential source and reservoir rocks. For reference, several composite stratigraphic columns, correlation charts, and cross-sections are presented here as figures 54-63; these show the nomenclature used in the various reference sections plus the lateral variations of major units. Also, see appendix B for the stratigraphic framework of these rocks in the seven key sections of the play.

STRATIGRAPHY OF THE FRANKLIN MOUNTAINS, TEXAS

Geochronologic Units	Chronostratigraphic Units			Group	BÖSE 1910 UNIT	Lithostratigraphic Units
NEOGENE	PLEISTOCENE					BOLSON DEPOSITS CAMP RICE FM.
NEOGENE	PLIO-PLEISTOCENE					FORT HANCOCK FM.
CRETACEOUS	CENOMANIAN	GULFIAN			BÖSE 1910 UNIT	CENTRAL TEXAS EQUIVALENTS
CRETACEOUS	CENOMANIAN	GULFIAN	BOQUILLAS FM.		10	EAGLE FORD
CRETACEOUS	CENOMANIAN / ALBIAN	COMANCHEAN	BUDA LS. DEL RIO FM. ANAPRA SS. MESILLA VALLEY SH. MULEROS FM. SMELTERTOWN FM.	WASHITA GROUP	9 8 7 6 5 4	BUDA DEL RIO MAIN STREET WENO-PAW-PAW FORT-WORTH-DENTON DUCK CREEK
CRETACEOUS	ALBIAN	COMANCHEAN	DEL NORTE FM. FINLAY LS.	FREDRICKSBURG GROUP	1-3	EDWARDS
CRETACEOUS	ALBIAN	COMANCHEAN	LAGRIMA FM.	TRINITY		TRINITY
PERMIAN	WOLFCAMPIAN			HUECO GROUP		ALACRAN MT. FM. CERRO ALTO LS. HUECO CANYON FM.
PENNSYLVANIAN	VIRGILIAN MISSOURIAN					PANTHER SEEP FM.
PENNSYLVANIAN	DES MOINESIAN ATOKAN MORROWAN			MAGDALENA GROUP		BISHOP CAP FM. BERINO FM. LA TUNA FM.
MISSISSIPPIAN	CHESTERIAN					HELMS FM.
MISSISSIPPIAN	MERAMECIAN					RANCHERIA FM.
MISSISSIPPIAN	OSAGE-MERAMEC					LAS CRUCES FM.
DEVONIAN	UPPER					PERCHA SHALE
DEVONIAN	MIDDLE					CANUTILLO FM.
SILURIAN	NIAGARAN (MIDDLE) ALEXANDRIAN (LOWER)					FUSSELMAN DOL.
ORDOVICIAN	CINCINNATIAN (UPPER)			MONTOYA GROUP		CUTTER FM. ALEMAN FM. UPHAM DOL.
ORDOVICIAN	CANADIAN (LOWER)			EL PASO GROUP		FLORIDA MTS. FM. SCENIC DRIVE FM. McKELLIGON FM. JOSE FM. VICTORIO HILLS FM. COOKS FM. SIERRITE FM.
CAMBRO-ORDOVICIAN	CROXIAN AND/OR CANADIAN.					BLISS SANDSTONE
YOUNGER PRECAMBRIAN	RIPHEAN	INTRUSIVES RIEBECKITE GRANITE RED BLUFF GRANITE COMPLEX MICROGRANITE SILLS				THUNDERBIRD GROUP { TOM MAYS PARK FM.; SMUGGLERS PASS FM.; CORONADO HILLS FM. } LANORIA QUARTZITE MUNDY BRECCIA CASTNER MARBLE

(LeMone 1982)

Figure 54--Stratigraphy of the Franklin Mountains, Texas. (From LeMone, 1984).

CORRELATION CHART

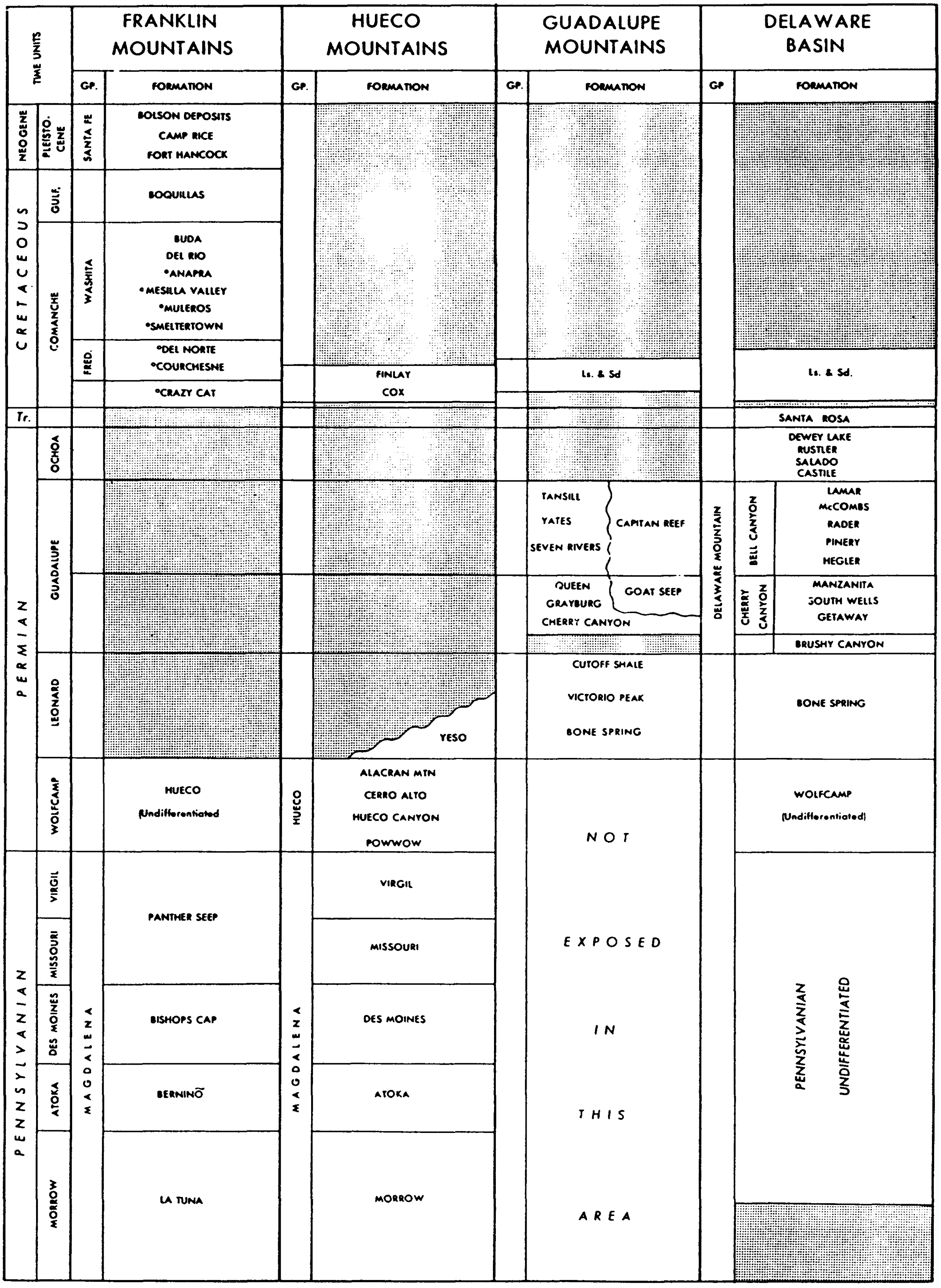

Figure 55--Stratigraphic correlation chart of the Franklin, Hueco, and Guadalupe Mountains, and Delaware basin. (From Stewart, 1969).

