UNITED STATES DEPARTMENT OF THE INTERIOR

THE GEOLOGIC SETTING OF SOUTHERN ARIZONA AND SOUTHWESTERN NEW MEXICO, WITH A RATIONALE FOR ASSESSMENT OF UNDISCOVERED, ECONOMICALLY RECOVERABLE OIL AND GAS: A SUMMARY OF FOUR POTENTIAL PLAYS

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

Four speculative petroleum plays, totalling more than 6,000 mi^2, have been identified in the U.S. Geological Survey assessment province which includes the Basin and Range physiographic province of southern Arizona and southwestern New Mexico. Although significant oil and gas shows have been found, this region presently is a frontier exploration area and has no known oil or gas accumulations. This summary addresses only the qualitative component of the Survey's national oil and gas assessment.

The first play is in eastern Hidalgo County of southwestern New Mexico and the second play is in southwestern Cochise County of southeastern Arizona. Regionally, these two plays are in the northwest-trending exploration fairway of the Texas lineament zone; locally, they are in Upper Paleozoic strata of the Pedregosa basin.

Two additional plays are located in fault-block basins of mid-Tertiary and younger age in Arizona. The third play includes alluvial-fluvial-lacustrine facies of several deep grabens, including all or part of the San Simon (Safford) Valley, Sulphur Springs Valley, San Pedro Valley, Teran Basin, and Santa Cruz Valley of Graham, Cochise, Pima, and Santa Cruz Counties. The fourth play is in southwestern-most Yuma County. It is based on occurrences of marine shales and sandstones interbedded with nonmarine clastics all of Miocene-Pliocene age in the Altar (San Luis) Basin -- a part of the northern Proto-Gulf of California which is hydrocarbon-productive nearby in Mexico.

The assessment province lies near the southwestern edge of the ancient craton and is entirely underlain by Precambrian crust. The province is characterized by a Precambrian and Phanerozoic history of exceptionally diverse tectonic regimes having varying directions of stress. The province has been progressively subjected to: continental-scale mega-shearing

(wrench-faulting); Ouachita-related plate convergence; arc magmatism; rifting incipient to ocean opening; Cordilleran-related subduction with regional underthrusting and local overthrusting; and, high-angle block plus normal listric detachment faulting. These tectonic episodes have led to common inter-systemic unconformities and other types of petroleum traps.

Because the tectonic and magmatic complexity of this province has resulted in a world-class mineral-producing region, the exploration for high-risk oil and gas has been secondary and understandably conservative. However, the impetus of higher demand for petroleum against a shrinking U.S. resource, plus imaginative exploration, should eventually lead to the discovery of economic petroleum in this assessment province.

INTRODUCTION

GENERAL STATEMENT AND PURPOSE

This report has two main sections: 1) an overview of the geologic setting of the assessment province, and 2) a discussion of factors considered in judging the potential of the four oil and gas plays. The first section (p. 1-55) is ancillary for those readers already familiar with the geology of southern Arizona and southwestern New Mexico.

This summary has been prepared for the national petroleum assessment program of the U.S. Geological Survey (province #93). The area investigated roughly includes southwestern New Mexico south of lat. 32°30′ and west of 107° W. long., and southern Arizona south of lat. 34°15′ in the western part and south of 33° 15′ lat. in the eastern part (fig. 1). Figure 2 outlines the four petroleum plays. Plays as described are limited by the province definition. Some plays terminate at political boundaries.

Information presented herein is the qualitative component forming the basis of the quantitative estimates prepared by the U.S. Geological

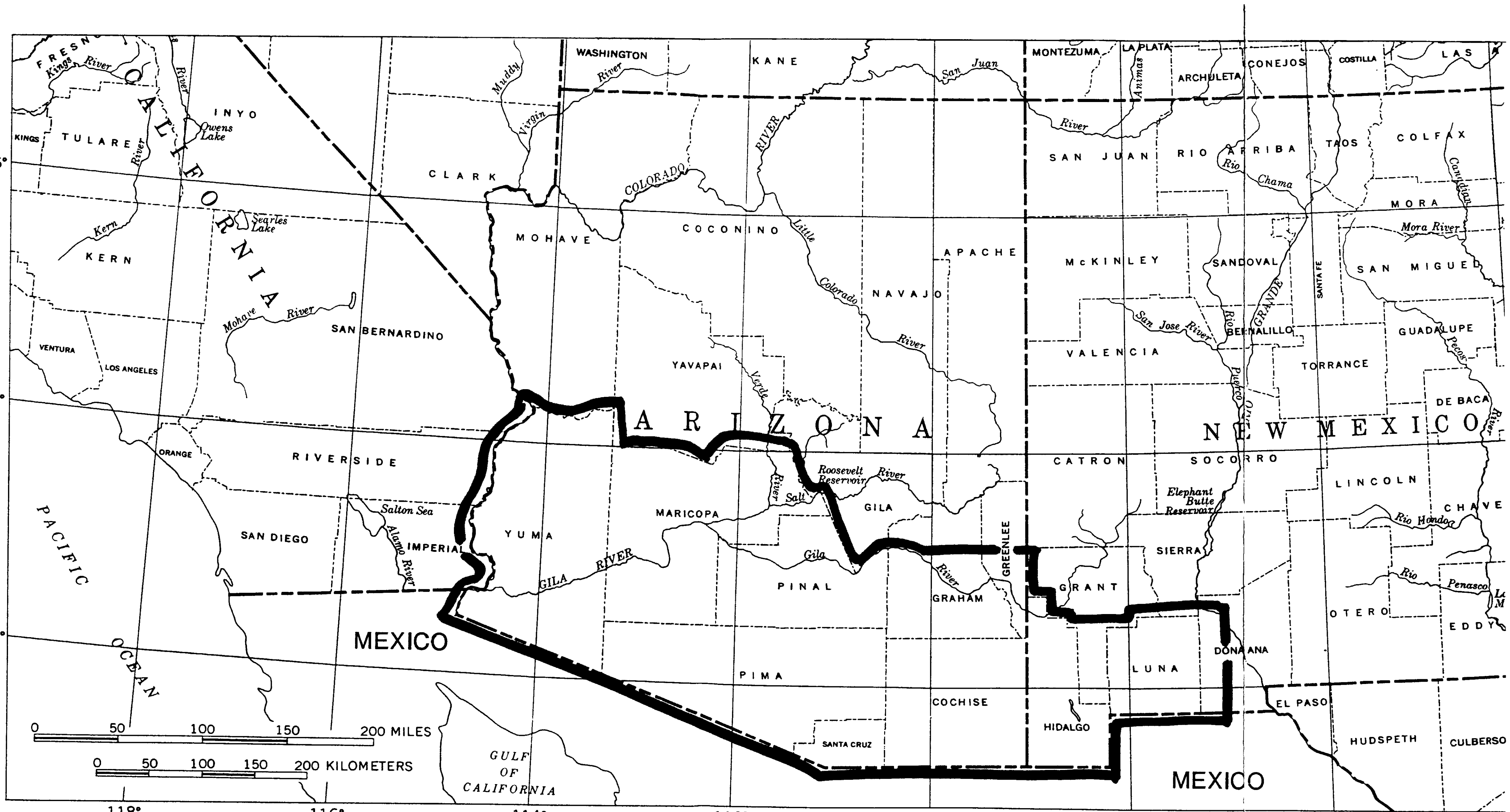
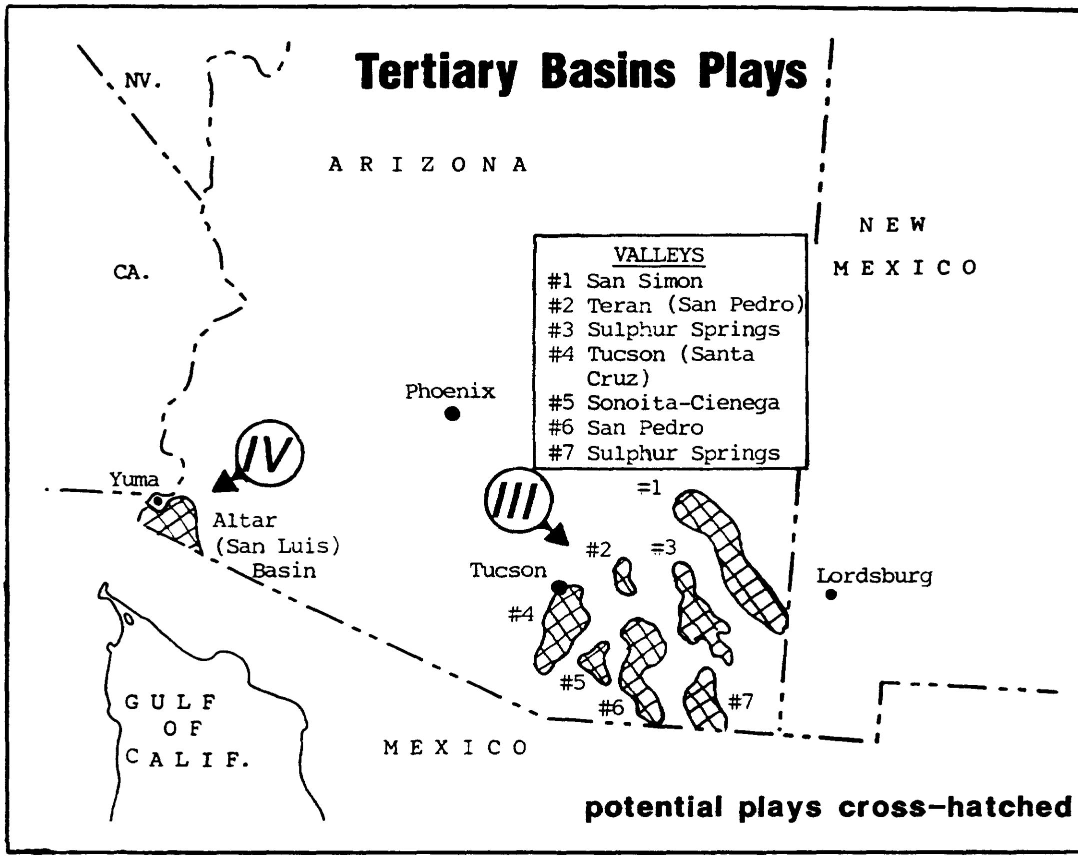


Figure 1--Index map showing area assessed (U.S. Geological Survey province #93). Oil and gas plays are within area outlined by heavy line.



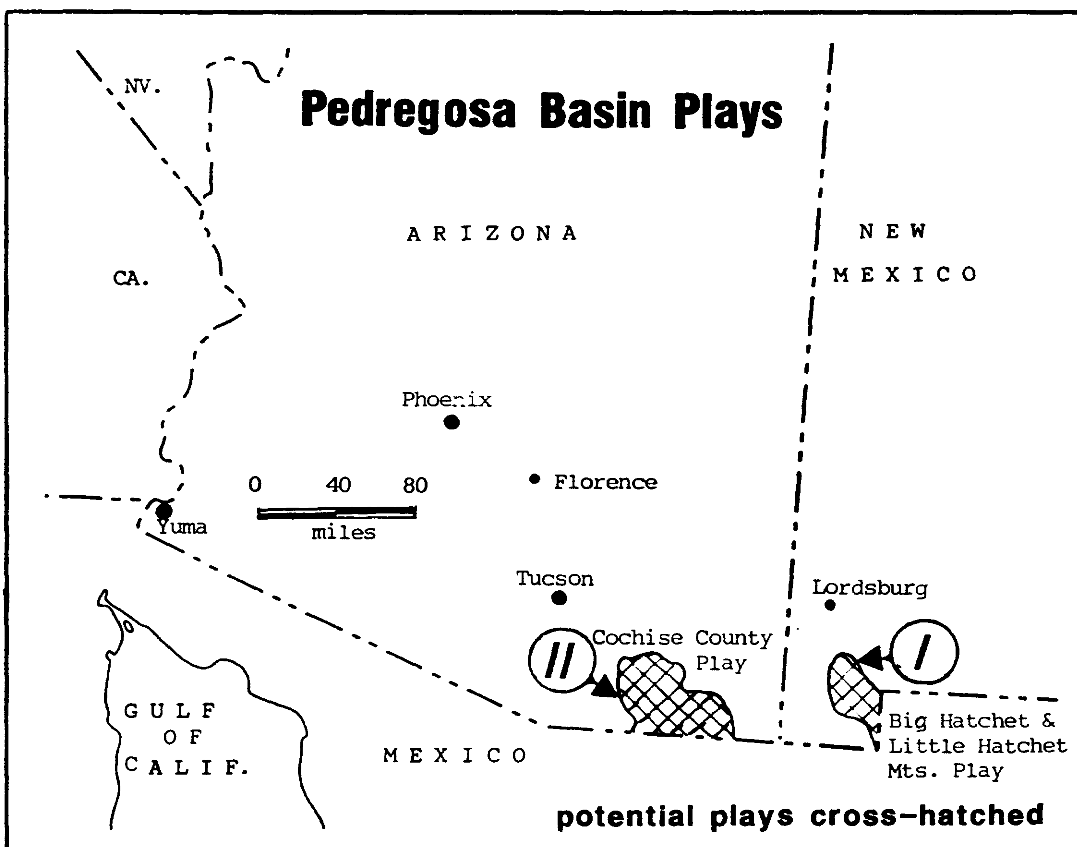


Figure 2--Map showing area of four petroleum plays.

Survey's assessment project (Mast and others, 1988). The purpose of the assessment is to delineate, based on present state of knowledge, all areas having the attributes necessary to form oil or gas deposits of one million barrels or 6 billion CFG and larger. These undiscovered accumulations must be large enough to be economically produced now or "in the near future". The assessment is thus a snapshot in time and does not portend to represent ultimately recoverable resources, which may be either more optimistic or less optimistic based on new subsurface information. This report is an overview of the factors considered during the resource appraisal process. For the most part, it does not interpret the geology or make detailed comparisons of working hypotheses, but rather presents basic information characterizing the region. Also, and most importantly, it documents sources of information, in addition to those cited, useful to a more comprehensive understanding of the regional geology.

General geologic information about the surface geology has been taken from the following geologic maps: Dane and Bachman (1965), Bayley and Muehlberger (1968), King (1969), Wilson and others (1969), Bayer (1983), Scarborough (1986), and Reynolds (1988). Syntheses of surface and subsurface geologic relationships and paleogeography have been notably drawn from Wilson (1962), Wilson and Moore (1962), Peirce and others (1970), Dott and Batten (1971), Mallory (1972), Cook and Bally (1975), Nations and Stump (1981), and Amer. Assoc. Petrol. Geol. (1983).

SCOPE AND DEPTH OF REPORT

This report generalizes the regional tectonic setting because there is no local production in this assessment province on which to focus concepts of oil or gas habitat. Also, the term "potential" becomes less clearly defined in such regions. Each mountain range has a unique geologic structure; to describe them individually goes beyond the detail intended.

Given the large and geologically-diverse assessment area, local structural complexities and stratigraphic nomenclature problems have been either treated superficially or omitted. Geophysical studies supporting assessment rationale and comparative hypotheses on tectonic evolution are noted without elaboration. Most of the essential references are cited in the narrative; others, from a larger data base, are listed as ancillary in the selected references. This approach provides a basic rationale for the assessment, with balance among disciplines, gives the reader a convenient way to pursue specialized topics, and remains consistent with assessment on a national scale.

ACKNOWLEDGEMENTS

Debra Higley and Tim Hester, geologists with the U.S. Geological Survey, kindly reviewed this report and made many useful suggestions. The author, however, is responsible for ideas presented and accuracy of data.

GENERAL TECTONIC AND DEPOSITIONAL SETTINGS

PRECAMBRIAN

General Statement and Overview

Precambrian rocks are described in this report because they set the early tectonic stage and are a pervasive rock unit caught up in the deformation of most mountain ranges. Also, they may include unique petroleum source beds in Arizona. According to Wrucke and others (1986) and Reynolds and others (1988), strata of Precambrian age have had some potential for generating petroleum in north-central Arizona; this is a topic of recent on-going research by M.W. Reynolds (pers. commun., U.S. Geol. Survey). Desborough and others (1984) have analyzed the favorable source-rock potential of unique unmetamorphosed Precambrian rocks in Gila County of east-central Arizona.

Precambrian rocks have influenced petroleum potential because: 1) the northwest-northeast structural grain of superjacent Phanerozoic rocks was inherited from the geometry of basement blocks; 2) tectonostratigraphic regimes were greatly influenced by basement topography; 3) the major lineament/fracture pattern of Arizona and western New Mexico can be attributed to the periodic rejuvenation along weak zones (master set of faults, fig. 3) in the basement; 4) basement rifts provided migration avenues thus controlling Laramide plutonism and mid-Tertiary to Quaternary volcanism; 5) hydrocarbons have been found beneath Precambrian thrust plates in the Rocky Mountains (Gries, 1983); and, 6) rejuvenation along basement flaws may have controlled migration and accumulation of hydrocarbons, such as hypothesized for northeastern Arizona (Davis, 1975) and for northwestern New Mexico (Stevenson, 1983). For a brief discussion of Paleozoic and Mesozoic subthrust plates below Precambrian rocks -- a highly speculative hydrocarbon-prospective area -- see the "Laramide Orogeny" section of this report. A better understanding of the Precambrian basement in Arizona may prove to be critical in the search for petroleum.

Most of the exposed Precambrian crystalline basement in Arizona occurs in the central mountain region, i.e. the normal-faulted and uplifted Mogollon Rim transition area (fig. 4 and 5) between the Colorado Plateau and the Basin and Range physiographic provinces (Peirce, 1985). The central region borders the northern edge of assessment province #93 (fig. 1), and has been briefly described in the U.S. Geological Survey petroleum assessment report for northern and central Arizona (Butler, 1988a).

The scattered, discontinuous, and complex nature of Precambrian outcrops in the southern Basin and Range province has made interpretation especially difficult. In particular, Coney and others (1980) recognized that southwestern-most Arizona is an allocthonous suspect terrane; large-

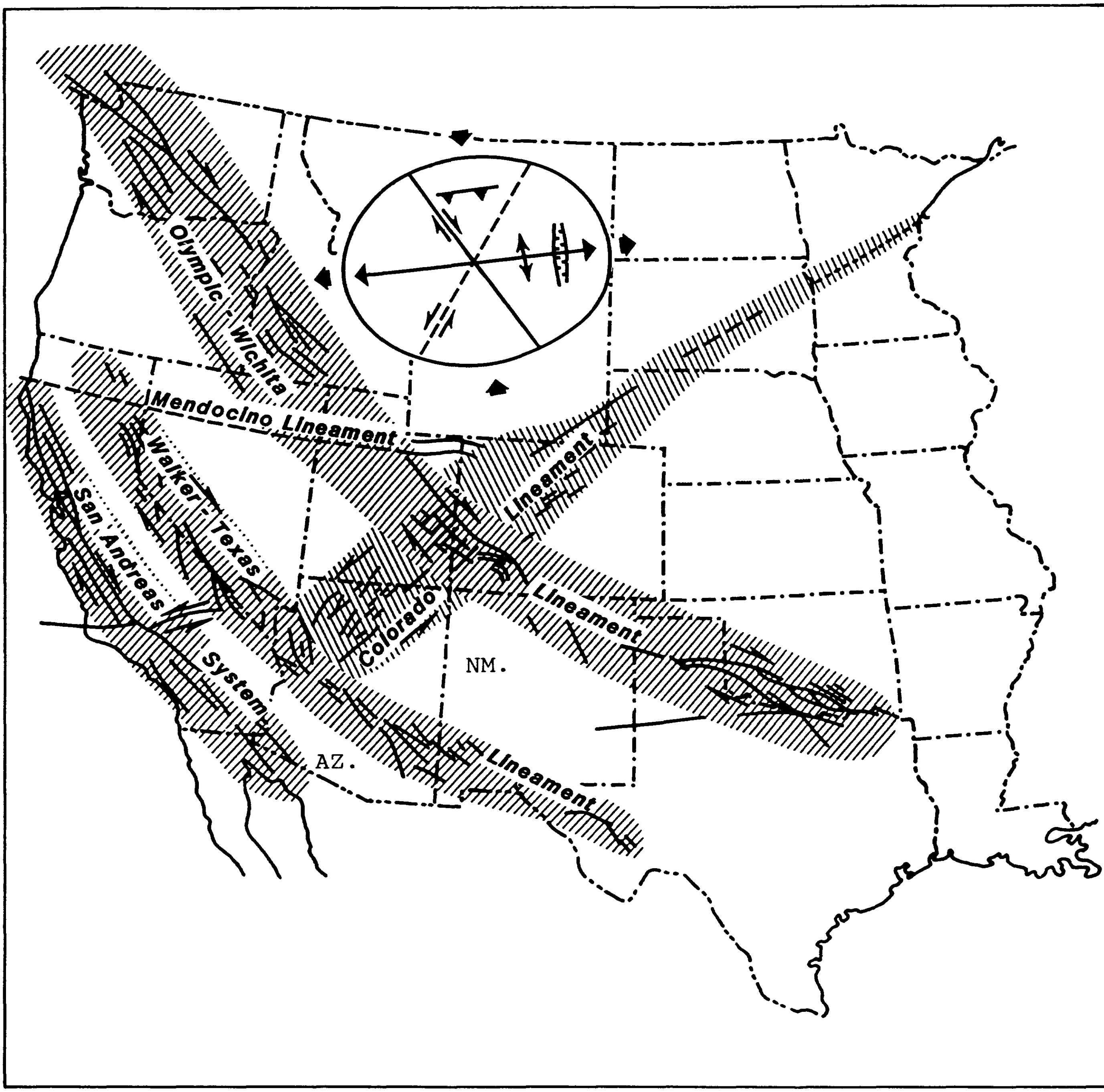


Fig. 3 –Map showing locations of major basement lineaments of western United States. Sense of strike-slip offset is shown by arrows; northwesterly lineaments are right lateral, northeasterly lineaments are left lateral. Stress-strain ellipsoid is so oriented that maximum compressive stress is directed from the north. (From Baars and Stevenson, 1982).

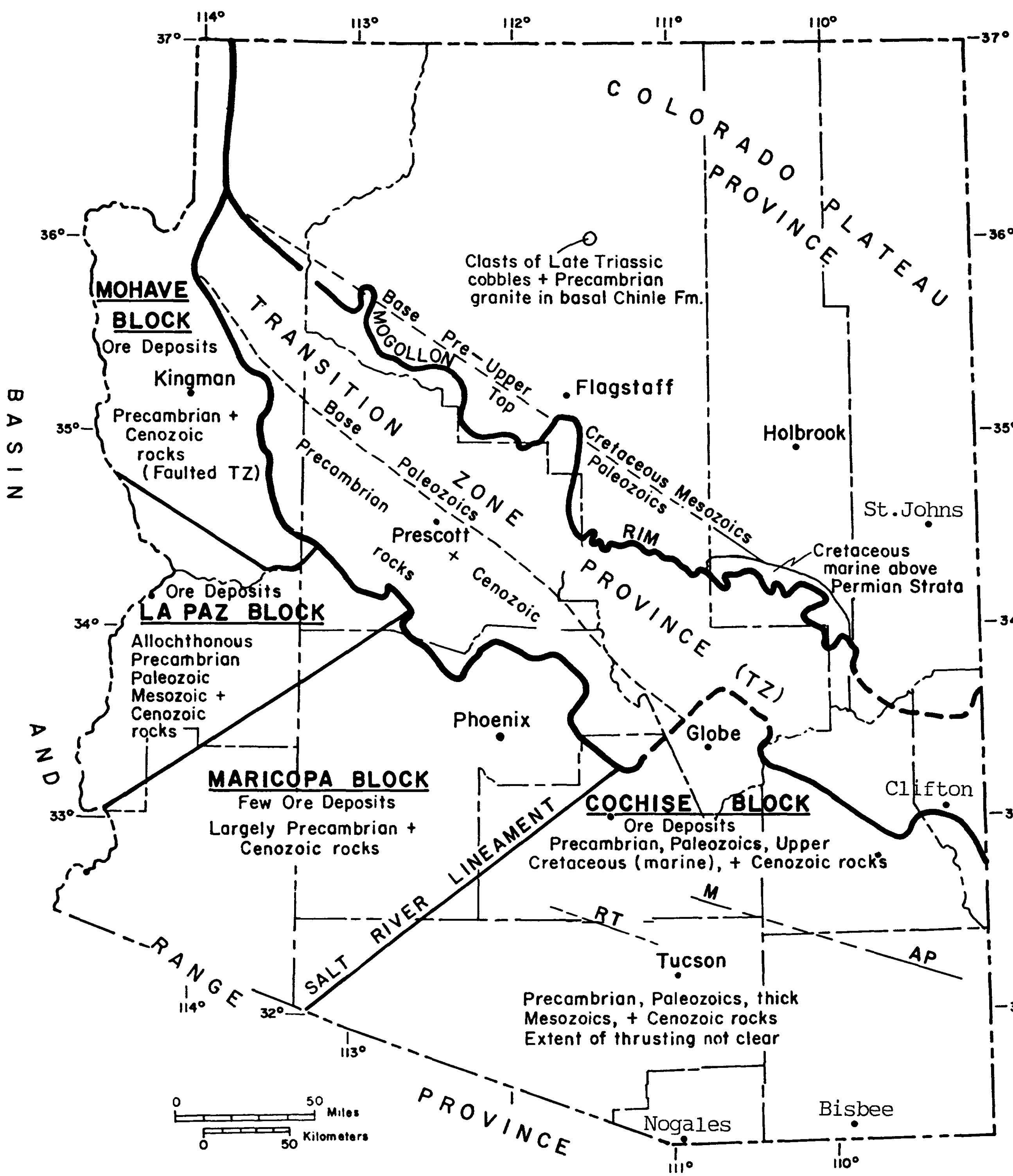


Figure 4-- Map of Arizona showing the three major physiographic provinces, four subdivisions of the Basin and Range Province, general rock and ore deposits distribution, and the Apache Pass (AP), Mogul (M), and Ragged Top (RT)-APMRT trends. (From Peirce, 1986).