CONTINUED

Time Units		Franklin Mountains Gp.	Franklin Mountains Formation	Hueco Mountains Gp.	Hueco Mountains Formation	Guadalupe Mountains Gp.	Guadalupe Mountains Formation	Delaware Basin Gp.	Delaware Basin Formation
MISSISSIPPIAN	CHESTER		HELMS		UPPER HELMS		NOT EXPOSED IN THIS AREA		
	MERAMEC		RANCHERIA		LOWER HELMS				some sh. & ls. Undifferentiated (Exact age unknown)
	OSAGE		LAS CRUCES						
	KINDERHOOK								
DEVONIAN	UPPER		PERCHA SHALE CANUTILLO		PERCHA ? SHALE Chert & Ls.				WOODFORD SHALE
	MIDDLE								
	LOWER								DEVONIAN Ls. & Dol.
SILURIAN	MIDDLE		FUSSELMAN		FUSSELMAN				FUSSELMAN
	LOWER								
ORDOVICIAN	UPPER	MONTOYA*	CUTTER ALEMAN UPHAM		MONTOYA				MONTOYA
	MID.								SIMPSON
	LOWER	EL PASO	+FLORIDA MTS. SCENIC DRIVE McKELLIGON CN. JOS'E +VICTORIO HILLS COOKS *(Note) SIERRITE		EL PASO				ELLENBURGER (EL PASO)
Є.ORDOV.			BLISS		BLISS				BLISS
PRECAMBRIAN		RED BLUFF GRANITE	RHYOLITE PORPHYRY LANORIA QUARTZITE MUNDY BRECCIA CASTNER LIMESTONE		GRANITE (Undifferentiated)				GRANITE (Undifferentiated)

* Not all present in Franklin Mts.

Figure 55--Continued.

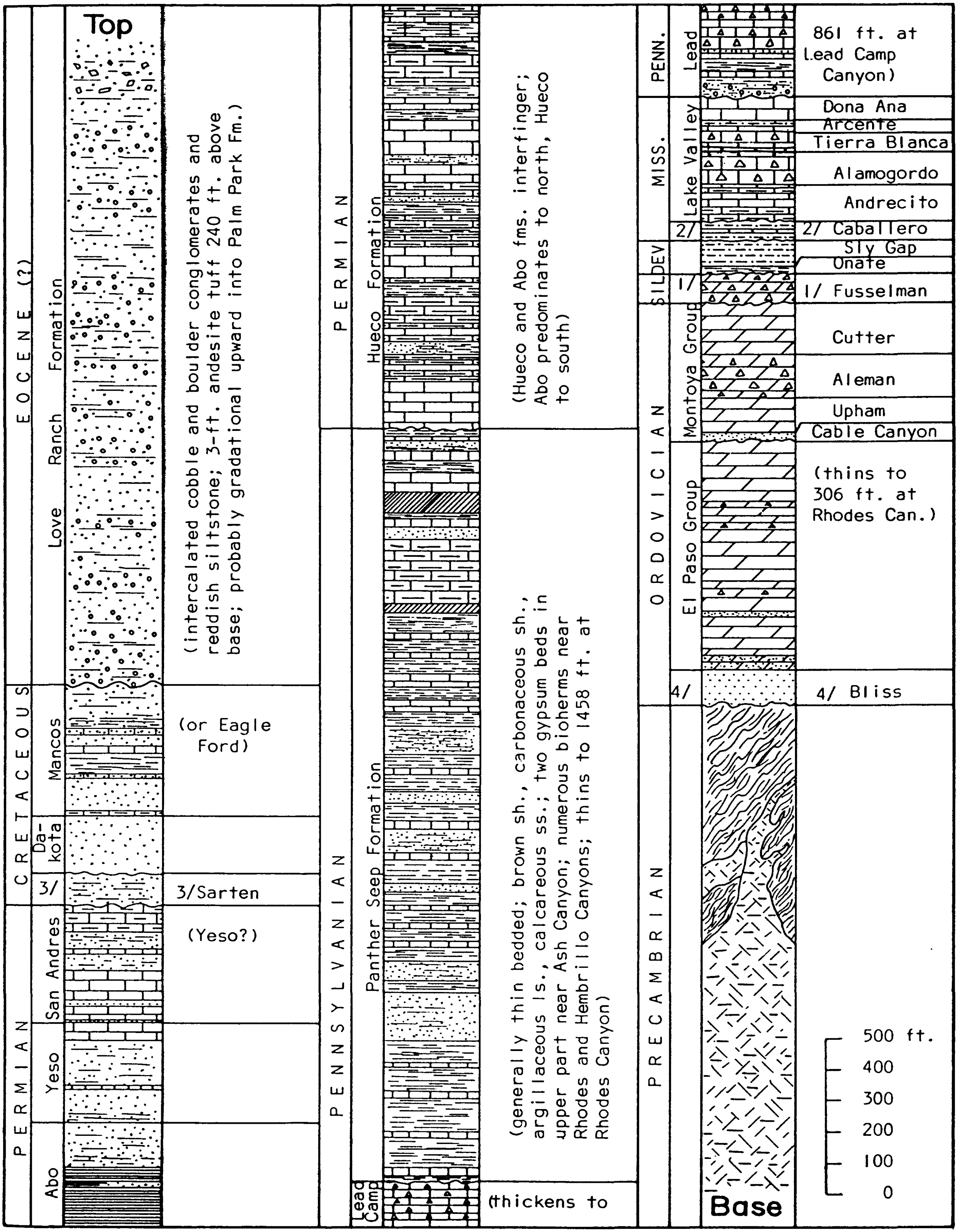

Figure 56--Composite columnar section of southern San Andres Mountains. (From Kottlowski and Hawley, 1975).