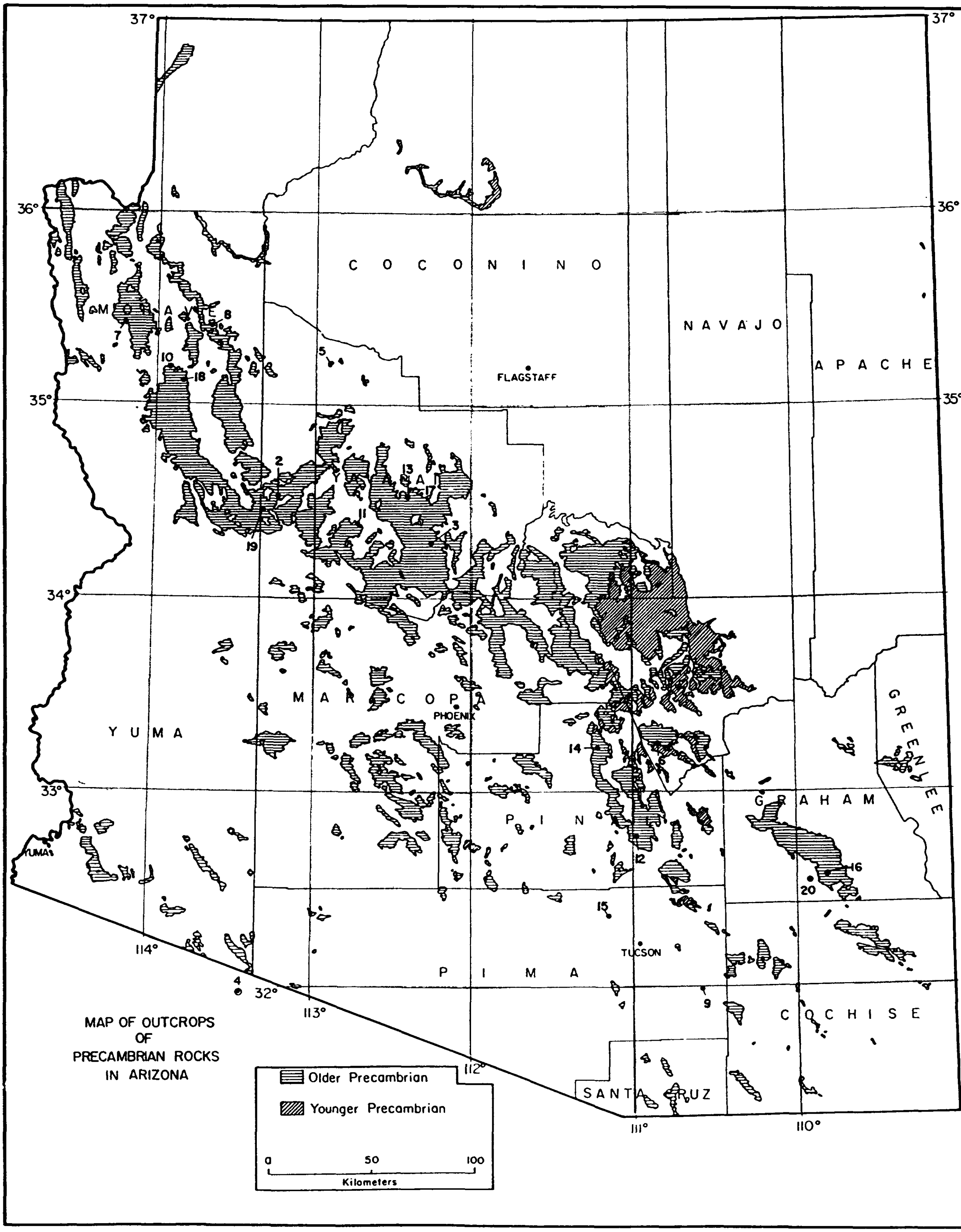


Figure 5--Map of "Older" and "Younger" Precambrian outcrops in Arizona. (From Shafiqullah and others, 1980).

scale left-lateral movement along the Mojave-Sonoran mega-shear (transform fault) occurred in this region during the Jurassic Period. Tosdal and Haxel (1982) recognized a belt of thrust faults in southwestern-most Arizona and suggested that during the Laramide orogeny exotic terranes of Precambrian and Mesozoic igneous rocks were displaced northeastward over indigenous continental crust. According to Howell (1986), the Precambrian metamorphic terrane of southwestern Yuma County, Arizona, referred to as Tujunga (Howell and others, 1985a,b), may be exotic allocthonous slivers of poorly-lineated tectonostratigraphic oceanic terranes which accreted onto the Precambrian craton at the leading edge of mobile tectonic plates. Timing of accretion of this fault-bounded collage is not certain.

History

Precambrian history from 1-2 b.y.a. in the assessment province is a story of continental accretion with growth to the southeast (Condie, 1982; Karlstrom and others, 1987). Tectonic plate divergence 1.72-1.76 m.y.a. allowed the opening of an ocean basin with accumulation of thick volcanic and marine clastic assemblages. Subsequence convergence (northwestward subduction), uplift, and mountain-building beginning in the latter Early Proterozoic welded these assemblages onto the craton.

Precambrian rocks of Arizona have traditionally been divided into two groups: the "older" (mostly Early Proterozoic) and "younger" (Middle and Late Proterozoic). The first group corresponds to rocks formed before and during the Mazatzal orogeny, and the second group represents post-Mazatzal orogeny sequences (fig. 6). Ages of the "older" sequence in west-central and southwestern to central Arizona are 1.73-1.80 b.y. In this area these predominately metavolcanic rocks probably include the Yavapai Series, Vishnu Schist, Big Bug Group, and Ash Creek Group (Nations and Stump, 1981). Wilson (1962) estimated the Yavapai Series to be 41,000 to 54,000

Designation on Arizona Bureau of Mines County Geologic Maps	CENTRAL ARIZONA	Thickness in feet	SOUTHERN AND SOUTHEASTERN ARIZONA	Thickness in feet	Designation on Arizona Bureau of Mines County Geologic Maps	NORTHERN ARIZONA	Thickness in feet	NORTHWESTERN AND WESTERN ARIZONA	
Diabase (db)	Grand Canyon Disturbance with intrusion by diabase dikes, sills, and irregular bodies		Grand Canyon Disturbance with intrusion by diabase		Diabase (db)	Grand Canyon Disturbance ; diabase intruding Unkar group		Not recognized	YOUNGER PRECAMBRIAN
Sandstone and quartzite (ss)	Sandstone and quartzite ; Troy quartzite north and northwest of Coolidge Dam (Figure 7)	0 - 1,250	Lower portion of the Troy quartzite between Latitudes 32°30' and 33°30', approximately (Figure 7)	800 to 1,500	Grand Canyon series (Agc)	Grand Canyon series Chuar group: sandstone, shale, basalt, and minor limestone	5,120		
	UNCONFORMITY		UNCONFORMITY			DISCONFORMITY			
Apache group (Au) Mescal limestone (Am) Lower Apache group (Aq)	Apache group Basalt . . . . Mescal limestone . . . . . Dripping Spring quartzite . . Barnes conglomerate . . . . Pioneer shale . . . . Scanlan conglomerate . . . Total (local maximum)	 0 - 375 225-500 400-680 0-40 150-500 0-20 1,600	Apache group			Unkar group: Dox sandstone . . . . Shinumo quartzite . . . . . . Hakatai shale . . . . Bass limestone . . . . Hotauta conglomerate . . . . . Total Unkar Total Grand Canyon series	 2,297+ 1,564+ 580+ 335+ 6+ 4,782 to 6,830 10,000 to 12,000		
	GREAT UNCONFORMITY					GREAT UNCONFORMITY			
Granite and related crystalline rocks (gr), diorite porphyry (di), pyroxenite (py), and granite gneiss (gn)	Mazatzal Revolution, culminating with intrusions ranging from granitic to gabbroic in composition				Granite and related crystalline rocks (gr), granite gneiss (gn)	Mazatzal Revolution, culminating with intrusions ranging from granitic to gabbroic in composition			
Mazatzal quartzite (mq)	Mazatzal quartzite, Maverick shale, and Deadman quartzite	5,400			Mazatzal quartzite (mq)	Mazatzal quartzite, small exposure near Fort Defiance			OLDER PRECAMBRIAN
	FAULT								
Schist (sch), rhyolite (rhy), and greenstone (gst)	(Yavapai schist) Alder group: Foliated volcanics and slate FAULT Red Rock rhyolite, 1,000+ feet FAULT	20,000 to 30,000	Pinal schist: Metamorphosed sedimentary and volcanic rocks	20,000+	Schist (sch)	Vishnu series (Vishnu schist): schist, quartzite, and metavolcanics	25,000+	Unnamed schist: Metamorphosed sedimentary and volcanic rocks	
	Yavapai series Ash Creek group: Basaltic, andesitic, rhyolitic, and dacitic flows and pyroclastic rocks and tuffaceous sedimentary rocks. Locally foliated. Total Yavapai	20,000 to 23,500 41,000 to 54,000							
	?		?			?		?	
Granite gneiss (gn)	Granite gneiss		Granite gneiss		Granite gneiss	Granite gneiss		Granite gneiss	

Figure 6--Precambrian rocks and events of Arizona. (From Wilson, 1962).

feet thick. In central Arizona the "older" sequence is younger (1.70-1.73 b.y.) and is represented by ten formations of metasediments and metavolcanics totalling up to 20,000 feet thick for the Alder Group and 6,500 feet thick for the coeval Haigler Group. These two groups are inferred to have been deposited in a near-shore marine environment, i.e a back-arc basin. In southeastern Arizona and southwestern New Mexico, the Pinal Schist, also about 1.70-1.73 b.y. old, includes over 20,000 feet of metasediments (graywacke) and metavolcanics, possibly deposited in a deep-marine environment.

Early Proterozoic plate convergence created first-order northeast-trending folds, northwestward thrusting, block-faulting, and granitic to gabbroic intrusions. Resulting tectonic patterns are clearly detectable by various geophysical methods. Contemporaneous with the Mazatzal orogeny, the ages of the rock sequence in southeastern Arizona and southwestern New Mexico are 1.65-1.73 b.y. (Condie, 1981). According to Karlstrom and others (1987), this province may be allochthonous Precambrian terrane displaced from the southeast over a great distance. Numerous younger granite and granodiorite intrusions, dated as young as 1.4-1.5 b.y. in the present-day Basin and Range, probably culminated the orogenic episode. Following the deposition and uplift of the "older" Precambrian sequences, nearly a half billion years of erosion ensued which wore down the northeast-trending Mazatzal Mountain range to sea level. Hence, a pronounced great unconformity separates the "older" and "younger" Precambrian sequences.

Periodic isostatic uplift of the northeast-trending mountain core, i.e. ancient plate suture, is represented in the Paleozoic Era by the Transcontinental Arch positive area that extends from Mazatzal Land of central Arizona (Wilson, 1962) to Minnesota. Mazatzal Land during the Late Paleozoic is referred to as the Sedona Arch (Blakey, 1980).