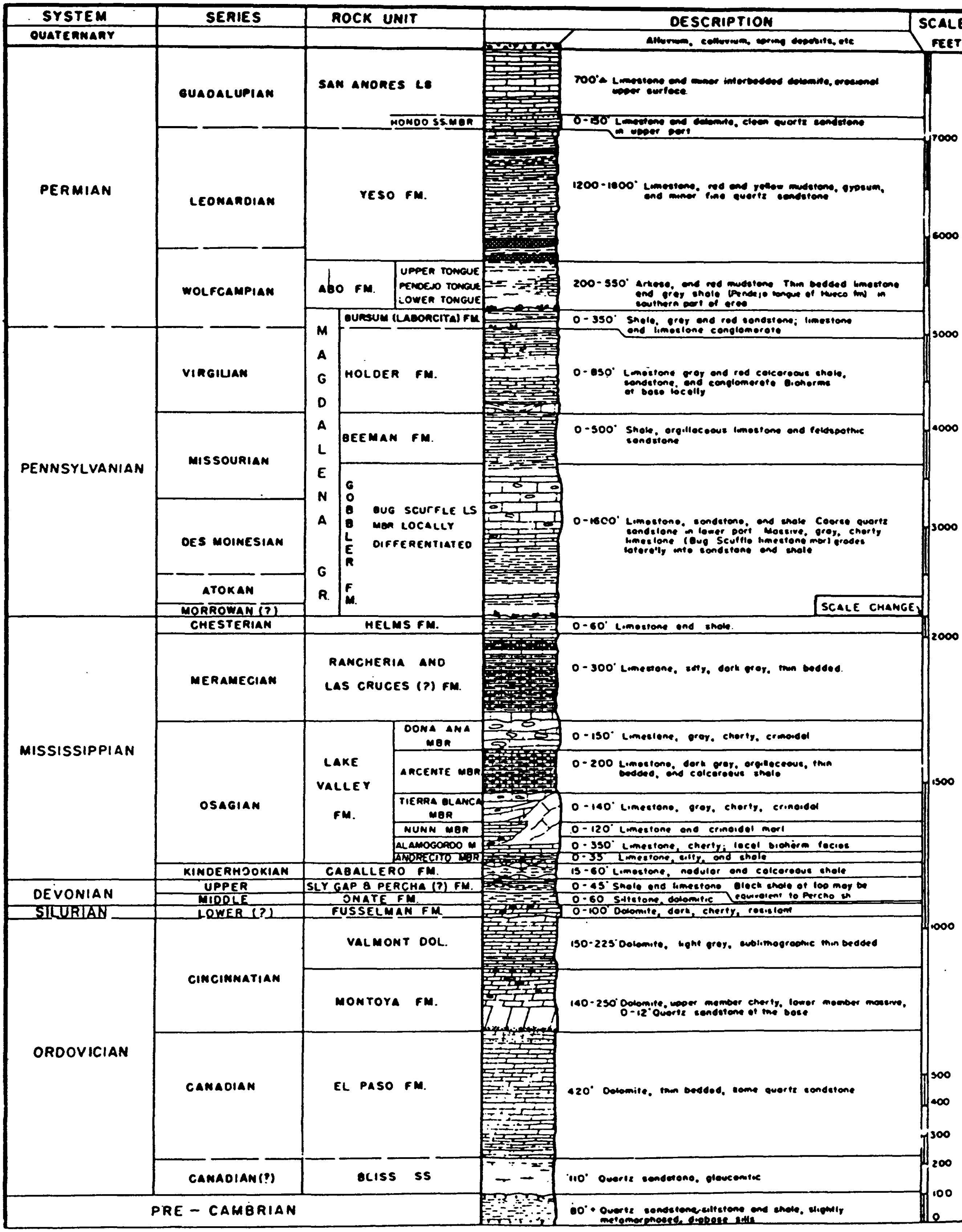

Figure 57--Composite columnar section, Sacramento Mountains, Otero County, New Mexico, (From Pray, 1977).

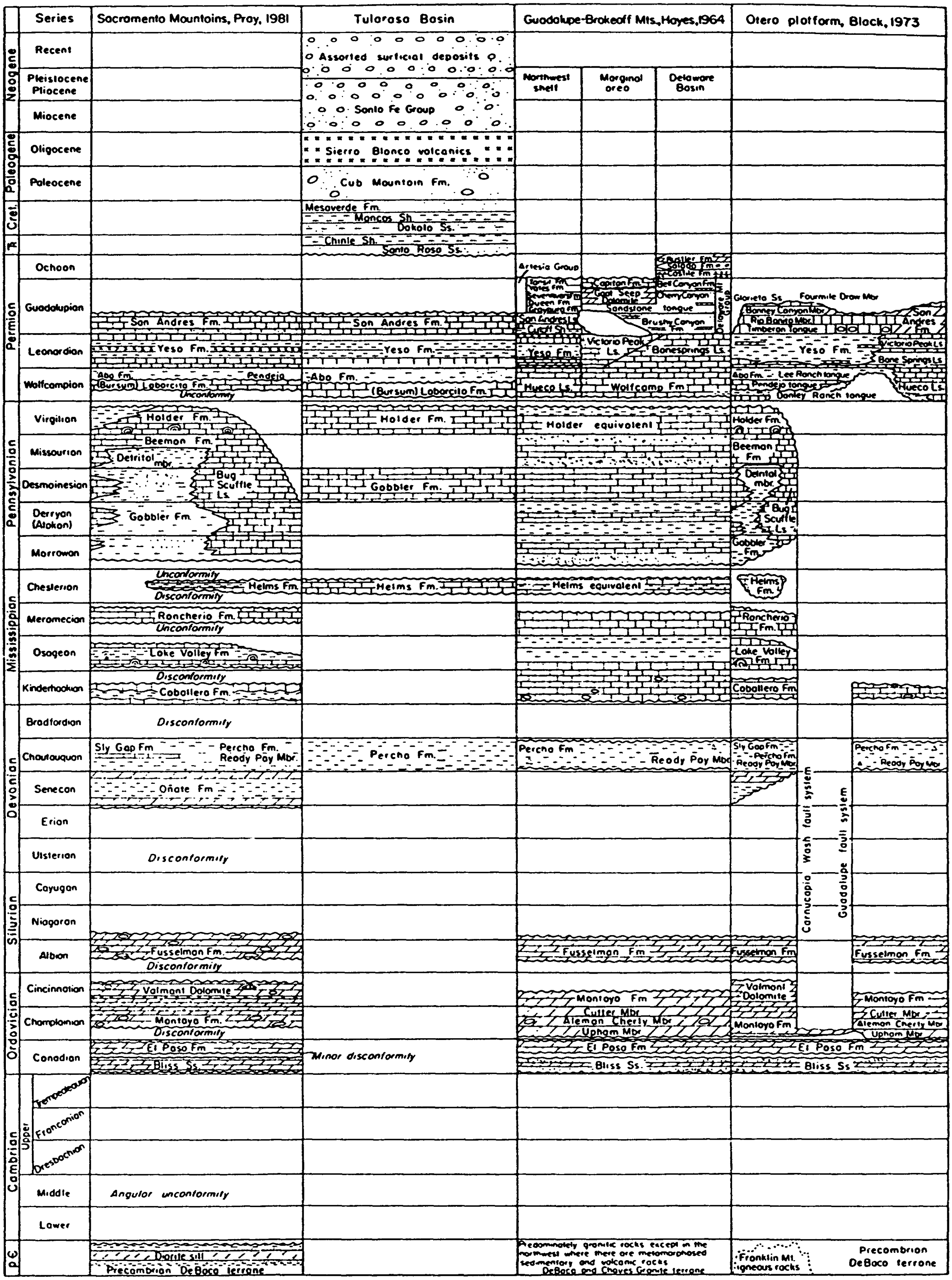

Figure 58--Stratigraphic sections of the Sacramento Mountains, Tularosa Basin, Guadalupe-Brokeoff Mountains, and Otero Platform. (From King and Harder, 1985).

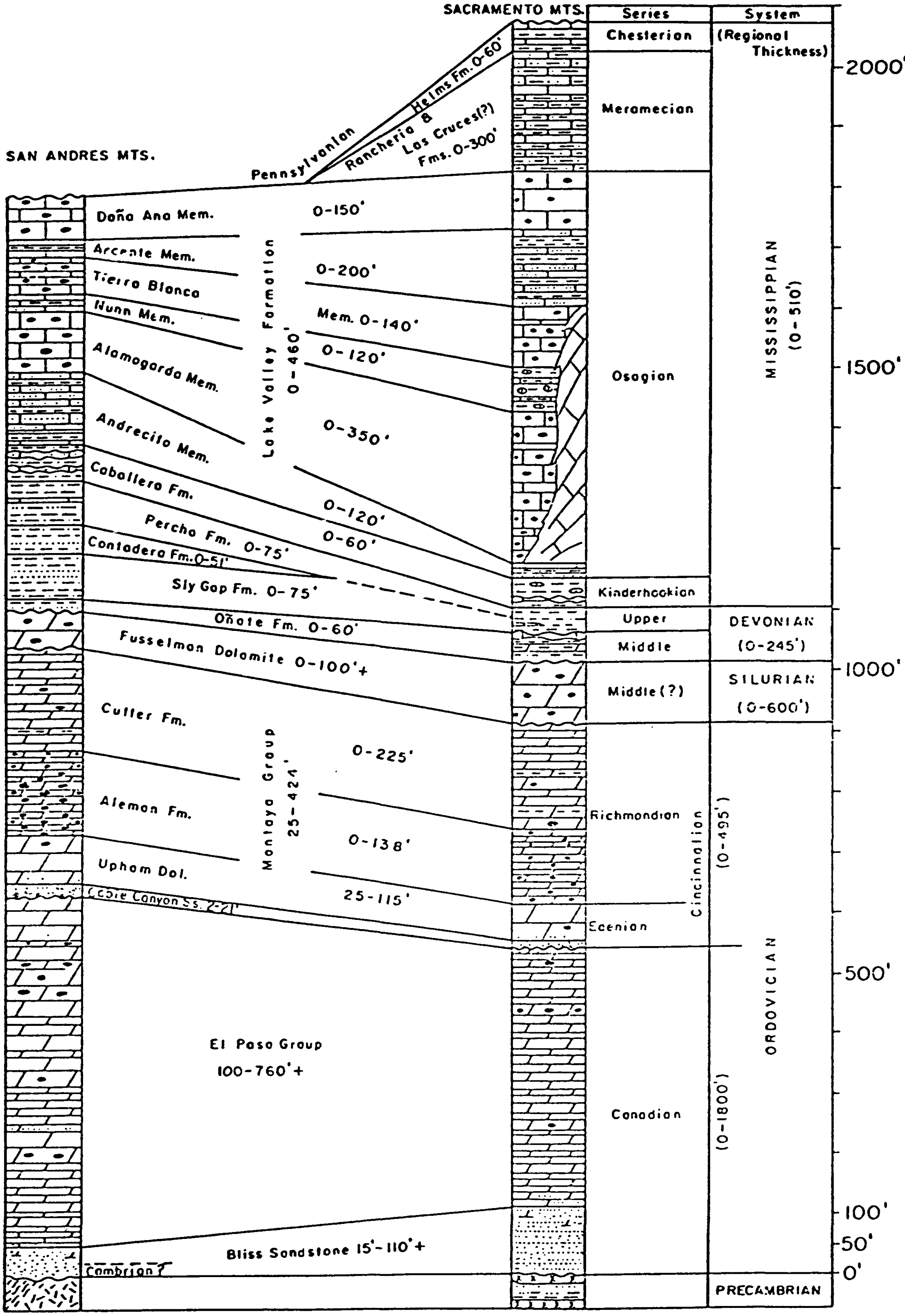

Figure 59--Stratigraphic correlation of pre-Pennsylvanian strata from the San Andres to Sacramento Mountains. (From Foster, 1978a).

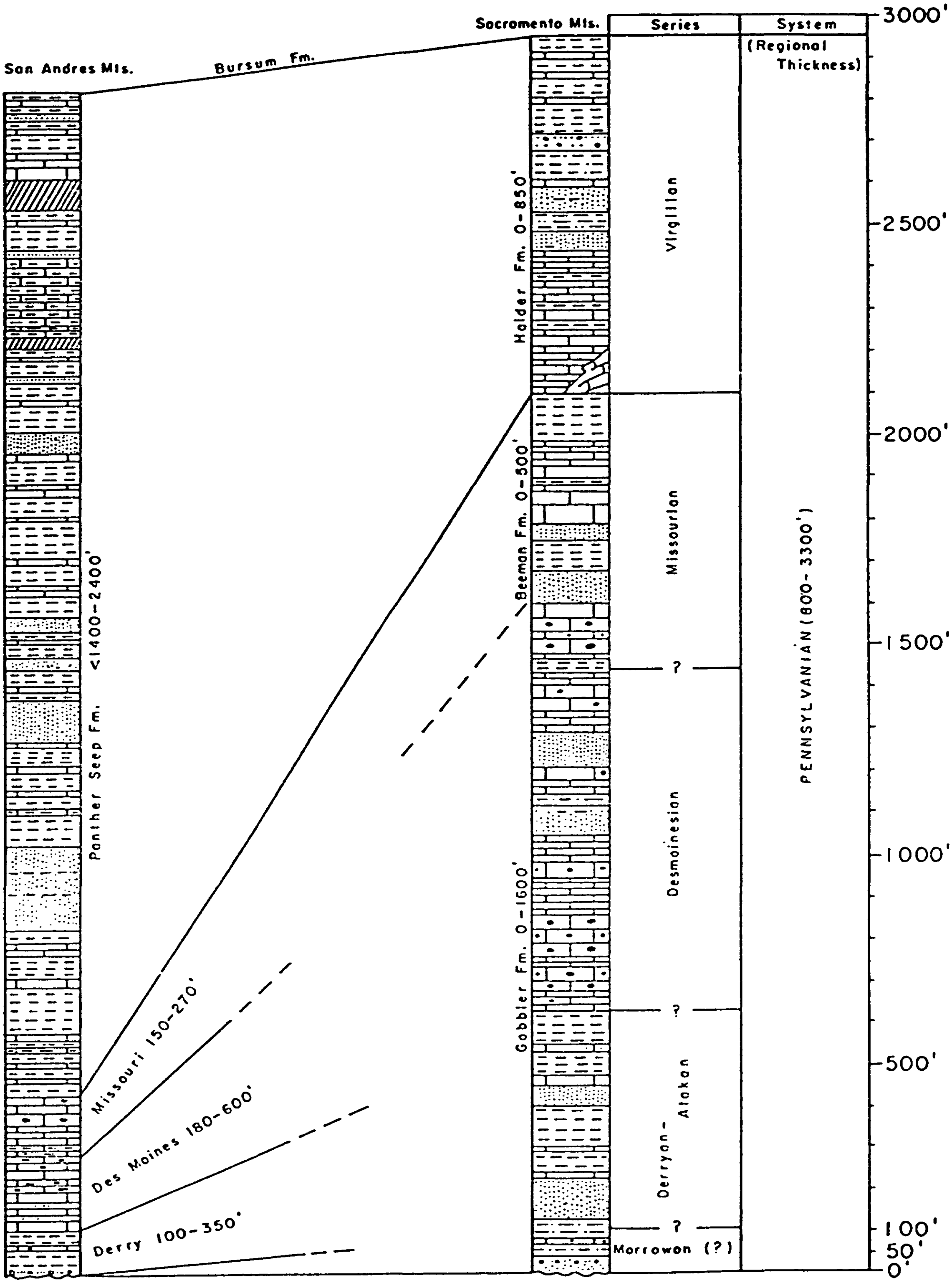

Figure 60--Stratigraphic correlation of Pennsylvanian rocks from the San Andres to Sacramento Mountains. (From Foster, 1978a).