The Apache Group is a 100- to 125-mile-wide north-south belt of supracrustal rocks extending from south-central Arizona to east-central and northeastern Arizona, and more-or-less separates the western and eastern assessment area. The group is at least 10,000 feet thick (1.0-1.3 b.y. old) and was deposited in the Tonto basin. Desborough and others (1984) and Wrucke and others (1986) considered some of the black siltstone-mudstone facies of the Dripping Springs Quartzite and Mescal Limestone within this group in Gila County, Arizona, to have had some source rock potential. This was based on rock-eval results which included a high (up to 6 percent TOC) content of unmetamorphosed hydrocarbons.

One of the last major tectonic events (Late Proterozoic, 1.1 b.y.a.) was the intrusion of extensive and thick diabase sills, particularly in the central mountain province. This period of metamorphism, tectonic relaxation, and regional block-faulting is called the Grand Canyon Disturbance. Up to 1,500 feet of shallow-marine, passive-margin sediments were deposited unconformably on the Apache Group in central and southeastern Arizona to end the Late Proterozoic Era.

The Texas Lineament

The Texas lineament is a cogent element to oil and gas exploration. It is possibly one of the most significant, if not longest, regmatic shear zones of the western hemisphere (Kelley, 1955; Albritton and Smith, 1957; Moody, 1966; Sales, 1968; Thomas, 1974; Fischer and Judson, 1975; Baars, 1976), is an enigmatic and controversial geologic feature within the assessment province. This structure has had cyclic popularity among geologists and is best explained in terms of global tectonics. Although there is wide latitude as to its interpretation, and hence whether it has merit and usefulness as a "real feature", the lineament's persistence in the literature since originally noted by Hill (1902) has given it credibility -- at least in terms of operational nomenclature. This lineament has been historically analyzed in southern Arizona in terms of fracture intersections and the relationship to the location of mineral deposits, especially porphyry copper (Billingsley and Locke, 1941; Mayo, 1958; Schmitt, 1966; Wertz, 1970). Because of its magnitude as a fundamental ancestral break or intraplate zone of weakness covering virtually the entire assessment province (fig. 7), the Texas lineament cannot be ignored with respect to assessing oil and gas potential. The aeromagnetic maps by Sauk and Sumner (1971) and Zietz (1982), and the gravity maps by Lysonski and others (1980) and Hildenbrand and others (1982) clearly illustrate the northwest-trending basement lineaments of this zone.

As a working hypothesis, the lineament is an loosely-defined zone of crustal instability, possibly bounded by wrench or transform faults. It is generally 60-300 miles wide in its central segment, e.g. from the southern edge of the Colorado Plateau to Caborca, Mexico. Specific studies (e.g., Swan, 1976) have limited the zone to 100-150 miles wide. It extends northwestward from at least El Paso, TX., to at least Las Vegas, NV., where it becomes more obscure and possibly intersects the Las Vegas shear and Walker Lane lineament (Livaccari, 1979). Other geologists have extended it from the Gulf of Mexico to the Transverse Ranges of California (Ransome, 1913) and the Murray Fracture Zone of the northeastern Pacific Ocean (Albritton and Smith, 1957; Vacquier and others, 1961). Along the northern border of the eastern assessment area concordant with the Texas zone, the Deming Axis is a term used for the alignment of Late Paleozoic positive areas, such as the Naco Highlands, Burro Uplift, and Florida Islands (Turner, 1962; Butler, 1971; Thompson, 1976). The zone's southern limit is the Mojave-Sonoran mega-shear -- a transform fault having maximum offset during the Jurassic opening of the Gulf of Mexico. See the

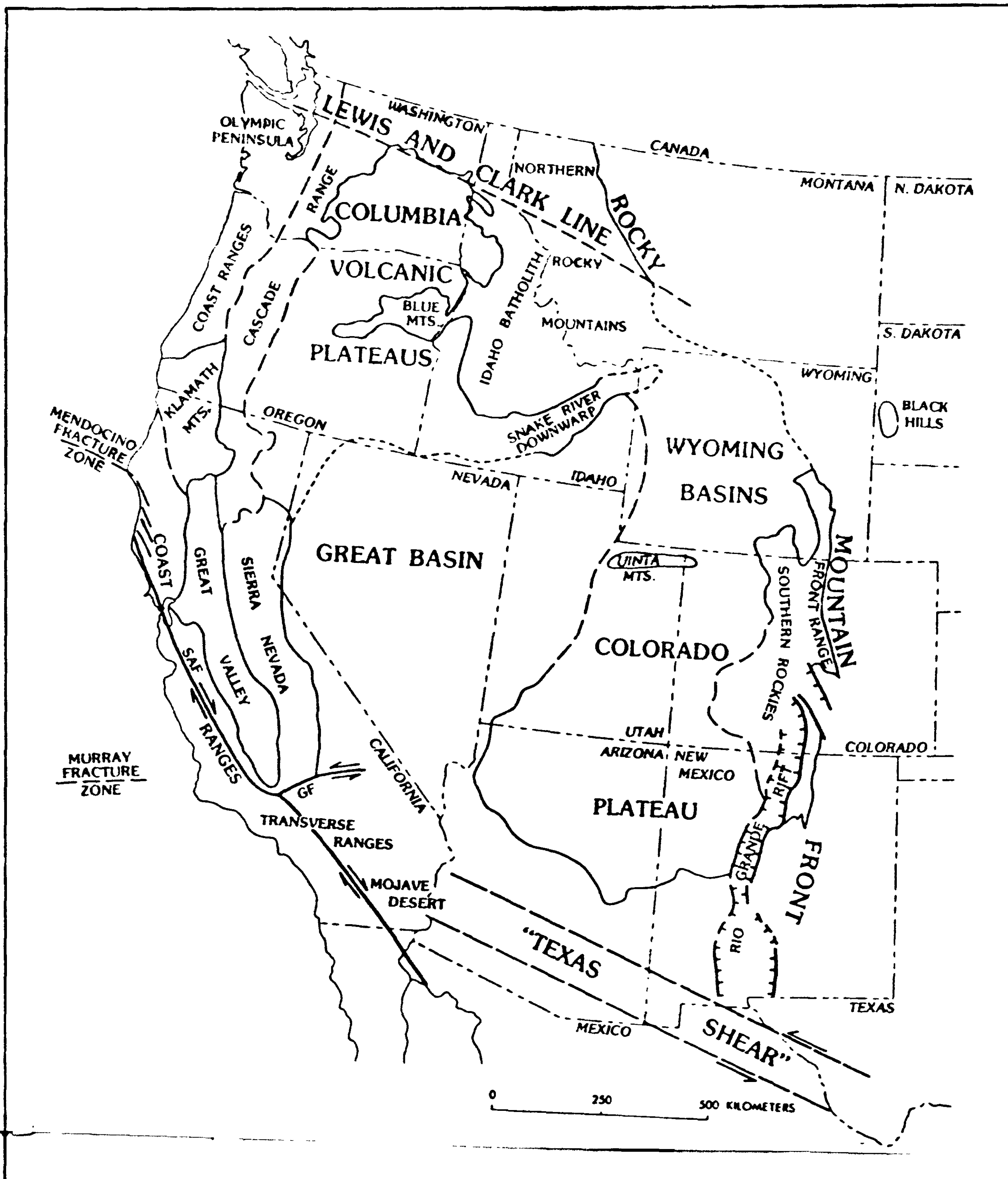


Figure 7--Map showing the Texas lineament shear zone of southern Arizona and southwestern New Mexico. (From Guild, 1978).

MESOZOIC ERA section of this report.

Originating during the Precambrian (Titley, 1976), the Texas lineament represents an area of both right- and left-lateral mega-shearing (Muehlberger, 1986) having offsets of only a few miles to 600 miles. It is obscured by both southwest- and northeast-directed thrusting and basement-rooted uplifts during the Laramide Orogeny (Keith and Wilt, 1986). Corbitt and Woodward (1973) believed that thrust faulting in southwestern New Mexico, to the exclusion of major strike-slip faulting, marked the northern limit of this Texas zone. Although Drewes and Thorman (1978) recognized that left-lateral strike-slip movement of basement rocks has occurred in the Precambrian, Mesozoic, and Cenozoic in numerous ranges of southeastern Arizona, Drewes (1978) nonetheless believed the Texas lineament zone is not marked by strike-slip tectonics but rather by a northwest-trending boundary of regional thrust-fault deformation.

The wrench-fault hypothesis (Lutton, 1958) is germane to hydrocarbon trap development (Moody, 1973; Wilcox and others, 1973; Harding, 1974; Aydin and Nur, 1985; Budnik, 1986), and is particularly relevant in this assessment area if indeed the Texas lineament is "for real". Transpressional and transtensional structures associated with slight bends in wrench-fault planes create thrust blocks, push-up ranges, tilt-blocks, and pull-apart basins (Chinnery, 1965; Stone, 1969; Crowell, 1974a,b; Reading, 1980; Sanderson and Marchini, 1984; Sylvester, 1984; Longoria, 1985; McCoss, 1986). Examples of these structures and basins containing highly petroliferous strata have been studied in the Anadarko basin (Wickham, 1978; Budnik, 1986) and Paradox basin (Gorham, 1975; Baars, 1976) along the Wichita lineament, and along the San Andreas Fault in southern California (Moody and Hill, 1956; Crowell, 1962; Harding, 1976; Sylvester and Smith, 1976; Blake and others, 1978). On a different scale, broad anticlinal welts, drag folds, and normal faults, all of which can trap hydrocarbons, continuously grow en echelon in the wrench fault zone. Fracture porosity is enhanced along the shear planes (Moody, 1973) -- an important factor for the generally tight Paleozoic formations cropping out in the assessment province. The fundamental question is raised, "Is the Texas lineament a pre-Cretaceous San Andreas-type fault zone with all the potential attendant hydrocarbon traps, but obscured by Laramide and basin-and-range tectonic overprinting?"

Due to the geologic complexity of the area, additional references are listed here which use the term Texas lineament or otherwise pertain to the Texas lineament "zone" and/or mega-shearing in the assessment vicinity: Hill (1928), Baker (1934), Moody and Hill (1956), Deutsch (1960), Turner (1962), Hunt (1963), Wise (1963), Muehlberger (1965), Nielsen (1965), Poole and others (1967), Stewart (1967), Stewart and others (1968), Wiley and Muehlberger (1971), Walper (1973), Abdel-Gawad and Tubbesing (1974), Horak (1974), Silver and Anderson (1974), Thomas (1974), King (1975), Swan (1975 and 1976), Titley (1976 and 1981), Woodward (1976), Drewes (1978), Eaton and others ((1978, p. 81), Guild (1978), Anderson and Silver (1979), Muehlberger (1980), Urrutia-Fucugauchi (1981 and 1984), Baars and Stevenson (1982), Drewes (1982), Gose and others (1982), and Swan and Keith (1986).