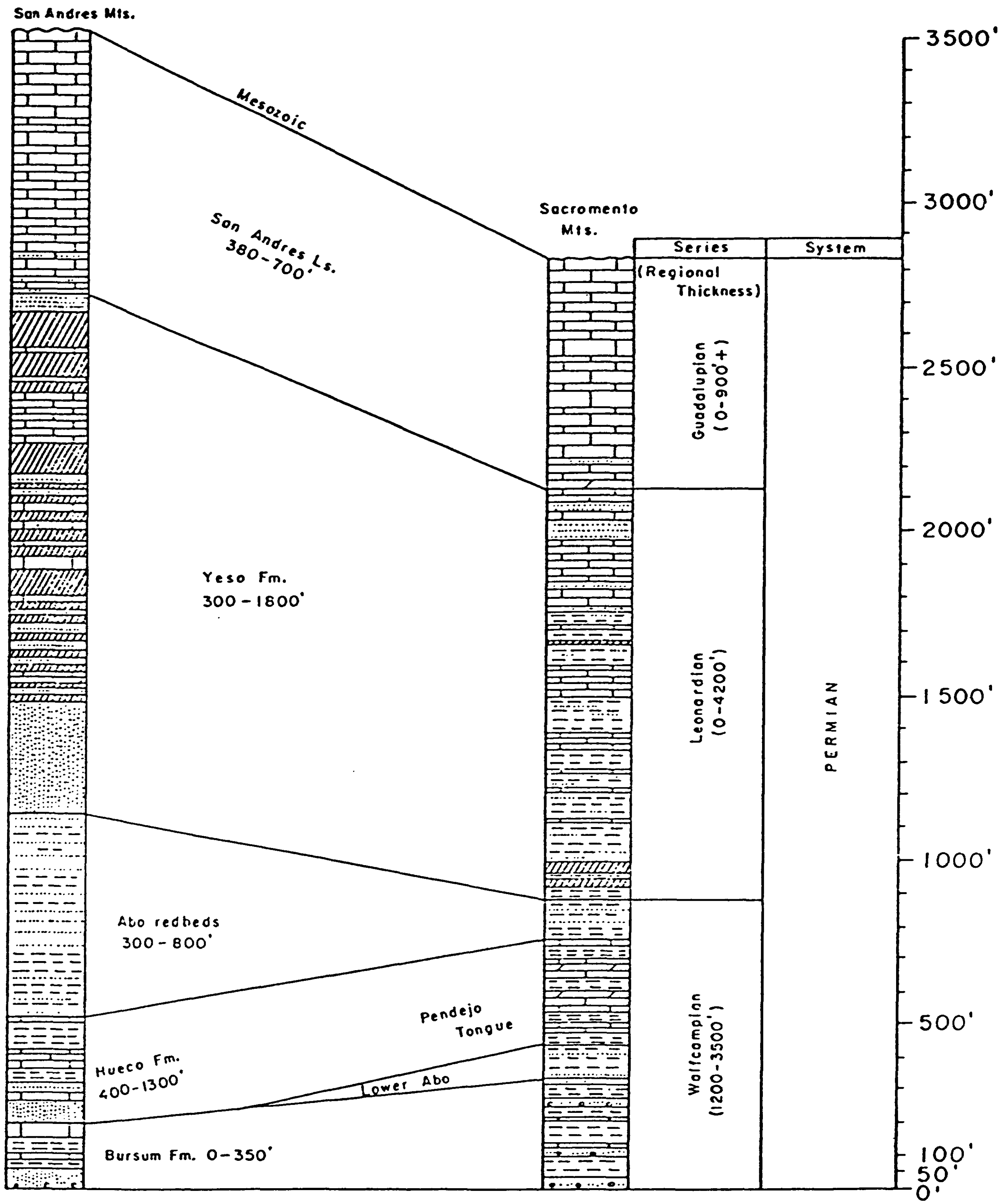

Figure 61--Stratigraphic correlation of Permian strata from the San Andres to Sacramento Mountains. (From Foster, 1978a).

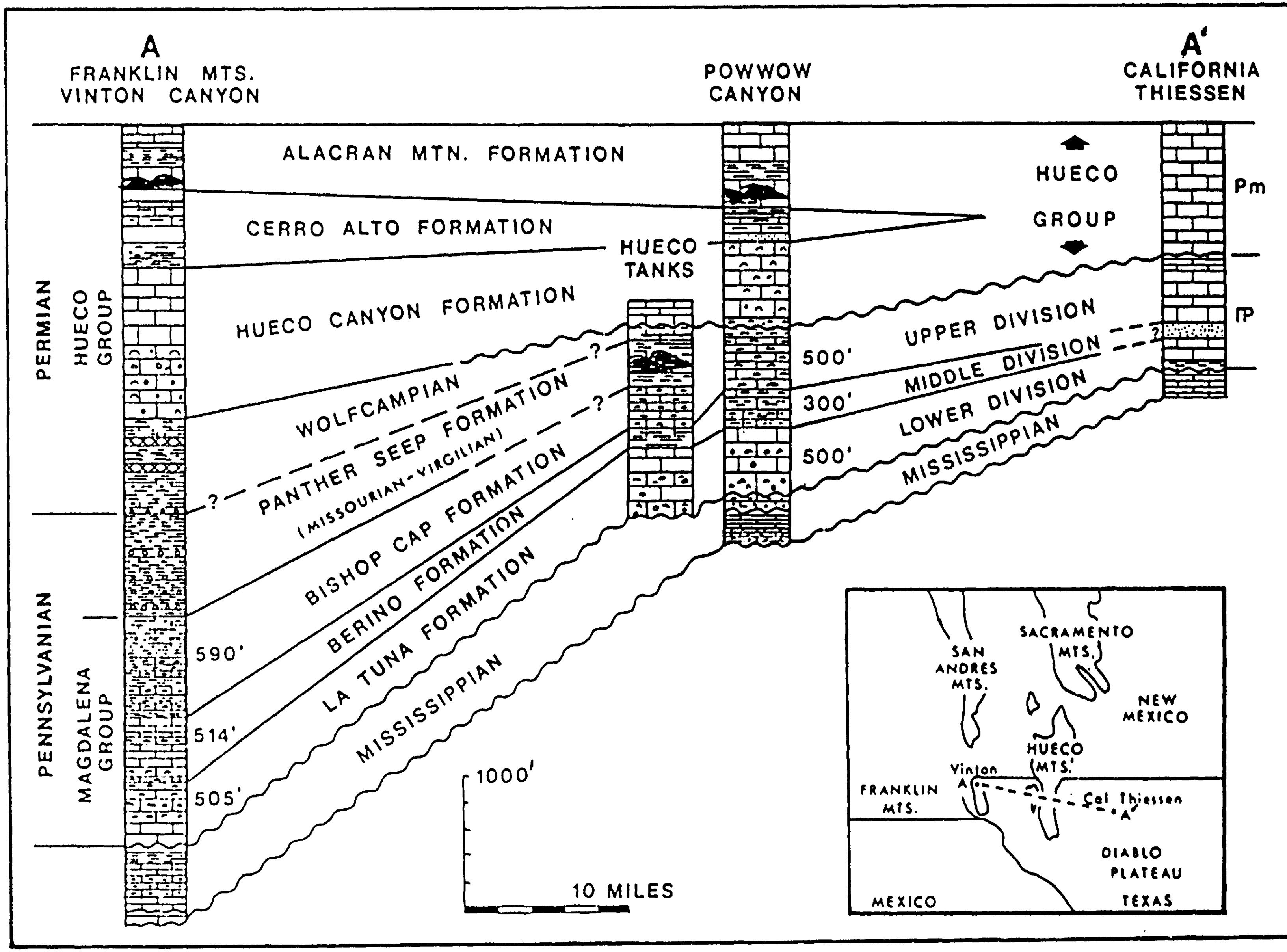

Figure 62--West-east stratigraphic correlation of Pennsylvanian and Permian strata from the Franklin Mountains to the Diablo platform. (From Connolly and Stanton, 1986).