STRATIGRAPHIC SECTIONS

Generalized composite stratigraphic sections are presented here as figures 8, 9, 10, and 11 to serve as a basis for the geologic history which is summarized below. These sections primarily represent the rocks of the eastern assessment area, i.e. the Pedregosa basin/Sonoran "geosyncline". The Paleozoic and Mesozoic sedimentary sections and history of the western half of the assessment area are obscure due to: 1) a sparcity of outcrops and boreholes, 2) difficulty in identifying formations and their contacts

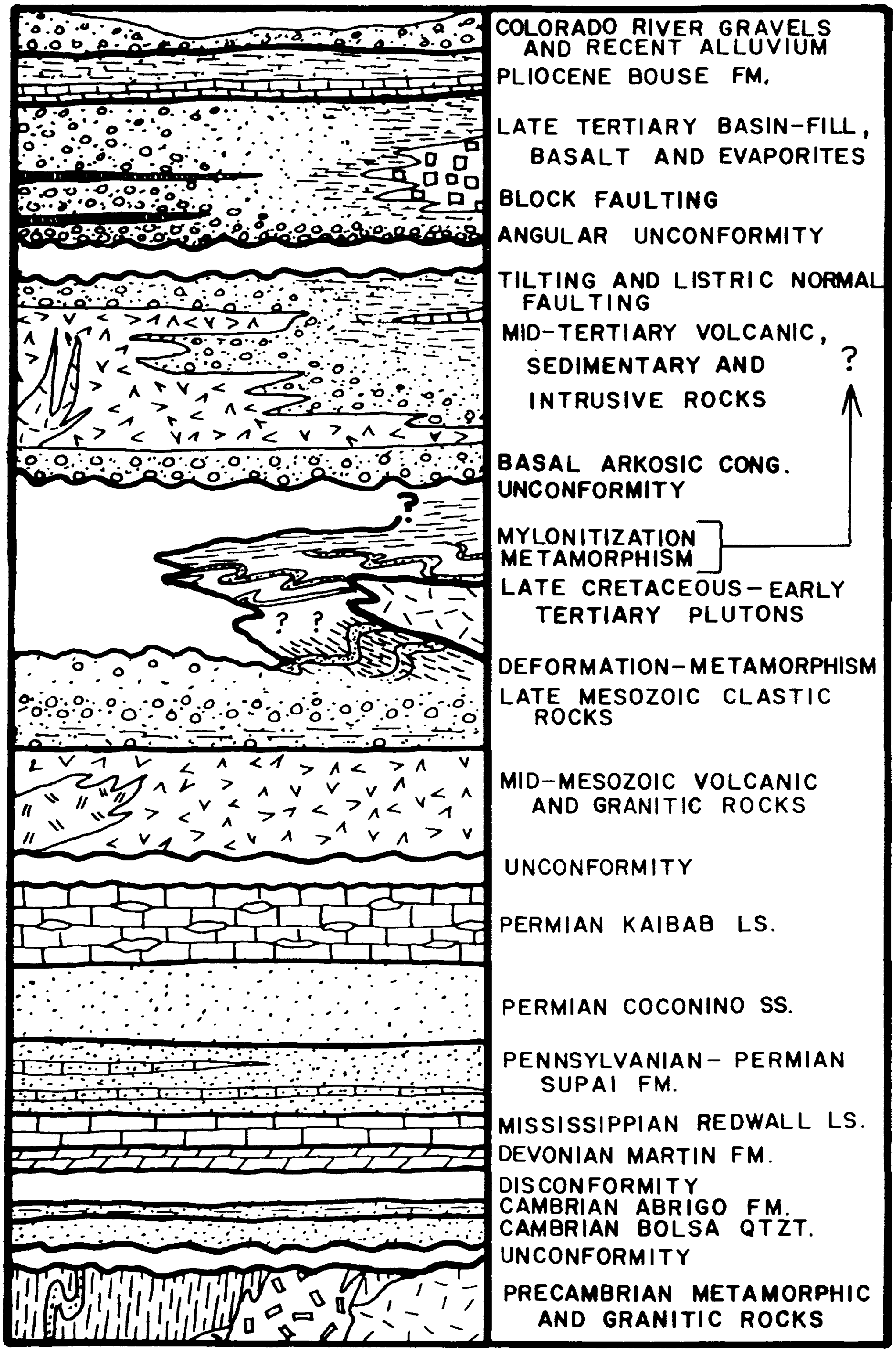


Figure 8--Chronology of rock units and major events of the westernmost assessment area. (From Reynolds, 1980).

Era	AGE	Group	FORMATIONS	THICKNESS
CENOZOIC	QUATERNARY		Alluvium	
CENOZOIC	TERTIARY		Volcanics and Clastics	
MESOZOIC	CRETACEOUS		Volcanics and Intrusives	
MESOZOIC	CRETACEOUS	BISBEE GROUP	Cintura Formation	600'-4000'
MESOZOIC	CRETACEOUS	BISBEE GROUP	Mural Limestone	550'-740'
MESOZOIC	CRETACEOUS	BISBEE GROUP	Morita Formation	1000'-4200'
MESOZOIC	CRETACEOUS	BISBEE GROUP	Glance Conglomerate	0-5000'
MESOZOIC	JURASSIC		Volcanics and Clastics	0-1100'
PALEOZOIC	PERMIAN	NACO GROUP	Rainvalley Formation	0-400'
PALEOZOIC	PERMIAN	NACO GROUP	Concha Limestone	0-570'
PALEOZOIC	PERMIAN	NACO GROUP	Scherrer Formation	0-720'
PALEOZOIC	PERMIAN	NACO GROUP	Epitaph Dolomite	780'-1190'
PALEOZOIC	PERMIAN	NACO GROUP	Colina Limestone	180'-900'
PALEOZOIC	PERMIAN	NACO GROUP	Earp Formation	400'-800'
PALEOZOIC	PENNSYLVANIAN	NACO GROUP	Horquilla Limestone	600'-1230'
PALEOZOIC	LOWER PENN/ UPPER MISS		Black Prince Limestone	0-280'
PALEOZOIC	MISSISSIPPIAN		Escabrosa Limestone	500'-790'
PALEOZOIC	DEVONIAN		Percha Shale	0-200'
PALEOZOIC	DEVONIAN		Martin Formation	200'-320'
PALEOZOIC	ORDOVICIAN/ CAMBRIAN		Abrigo Formation	800'-870'
PALEOZOIC	ORDOVICIAN/ CAMBRIAN		Bolsa Quartzite	440'-470'
PRECAMBRIAN			Granite and Metamorphics	

Figure 9--Generalized stratigraphic column for southeastern Arizona. (From Robinson, 1982).

Era	Period	Epoch	Big Hatchet Mtns. (after Zeller)	Northwest Chihuahua Mexico (after Diaz & Navarro)	Southeast New Mexico
CENOZOIC	Quaternary		Alluvium		
	Tertiary		Fanglomerate		
MESOZOIC	Cretaceous	Upper			
		Lower	Mojado Fm. 5195'		
			U-Bar Fm. 3500'		
			Hell-to-Finish Fm. 1274'	Las Vigas	
PALEOZOIC	Permian		Concha Limestone 1376'	Concha Ls. 590' (179m)	San Andres Ls. 1360'
			Scherrer Sandstone 20'	Scherrer Ss. 10' (3m)	Glorieta Ss. 40'
			Epitaph Dolomite 1500'	Epitaph Dolomite 1553' (472m)	Yeso Fm. 2000'
			Colina Limestone 440'	Colina Limestone 609' (185m)	
			Earp Fm. 997'	Earp Fm. 707' (215m)	Abo Fm. 1100'
			1500'	1030' (308m)	Wolfcamp Series 1000'
	Pennsylvanian		Horquilla Limestone 2100'	Horquilla Ls. 2515' (764m)	Virgil Series
					Missouri Series
					Des Moines Series 2500'
					Atoka Series
					Morrow Series
	Mississippian		Paradise Fm. 318'	Paradise Fm. 352' (107m)	Helms or Barnett Fm. 100'
			Escabrosa Fm. 1261'	Hachita Fm. 296' (90m)	
				Keating Fm. 109' (33m)	Limestone 500'
	Devonian		Percha Shale 280'		Woodford Shale 100'
					Limestone 1000'
	Silurian				Fusselman Dolomite 600'
	Ordovician		Montoya Dolomite 385'		Montoya Dolomite 900'
					Simpson Sandstone 200'
			El Paso Limestone 1070'		Ellenburger Dolomite 450'
	Cambrian		Bliss Sandstone 250'		Bliss Sandstone 80'
	Precambrian		Precambrian		Precambrian

Figure 10--Stratigraphic nomenclature chart for southwestern New Mexico and vicinity. (From Zeller, 1970b).

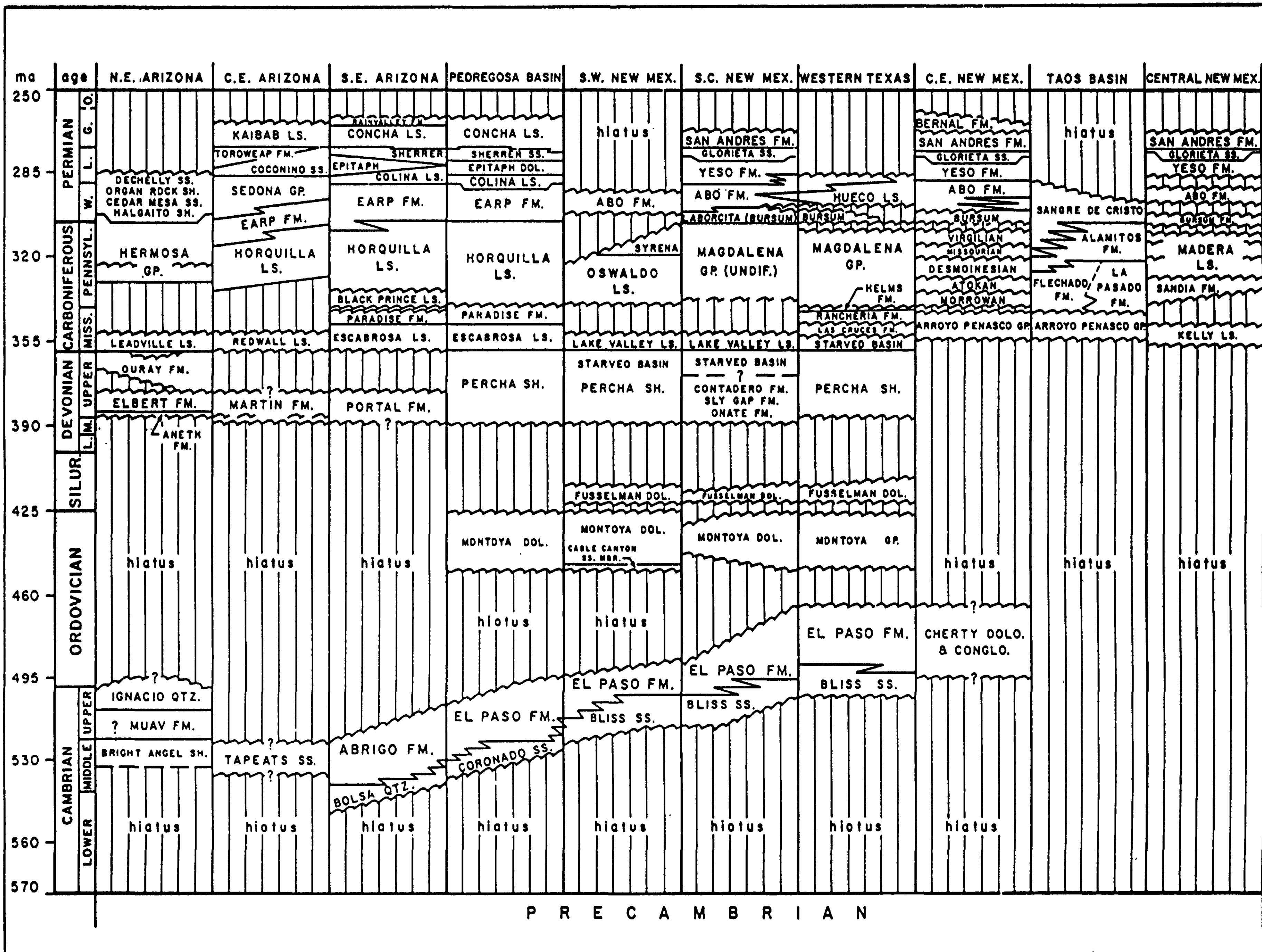


Figure 11 --Correlations of Paleozoic strata in Arizona, New Mexico, and West Texas. (From Ross and Ross, 1986).

due to long distances from type sections, 3) widespread alluvium, 4) intense regional metamorphism, and lack of public seismic data.

PALEOZOIC ERA

General Statement and Overview

Synopses of the tectonic setting through time are illustrated in figures 12 and 13. Paleogeographically, Paleozoic sediments present within the assessment province were discontinuously deposited on a shallow marine (shelf-miogeosynclinal) platform (fig. 14). These sediments are relatively thin in the western assessment area and thicken eastward to 5,500-7,000 ft in Cochise County (Peirce, 1976a) and up to 15,000 ft in southeastern Hidalgo County (Thompson, 1982b). Some estimates of the total Paleozoic section in Cochise County, however, may be as much as 9,500-10,000 ft thick. Figures 15 and 16 show thicknesses of Paleozoic strata of this assessment province which generally define the Late Paleozoic Pedregosa basin of southwestern New Mexico and southeastern Arizona. Cambrian through Permian metasedimentary rocks, 2,850-4,125 ft thick, have been mapped in west-central Arizona. Paleozoic strata thicken rapidly west of the Arizona shelf into the Cordilleran miogeosyncline of southeastern California and southeastern Nevada.