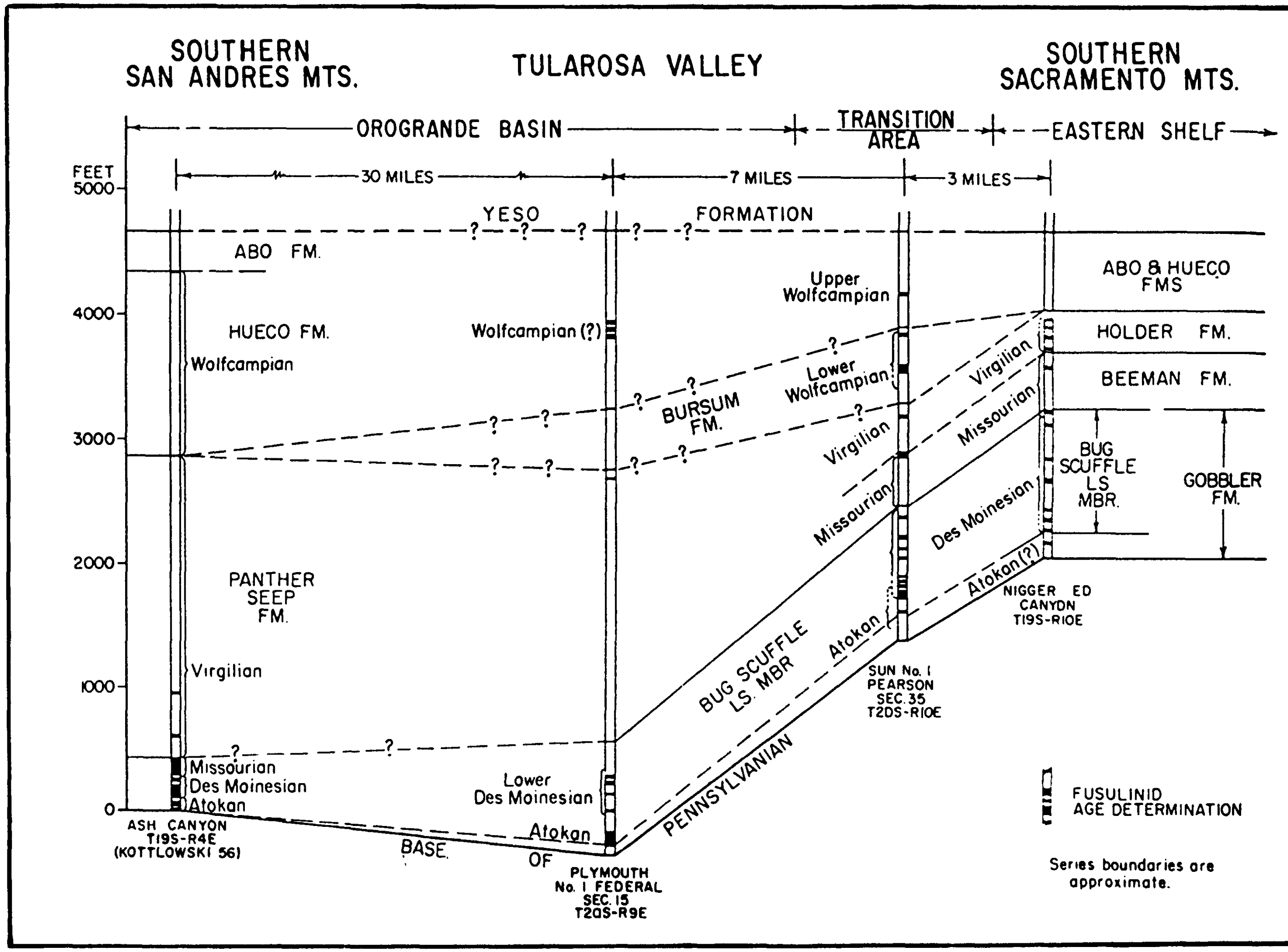

Figure 63--West-east cross-section of Pennsylvanian and Lower Permian strata from southern Sacramento Mountains to San Andres Mountains showing interpretation of position of Orogrande basin and its eastern shelf. (From Pray, 1961).

APPENDIX B: GENERAL STRATIGRAPHIC FRAMEWORK

The major stratigraphic units of each play with their generalized thicknesses and lithologies are listed below from oldest to youngest:

Cretaceous Coalbed Methane Play

Paleozoic units include: unconformably on Proterozoic granite and gneiss is the Abo Formation (600-800 ft) consisting of alluvial, fluvial, deltaic, and tidal flat red beds and evaporites, and in part equivalent to the Supai, Organ Rock, Cutler, Hermit and Earp formations elsewhere all of Early Permian age; the Yeso Formation (1,000-1,200 ft) consisting of mixed carbonates, clastics, and evaporites deposited as coastal dunes and in lagoons, sabkhas, and mud and sand flats, and in part equivalent to the lower DeChelly Sandstone and upper Supai Formation to the west and the Epitaph Dolomite to the south all of Early to Middle Permian age; the Glorietta Sandstone (150-250 ft) consisting of eolian sands near the shoreline of a shallow clastic shelf and equivalent in part to the upper DeChelly, Coconino, White Rim, Scherrer, and Toroweap formations elsewhere all of Middle Permian age; the San Andreas Limestone (250-350 ft) consisting of fossiliferous shelf carbonates and evaporites and equivalent in part to the Kaibab Limestone, Concha Limestone, and Rainvalley Formation elsewhere all of Middle Permian age.

Strata of Mesozoic age include: the Chinle Formation (750-1,100 ft) consisting of mostly floodplain deposits of the ? Shinarump Conglomerate, ? Monitor Butte, Petrified Forest, and ? Owl Rock members all of Late Triassic age; undifferentiated Upper Jurassic sandstones (0-250 ft but most likely 100 ft) of possible marine origin and possibly equivalent to the Morrison Formation; the Dakota Sandstone (30-100 ft, main body) mostly nonmarine, transgressive conglomerate, sandstone, shale, coal, and other carbonaceous deposits representing fluvial, floodplain, back-barrier bar, paludal, littoral and other marginal marine (brackish) settings of Late Cretaceous age; the Mancos Shale (500-850 ft) of marine shale, siltstone, and thin limestones with some sandstone lenses which include the marine Two Wells Tongue (5-50 ft) of the Dakota Sandstone, a clastic wedge called the Tres Hermanos Formation (lower part is the regressive-marine Atarque member, 50-100 ft thick, the middle part is carbonacous and nonmarine, 100-170 ft thick, and the upper part is the transgressive-marine Fite Ranch member, 10-20 ft thick) all of Late Cretaceous age; the Mesaverde Group (625-1,650 ft) of Late Cretaceous age consisting of the: a) regressive Gallup Sandstone (190-330 ft, including Dilco coal beds of 50 ft and much carbonaceous clastics of fluvial origin) deposited in both nearshore littoral marine and nonmarine environments, b) the Crevasse Canyon Formation (100-200 ft) consisting of fluvial to marginal-marine deltaic clastics with the Gibson coal (60-75 ft), and c) the Menefee Formation (very thin to ? absent) consisting of nonmarine sandstone and paludal shale and coal. The total Cretaceous section is about 1,100 to 2,500 ft thick. Because of the constantly shifting shorelines and rapidly changing nature of the marine and nonmarine strata, complex intertonguing developed within the Mancos Shale and the Mesaverde Group; thus, correlations and nomenclature vary widely with different authors. The total Mesozoic section is 3,000-4,000 ft thick.

Cenozoic rocks include: the Baca Formation (about 325-450 ft) consisting of coarse alluvial fan clastics and perhaps minor finer-grained lacustrine clastics and fan deltas of Eocene age (Cather, 1983; Cather and

Johnson, 1984); the Spears and Datil formations (300-350 ? ft) consisting of volcaniclastic and other clastic rocks of probable Oligocene age; unnamed andesite, basalt, volcanic breccia and tuff of ? Miocene and/or ? Pliocene age cap Cebollita Mesa; Quaternary alluvium and pyroclastics (variable and speculative thickness of 50-500 ft); and, Holocene basalt flows (50-300 ft, roughly estimated). Holocene basalt flows cover the stratigraphic section and because no oil or gas exploratory wells have been drilled in the play, subsurface mapping is an exercise in interpolation from the surrounding outcrops.

Late Paleozoic Orogrande Basin Play

The large size of this play requires that several geographically-spaced geologic columns be presented to adequately characterize and define the regional stratigraphic variations. Areas in or bordering the play where seven stratigraphic sections are described below include: the Franklin and Organ-Southern San Andres Mountains in the southwest, the Hueco Mountains-central Fort Bliss area in the south-central part, Sierra Diablo (Texas) in the southeast, the Sacramento Mountains in the east, the San Andres Mountains in the central region, and the Carthage area in the northwest. Nomenclature problems are widespread because of the difficulty in trying to correlate complex facies among widespread mountain ranges. Physical and biostratigraphic correlation methods are sometimes confused in naming units in the literature leading to splitting of units, i.e. a different set of formations names has evolved for each major stratigraphic section. Much of the information below is from Amer. Assoc. Petrol. Geol. (1983). A star (*) in the descriptions below indicates an erosional unconformity.

Franklin Mountains

The dominant lithologies include the following: intrusive granite plus metasediments and metavolcanics of Proterozoic age; * the Bliss Formation (0-300 ft) sandstone of Late Cambrian to Early Ordovician age; the El Paso Group (1,550 ft) carbonates of Early Ordovician age; * the Montoya Group (365 ft) of Late Ordovician age; the Fusselman Dolomite (550 ft) carbonates of Early Silurian age; * the Canutillo Formation (250 ft) carbonates of Middle Devonian age; the Percha Shale (90 ft) carbonates of Late Devonian age; * the Las Cruces Formation (40-50 ft) carbonates, and the Rancheria Formation (375 ft) carbonates both of Middle Mississippian age; the Helms Formation (160 ft) shale of Late Mississippian age; the La Tuna Formation (160 ft) carbonates, the Berino Formation (380 ft) carbonates, and the Bishop Cap Formation (625 ft) carbonates all of Early Pennsylvanian age; * the Panther Seep Formation (? 475-600 ft) carbonates of Late Pennsylvanian age; * the Hueco Group (1,685 ft) carbonates of Early Permian age consisting of the Hueco Canyon Formation (605 ft), the Cerro Alto Limestone (460 ft), and the Alacran Formation (620 ft); * undifferentiated sandstone, shale, and limestone (1,570 ft) of late Early to early Late Cretaceous age; * the Fort Hancock Formation (unknown thickness) shale of Pliocene age; and, * undifferentiated bolson-fill and other Quaternary alluvium mostly of sand and gravel (0-9,000 ft).

Organ and Southern San Andres Mountains

The predominate lithologies include the following: gneiss, schist, and intrusive granite of Proterozoic age; * the Bliss Formation (125-145 ft) glauconitic sandstone of Late Cambrian to Early Ordovician age; the El Paso Group (780-1,000 ft) carbonates of Early Ordovician age; * the

Montoya Group (365-470 ft) carbonates of Late Ordovician age; the Fusselman Dolomite (110-310 ft) carbonates of Early Silurian age; * the Percha Shale (60-170 ft) dark basinal shale of Middle and Upper Devonian age; * the Caballero Formation (5-30 ft), * the Lake Valley Formation (5-180 ft), * the Las Cruces Formation (0-125 ft), and the Rancheria Formation (170-265 ft) all consisting of carbonates of Mississippian age; * the Helms Formation (0-130 ft) shale of Late Mississippian age; * the Lead Camp Limestone (650-870 ft) carbonates of Pennsylvanian age; the Panther Seep Formation (2,035 ft) shale of Late Pennsylvanian age; the Hueco Formation (1,675-1,875 ft) carbonates, and the Abo Sandstone (400 ft) sandstone both of Early Permian age; the Yeso Formation (300 ft) carbonates of Early to Middle Permian age; the San Andres Formation (550 ft) of Middle Permian age; * the Sarten-Dakota formations (360 ft) sandstone of late Early to early Late Cretaceous age; the Mancos Shale (1,000 ft) shale with stray sands; * the Love Ranch Formation (0-2,000 ft) conglomerates of Paleocene age; * undifferentiated andesites, tuffs, rhyolites and lavas (up to 12,000 ft with over 5,000 ft as graben-fill in the Rio Grande Rift) of Eocene to Early Miocene age; * undifferentiated alluvial sandstones (unknown thickness) of Quaternary age.

Hueco Mountains - Central Fort Bliss Military Reservation Area

The dominant lithologies and ages include the following: Proterozoic granite and metasedimentary rocks; * the Bliss Formation (100-250 ft) sandstone of Upper Cambrian age; El Paso Group (420-1300 ft) cherty dolomite with some siltstone and sandstone of Early Ordovician age; * The Montoya Group (400-500 ft) cherty dolomite with some basal sandstone of Late Ordovician age; * the Fusselman Dolomite (95-540 ft, probably 250-325 ft most commonly) cherty dolomite of Silurian age; * the Onate Formation (0-60 ft) siltstone, shale, and calcareous clastics, * the Sly Gap Formation (0-45 ft) fine clastics, and the Contadero-Percha Shale (60-130 ft) black shale with siltstone all of Devonian age; * the Caballero Formation (30 ft) dolomite with siltstone and , the Las Cruces Formation (80 ft) carbonates, the Rancheria Formation (280 ft) biohermal, cherty carbonates, the Helms Formation (140 ft) cherty carbonates with siltstone and shale all of Mississippian age; * the Gobbler-La Tuna formations (280 ft) carbonates, the Magdalena Group (700-1,000 ft) mixed cyclic biohermal carbonates and clastics consisting of the Berino member (525 ft) carbonate and shale, and the Bishop Cap member (200-300 ft) shale and cherty carbonate; the Panther Seep Formation (475-800 ft) algal and biohermal carbonates, shale, sandstone, and siltstone all of Pennsylvanian age; * the Hueco Group (1,500-2,700 ft) cherty biohermal carbonates consisting of the Powwow member (20 ft), the Hueco Canyon member (600 ft), the Cerro Alto member (460 ft), and the Alacran Mountain member (625 ft) all of Early Permian age; the (?) Abo Formation (thin if present); the Yeso Formation (400-500 ft) carbonates, clastics, and evaporites of Early Permian age; the (?) Glorieta Sandstone (thin if present); the San Andres Limestone (200 + ft) carbonates of Middle Permian age; * the Dakota Sandstone (? 200 ft) sandstone of "middle" Cretaceous age; the Eagle Ford-Mancos formations (? 0-1,350 ft) of sandstone, siltstone, and dark shale of Late Cretaceous age; the Mesaverde Group (unknown thickness) of clastics of Late Cretaceous age; * undifferentiated rhyolites, tuffs and other volcaniclastics (0-1,000 ft) of middle Tertiary age; and, * undifferentiated alluvial basin fill (0-2,000 ft) coarse clastics of Quaternary age. The maximum thickness of bolson fill in the Tularosa Basin has been estimated at about 8,000 ft by Keller and others (1984).