Left- and right-lateral movements in the Texas lineament zone occurred during the Middle Paleozoic (Poole and others, 1967; Horak, 1974) at a time when the Farallon plate probably began its subduction into the trench near the continental margin in central Nevada. During the Pennsylvanian, a progressive amagmatic collision with possibly south-dipping subduction (Wickham and others, 1976) between the North American and South American plates resulted in closing of the Proto-Atlantic ocean plus localized fault-bounded basement-cored uplifts, basins, and left-lateral mega-shearing in the foreland of southwestern United States (Walper, 1977; Burchfiel,

Eras	Periods and Epochs	Age: Millions of Years	Geologic Highlights of Basin — Range Province of Arizona		Southeast Arizona: Oil or Gas Shows	Southeast Arizona: Drilling Objectives
CENOZOIC	Quaternary: Recent		Alluvial sediments.	Uplift and erosion		
	Quaternary: Pleistocene	.011	Stream, river, and lake deposits; basaltic volcanics.	Uplift and erosion Volcanism		
	Tertiary, Late: Pliocene	1	Locally, thousands of feet of non-marine sediments including evaporitic lacustrine deposits; marine embayment in south-western Arizona. Basaltic volcanics.	Basin and Range orogeny: Uplift; faulting; magmatism; erosion	* ?	* ?
	Tertiary, Late: Miocene	12				
			Unconformity			
	Tertiary, Middle: Oligocene	23	Locally, thousands of feet of non-marine sediments and volcanics; Pantano Formation, Helmet Fanglomerate, Whitetail Conglomerate, etc.			
		40	Unconformity			
	Tertiary, Early: Eocene		Claflin Ranch Formation, Cloudburst Formation, and other unnamed units; multiple igneous rocks.	Laramide Revolution: Uplift; folding and faulting; granitic intrusions, volcanism; widespread mineralization.		
	Tertiary, Early: Paleocene					
		70	Unconformity			
MESOZOIC	Cretaceous		About 15,000 feet marine and non-marine sediments, principally sandstone and shales but with thick marine carbonate zone in lower part. Volcanics.		*	*
		135	Unconformity			
	Jurassic		Igneous rocks.	Nevadan Revolution: Granitic intrusions Volcanic activity Mineralization Uplift and erosion		
	Triassic	180	Probable igneous rocks; possible sedimentary rocks.			
		220	Unconformity			
PALEOZOIC	Permian		2,500 or more feet of marine sediments, principally carbonates with some clastics and gypsum.	General Uplift		*
	Pennsylvanian	270	Up to 2,500 feet of marine sediments, principally carbonates and shales.		*	*
	Mississippian	320	Up to 800 feet of marine sediments, principally carbonates.	Uplift in central Arizona	*	*
	Devonian	350	Up to 500 feet of marine sediments, principally carbonates.		*	*
		400	Unconformity			
	Silurian		Not known in Arizona.	General Emergence		
	Ordovician		Up to 700 feet of marine sediments, principally carbonates.			*
	Cambrian	490	Up to 1,500 feet of marine sediments, principally carbonates, quartzite, sandstones, and shales.			*
		600	Unconformity			
YOUNGER PRECAMBRIAN			Up to 1,000 feet of Troy Quartzite in central Arizona. Up to 1,200 feet of Apache Group, principally quartzite, shales, and carbonates, probably marine. Some basalt.	Diabase intrusion some volcanism		
		1600	Unconformity			
OLDER PRECAMBRIAN			Several thousands of feet of metamorphosed sediments and volcanics (schists and gneisses). Some quartzite, shales and volcanics relatively unaltered.	Mazatzal Revolution: Granitic intrusions Folding Uplift and erosion		
		2000+	Mineralization	Earlier disturbances		

Figure 12-- Time scale with geologic highlights of the Arizona Basin and Range province; stratigraphic occurrence of oil and gas shows and drilling objectives in the southeastern portion of the province. (From Aiken and Sumner, 1974).

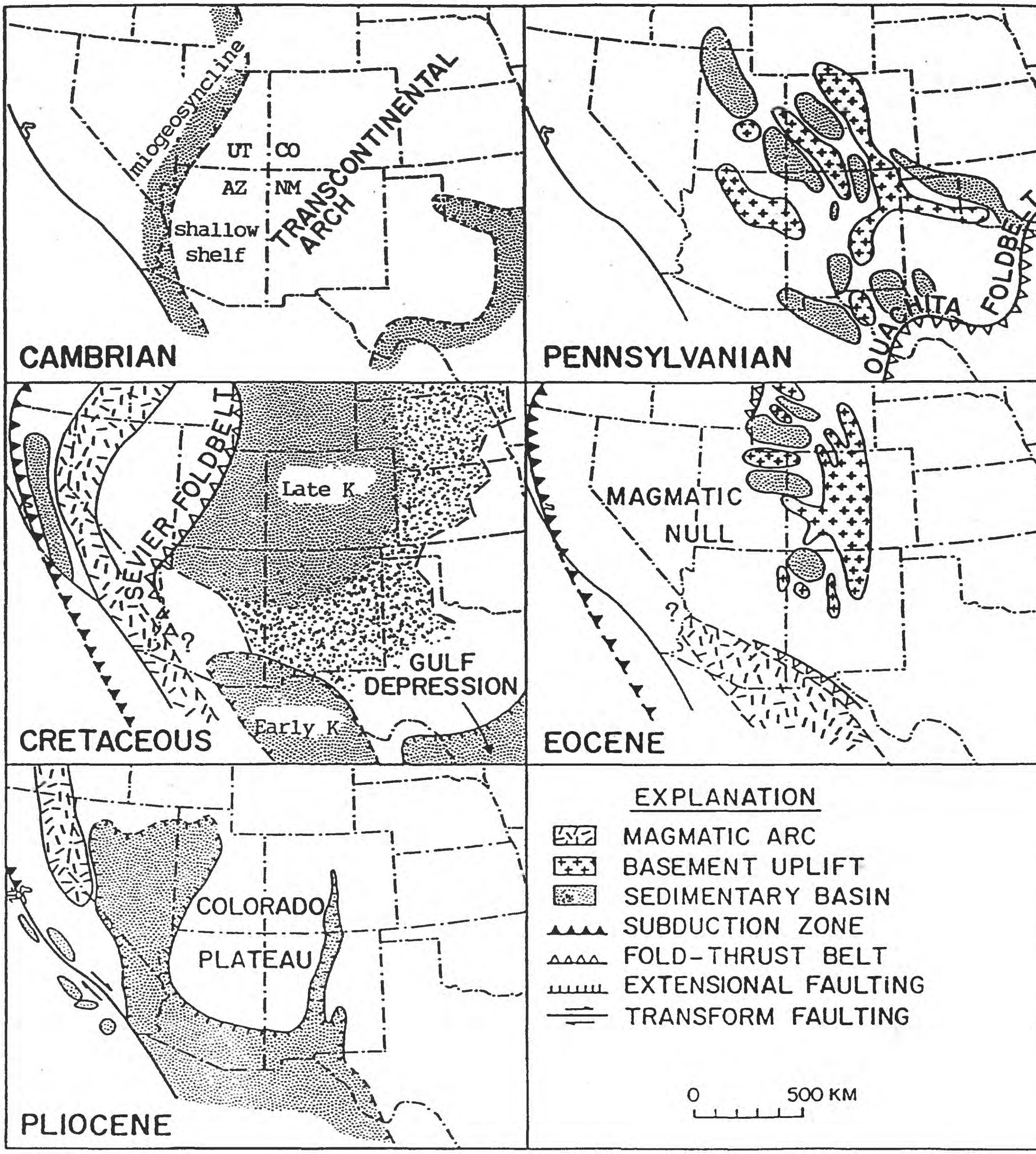


Fig. 13--Schematic paleotectonic setting of southwestern United States. The maps are not palinspastically restored. (Modified from Woodward and Ingersoll, 1979).

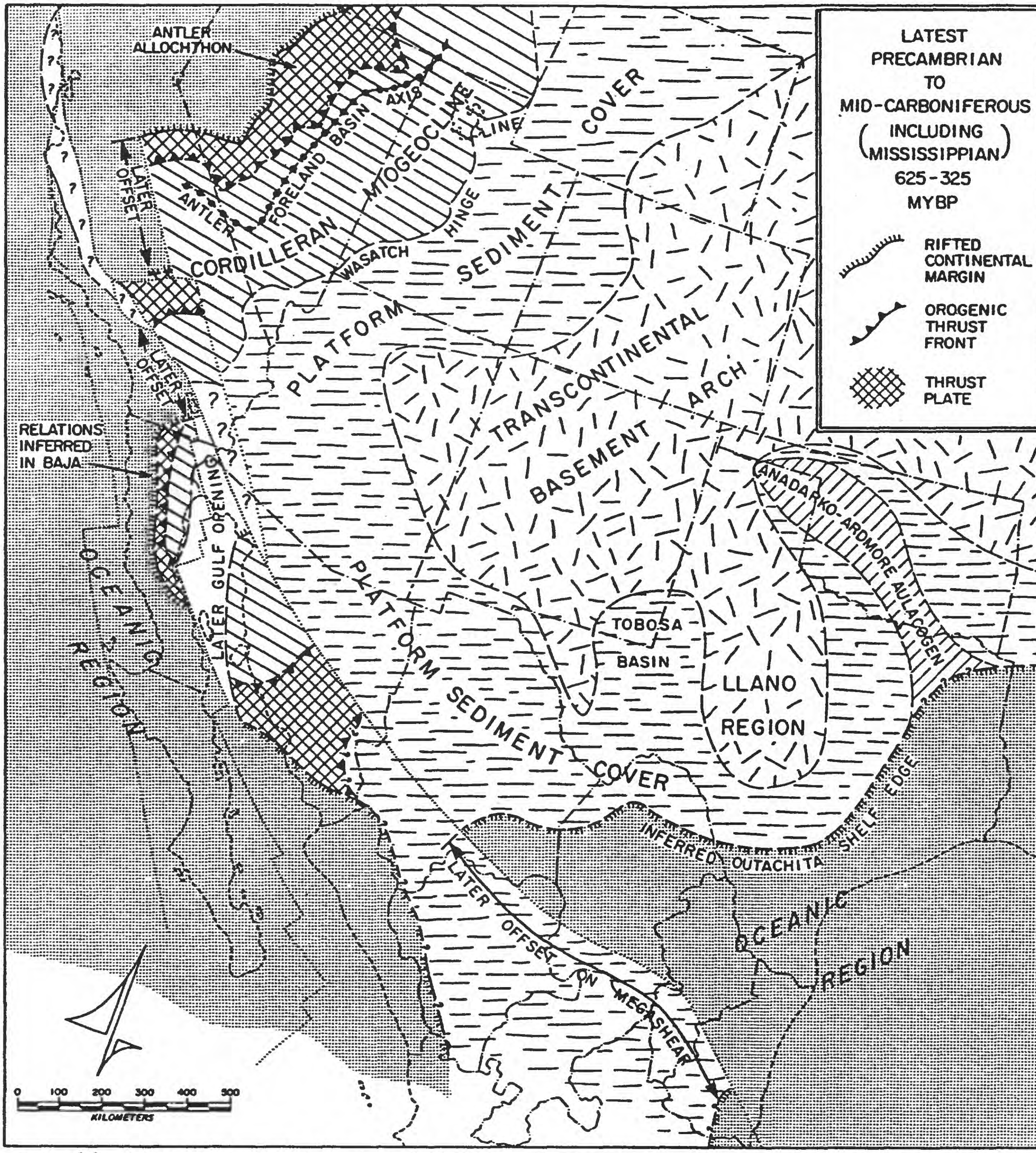


Figure 14 – Paleotectonic map of southern Cordillera, latest Precambrian to mid-Carboniferous (Mississippian-Pennsylvanian boundary) time, 625-325 myBP. Rifted continental margins to northwest and southeast of transcontinental arch of Precambrian basement formed 600-650 myBP in Cordilleran region and 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).

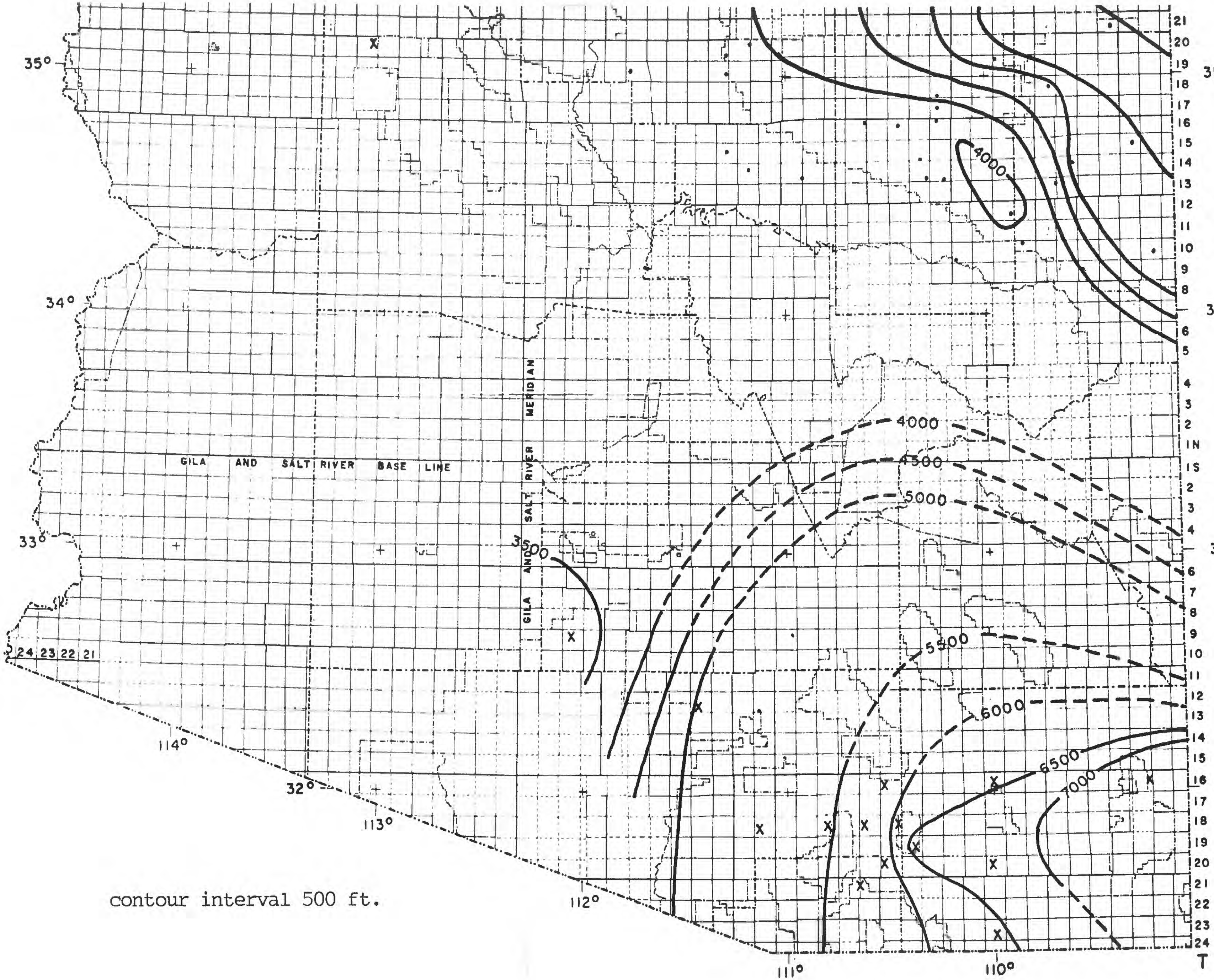


Figure 15--Map showing total Paleozoic isopachs of southern Arizona. (From Peirce and others, 1970).

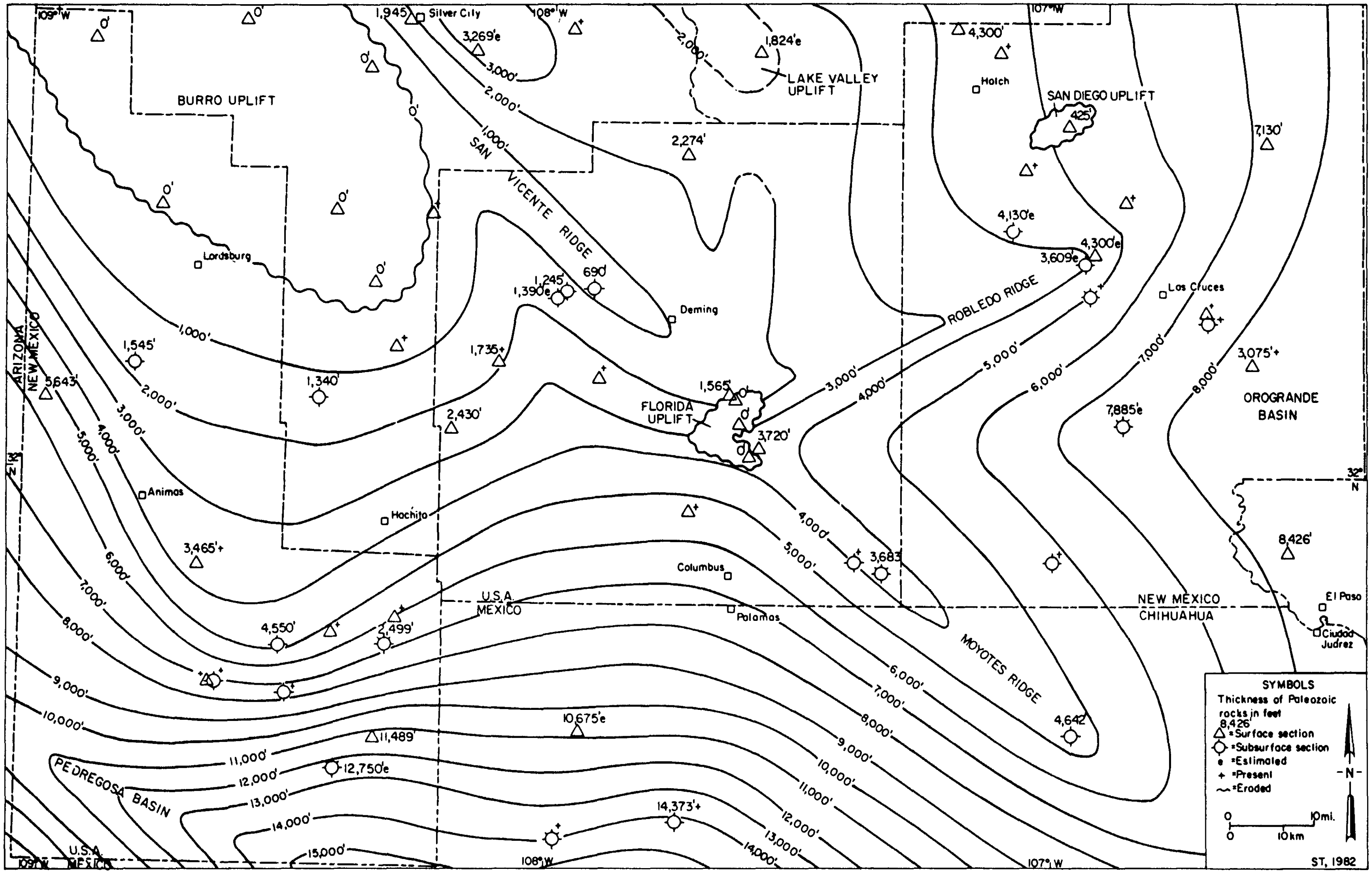


Figure 16--Paleozoic isopach map of southwestern New Mexico. The 1000-foot contour interval is considered small enough to show significant regional features and large enough to smooth over minor local variations and structural complexities. (From Thompson, 1982b).

1979; Ross, 1979a; Kluth and Coney, 1981; Budnik, 1986; Kluth, 1986).

During the Late Permian and Triassic, the Mojave-Sonoran mega-shear was probably beginning to be active in southwestern Arizona. However, Paleozoic strata in the remainder of Arizona were not significantly disturbed by Upper Paleozoic intraplate tectonism (fig. 17) which included mainly uplift, sagging, and minor tilting (Peirce, 1976a). Rapid thinning occurs toward the Burro uplift of northern Hidalgo and west-central Grant counties and the Florida uplift/islands of central to northwestern Luna County (Kottlowski, 1958 and 1962a,b; Elston, 1958). Some bimodal sandstones indicate there may have been several source areas for the Pennsylvanian-Permian clastics, but the predominate area was probably the Defiance-Zuni uplift of northeastern Arizona and west-central New Mexico.

History

Shallow Cambrian seas of the Cordilleran geosyncline invaded southern Arizona from the west. As the seas periodically transgressed and regressed, littoral sands and argillaceous to stromatolitic carbonate muds were deposited in Arizona (Lochman-Balk, 1972). Isolated outcrops (beach sands and offshore bars) of the eastward transgressive Bolsa Quartzite and the Abrigo Formation (mixed carbonates and fine clastics of intertidal to supratidal origin) occur in southeastern Arizona. Together these two formations consist of up to 1,000 ft of medium- to fine-grained siliciclastic sediments, limestone, and sandy limestone and dolomite. These upper Middle Cambrian units unconformably overlie Precambrian crystalline basement. The regressive Bliss Sandstone (100-325 ft thick) is a glauconitic sandstone, quartzite, dolomite, and arkosic conglomerate of Upper Cambrian age. Cambrian rocks are absent in the western half of the assessment area due to erosion.

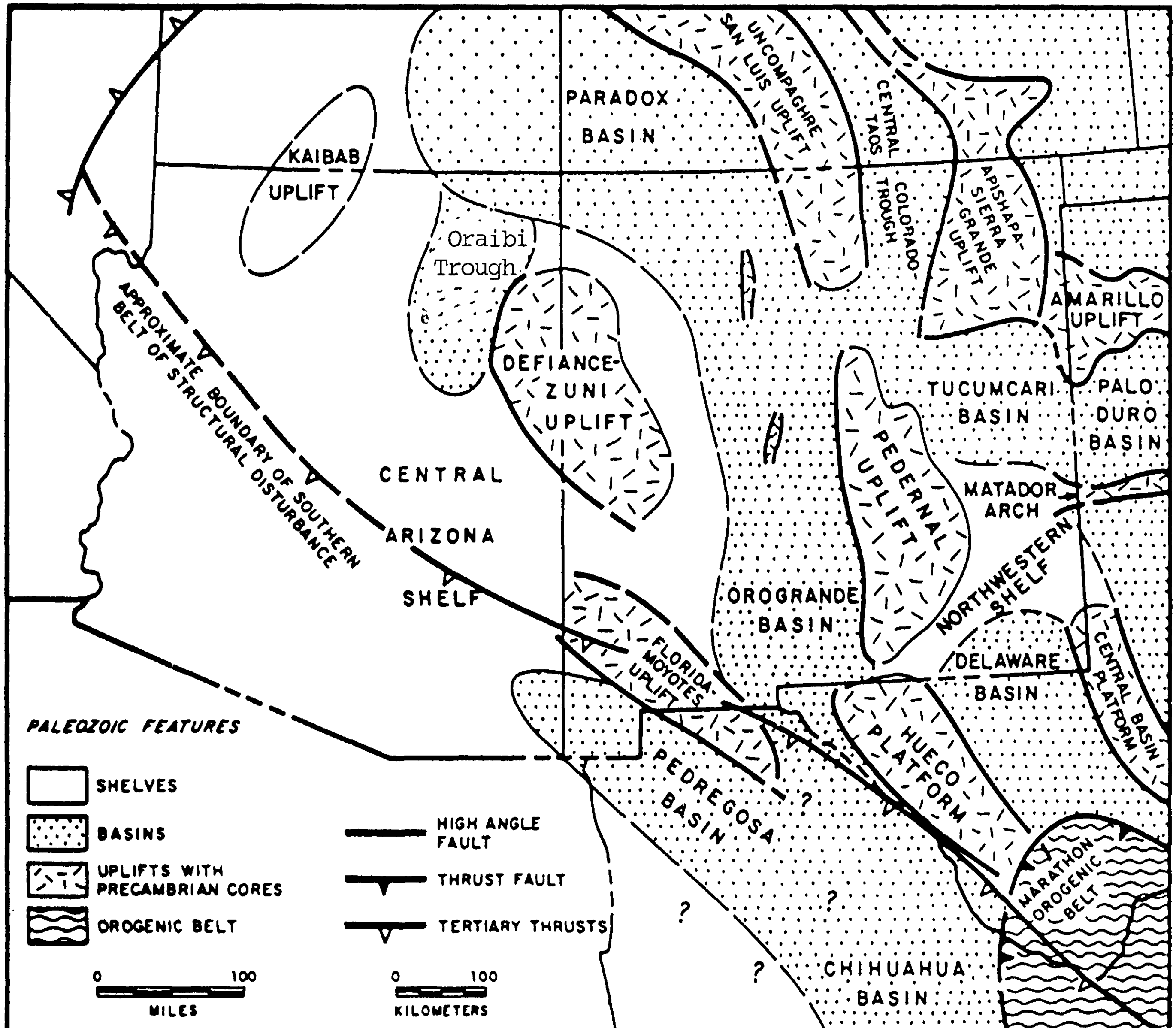


Figure 17--Map showing Paleozoic tectonic features of Arizona and New Mexico and hypothesized Laramide overthrust belt. (From Ross and Ross, 1986).