Sierra Diablo

The dominate lithologies and their ages include the following: Igneous intrusions and metasedimentary and metavolcanic rocks of Proterozoic age; * the Bliss Formation (100-200 ft) sandstone of Early Ordovician age; the El Paso Group (1,150 ft) carbonates of Early Ordovician age; * the Montoya Group (230-450 ft) carbonates of Late Ordovician age; the Fusselman Dolomite (300-450 ft) carbonates of Early Silurian age; * unnamed chert (125 ft) of Late Devonian age; * the Barnett Shale (135 ft) shale of Late Mississippian and Early Pennsylvanian age; * undifferentiated carbonates (unknown thickness) of (?) Late Pennsylvanian age; * the Hueco Formation (300-1,500 ft) carbonates, * the Bone Spring Limestone (900-1,300 ft) carbonates, the Victoria Peak Limestone (900-1,500 ft) carbonates, the Cutoff Shale (275 ft) shale, the Brushy Canyon Formation (unknown thickness) sandstone, and the Cherry Canyon Formation (150-200 ft) sandstone all of Early Permian age; the Goat Seep Limestone (200+ ft) carbonates of Middle Permian age; * undifferentiated carbonates and siliciclastics (2,000-3,925 ft) of Early Cretaceous age; * the Eagle Ford Formation (1,500 ft) shale of Late Cretaceous age; * undifferentiated sandstones and volcanic rocks of unknown thickness and Pliocene and Quaternary age.

Sacramento Mountains

The major mapped units with their approximate thicknesses, dominant lithologies, and ages include the following: quartzite and other metasedimentary rocks of Proterozoic age; * the Bliss Formation (110 ft) sandstone of Late Cambrian and Early Ordovician age; the El Paso Formation (425-450 ft) carbonates of Early Ordovician age; * the Montoya Group (225 ft) carbonates of Late Ordovician age; the Valmont Dolomite (185 ft) carbonates of Late Ordovician-Early Silurian age; the Fusselman Dolomite (20-100 ft) carbonates of Early Silurian age; * the Onate Formation (10-70 ft) shale of Middle Devonian age; the Sly Gap Formation (30-40 ft) shale, * the (?) Percha Shale (10-20 ft) shale, and the Caballero Formation (15-60 ft) carbonates all of Late Devonian age; * the Lake Valley Formation (400 ft) biohermal carbonates of Early Mississippian age; * the Rancheria Formation (0-300 ft) carbonates of Middle Mississippian age; the Helms Formation (0-60 ft) shale of Late Mississippian age; * the Cobbler Formation (1,200-1,600 ft) shale, sandstone, and cherty carbonates of Early-Middle Pennsylvanian age and consisting of a lower Bug Scuffle member (840 ft) carbonate; the Beeman Formation (0-500 ft) biohermal algal mound carbonates, shale, and sandstone, and the Holder Formation (300-900 ft) carbonates with algal reefs both of Late Pennsylvanian age; * the Bursum Formation equivalent to the Laborcita Formation (335 ft) shale, the Abo Formation (250-500 ft) shale, siltstone, and red beds, and the Yeso Formation (1,200-1,800 ft) mixed carbonates, siltstone, evaporites, and marl all of Early Permian age; the San Andres Formation (200-700 ft) carbonates of Middle Permian age; * the Dakota Sandstone (0-200 ft) sandstone of early Late Cretaceous age; * undifferentiated sandstones (up to 1,800 ft) of Neogene age.

Northern San Andres Mountains and Central Jornada del Muerto Basin

From oldest to youngest the major mapped units with their approximate thicknesses, dominant lithologies, and ages include the following: Proterozoic granite; * the Bliss Formation (50 ft) sandstone of Late Cambrian-Early Ordovician age; the El Paso Formation (300 ft) carbonates of Early Ordovician age; * the Montoya Group (325 ft) carbonates with basal sandstone of Late Ordovician age; * the Onate Formation (30 ft) shale of Middle Devonian age; the Sly Gap Formation (30 ft) shale, the Contadero Formation (5 ft) shale, and the Percha Formation (75 ft) shale all of Late Devonian age; * the Lake Valley Formation (65 ft) carbonates of Early Mississippian age; * the Pennsylvanian Magdalena Group can be divided into the Derry Series equivalent (230 ft) sandstone; * the DesMoinesian Series equivalent (625 ft) carbonates; the Missourian Series equivalent (195 ft) carbonates; the Panther Seep Formation (1,450 ft) shale of Late Pennsylvanian age; * the Bursum Formation (265 ft) reef-like carbonates with siliciclastics, the Hueco Formation (420 ft) carbonates, the Abo Formation (835 ft) fine-grained clastic red beds, the Yeso Formation (1,580) sandstone, the Glorieta Sandstone (210 ft) sandstone, and the San Andres Formation (395 ft) carbonates all of Early Permian age; * the Dockum Formation (50 ft) shale of Triassic age; * the Dakota Sandstone (40+ ft) of early Late Cretaceous age; the McRae Formation (0-500 ft) of Late Cretaceous-Early Tertiary age; * undifferentiated basin-fill sandstones and other alluvium (thickness highly variable) of Quaternary age.

Carthage Area (Northern Jornada del Muerto Basin)

The major mapped units with their approximate thicknesses, dominant lithologies, and ages include the following: Proterozoic granite; * the Sandia Formation (15-635 ft) sandstone, and the Madera Limestone (80-1,660 ft) carbonates both of Pennsylvanian age; * the Bursum Formation (90-250 ft) sandstone and reef-like carbonates, and the Abo Formation (300-790 ft) sandstone, the Yeso Formation (720-1,700 ft) sandstone, evaporites, and shale, the Glorieta Sandstone (30-200 ft) sandstone, and the San Andres Formation (270-400 ft) carbonates all of Early Permian age; * the Dockum Group (0-500 ft) sandstone of Triassic age; * the Dakota Sandstone (75-90 ft) medium-grained quartz sandstone, the Mancos Shale (975 ft which includes about 260 ft of sandstone) shale and sandstone (Tres Hermanos and D-Cross), the Gallup Sandstone (65 ft) sandstone, and the Crevasse Canyon Formation (650-1,040 ft) sandstone and other siliciclastics and coal all of Late Cretaceous age; * the Baca Formation (? 750-1,025 ft) coarse to fine siliciclastics of Eocene age; * volcaniclastic and alluvium (thickness unknown) of Oligocene age; * the Santa Fe Group (up to ? 2,000 ft) alluvial clastics with sills and dikes all of Miocene-Pliocene age; * undifferentiated basin-fill clastics of variable thickness and Holocene age.