The Ordovician and Silurian Periods were times of general emergence in Arizona. The El Paso Formation of Late Cambrian to Early Ordovician age is mostly a silty subtidal to intertidal finely-crystalline carbonate about 1,000-1,250 ft thick in Dona Ana County, New Mexico. It thins to 500 ft in southern Hidalgo County, New Mexico, and feathers-out to zero in western Cochise County, Arizona. Unconformably superjacent are 350-400 feet of the Montoya Dolomite, and possibly the Fusselman Dolomite, which together consist of a thin, basal sandstone plus dark, porous dolomite and calcarenite of Late Ordovician and Early Silurian age. From the El Paso to Deming area, the Fusselman is as thick as 1,000 ft (Kottlowski and Pray, 1967).

In the eastern assessment area the Upper Devonian Martin Formation (up to about 400 ft thick) and superjacent Percha Shale (up to 250 ft thick) are separated by a disconformity; they unconformably onlap older strata and consist of dark to variegated mudstone, shaly and silty carbonates, and siltstone (Schumacher and others, 1976). Devonian strata from 100-300 ft thick were probably deposited on the western edge of the Transcontinental Arch (Mazatzal Land) in Yuma County, and from 300-600 ft thick on the southern edge in Pima County (Nydegger, 1982), and about 400 ft in the Pedregosa basin according to Kottlowski's (1971) map (fig. 18).

Mississippian strata, assigned to the Lake Valley Limestone in southern Hildalgo County and the Escabrosa Limestone plus Paradise Formation in Cochise and Hidalgo Counties, are 900 to 1,250 ft thick in New Mexico according to Kottlowski (1970), and 500 to 1,250 ft thick in Arizona (fig. 19) according to Peirce (1979) and Armstrong and others (1980). These shelf strata are primarily subtidal cherty bioclastic carbonates with some shale and black biostromes becoming thin-bedded calcareous clastics, oolitic limestone, sandstone, and shale as seen in the regressive Paradise Formation. Mississippian strata of the Mazatzal Land area in central

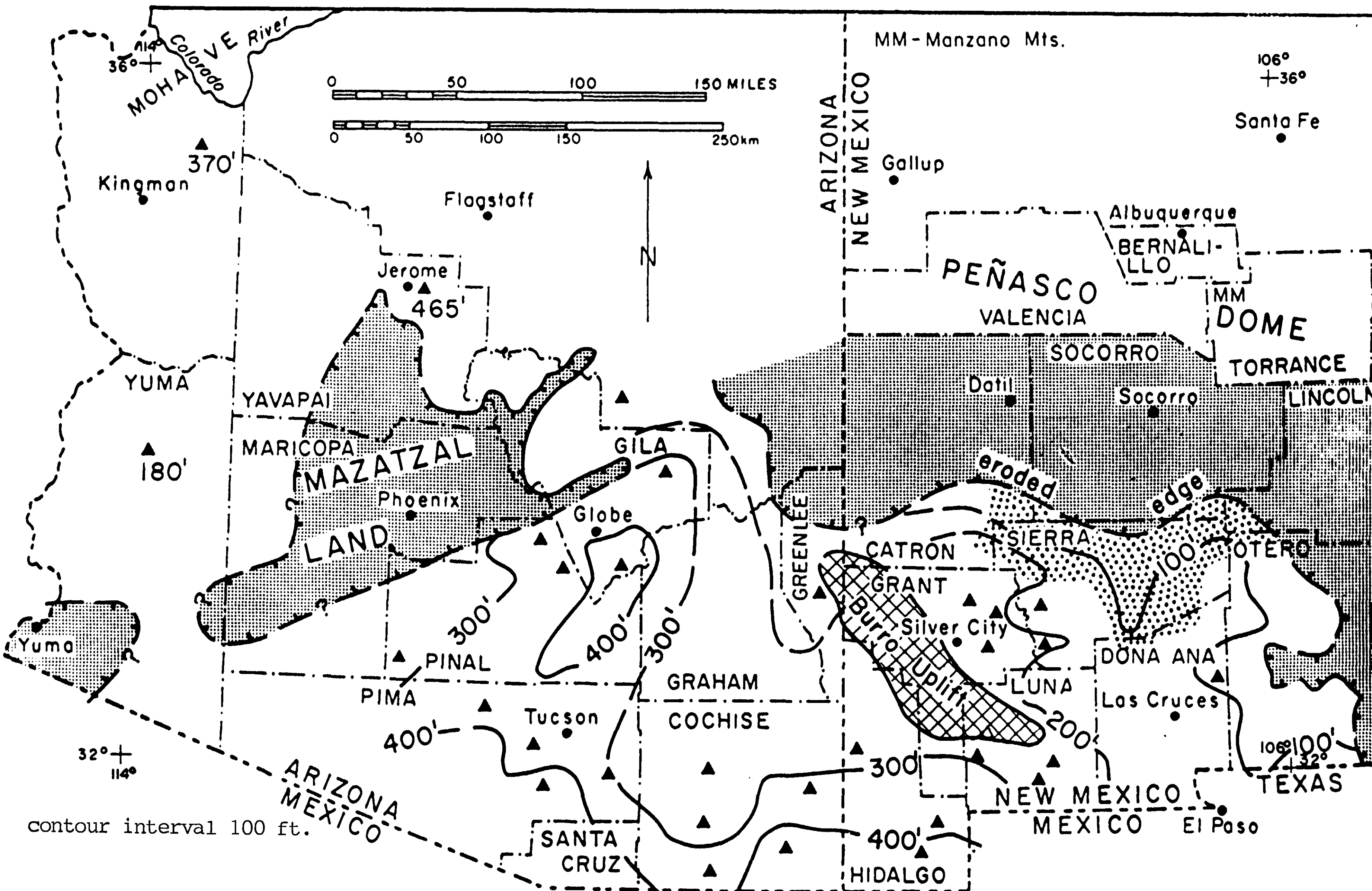


Figure 18-- Isopach map of Devonian strata in southern Arizona and southwest New Mexico. (From Kottlowski, 1971).

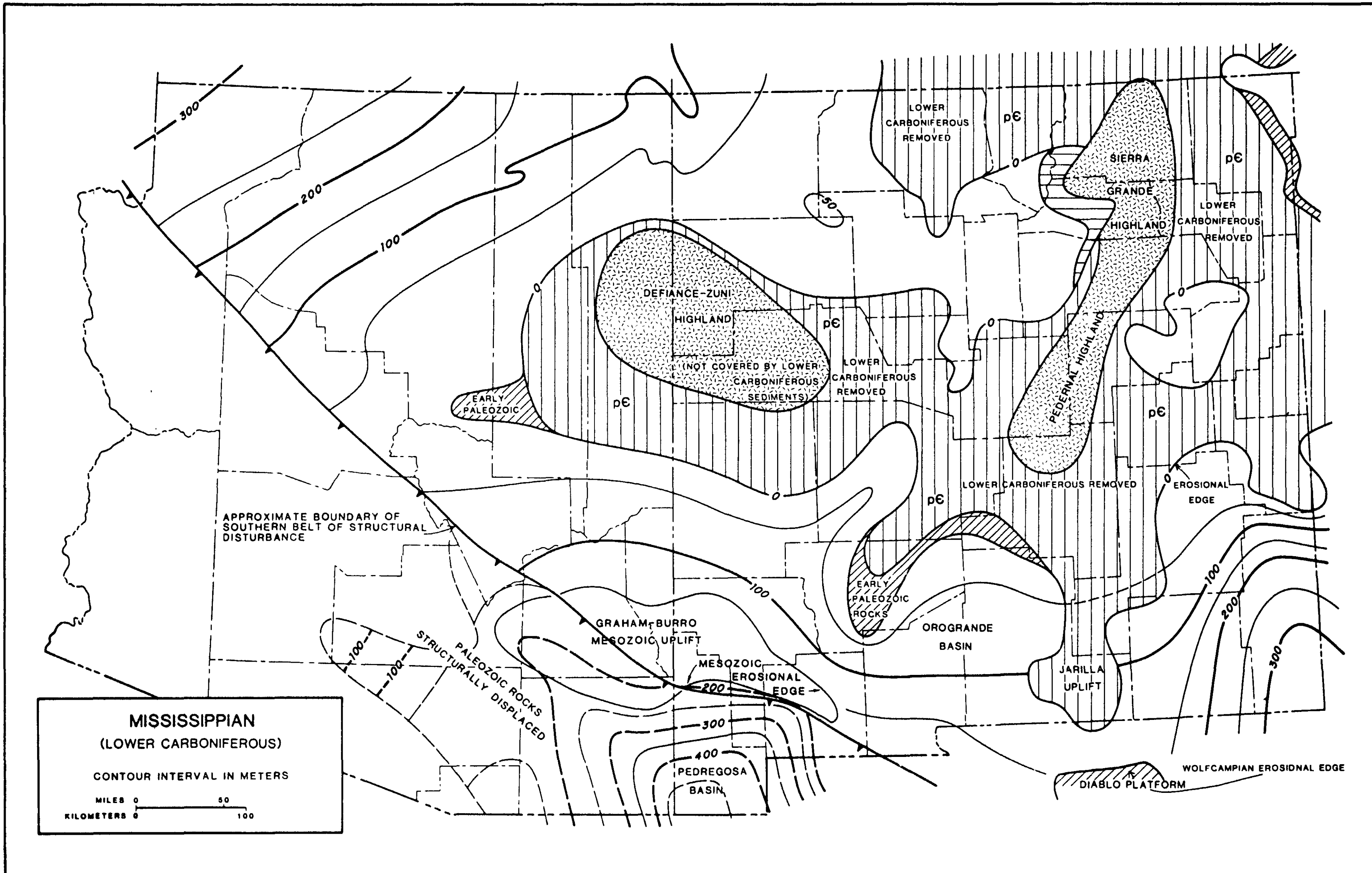


Figure 19--Distribution of Mississippian strata in Arizona and New Mexico. (From Ross and Ross, 1986).

Arizona underwent erosion and karst development due to Late Mississippian uplift. About 30 miles east of the Big Hatchet Mountain area, Moore (1988) identified deeper-water deposits and the shelf edge. Mississippian strata of the Pedregosa basin are unconformably overlain by the Horquilla Limestone of Pennsylvanian and Early Permian age.

In Cochise and Hidalgo Counties the total Pennsylvanian section (fig. 20) is 1,000 to 2,500 ft thick (Kottlowski, 1970; Peirce, 1979; Ross and Ross, 1986) and consists of carbonate, sandstone, and shale. Marked facies changes and unconformites are common. The Horquilla is 2,500-3,500 ft thick, although some stratigraphic descriptions document up to 4,725 ft. Mudstones and limey mudstones of the Horquilla were deposited in the deepest part of the Pedregosa basin (Alamo Hueco basin); up-dip carbonate shelf facies are represented by porous crinoidal calcarenite and dolomite containing bioherms and algal mounds (Wilson, 1977). Occasional calcareous siltstones plus sandstones reflect uplift of the Defiance positive area to the north. Fluvial to supratidal, intertidal, and subtidal deltaic clastics of the Earp Formation were transported into the Pedregosa basin from the northwest (Lodewick, 1970). These mostly-shoreline clastics, with mixed carbonates, grade into mostly carbonate rocks in southeastern Cochise County and intertongue with the upper Horquilla and Hueco formations -- an interval spanning the Pennsylvanian-Permian time line. The clastic ratio of the Earp Formation increases in Hidalgo County where strata are correlated with the interfingering Abo Formation of Early Permian age (Kottlowski, 1970). Red beds of the lower Supai Formation intertongue with the Earp in the Graham County area. Thicknesses of the Earp Formation show a depocenter in northeastern Cochise County (1,600 ft) with thinning to 400-800 ft in eastern Pima County and to about 1,000 ft in the Big Hatchet Mountains.

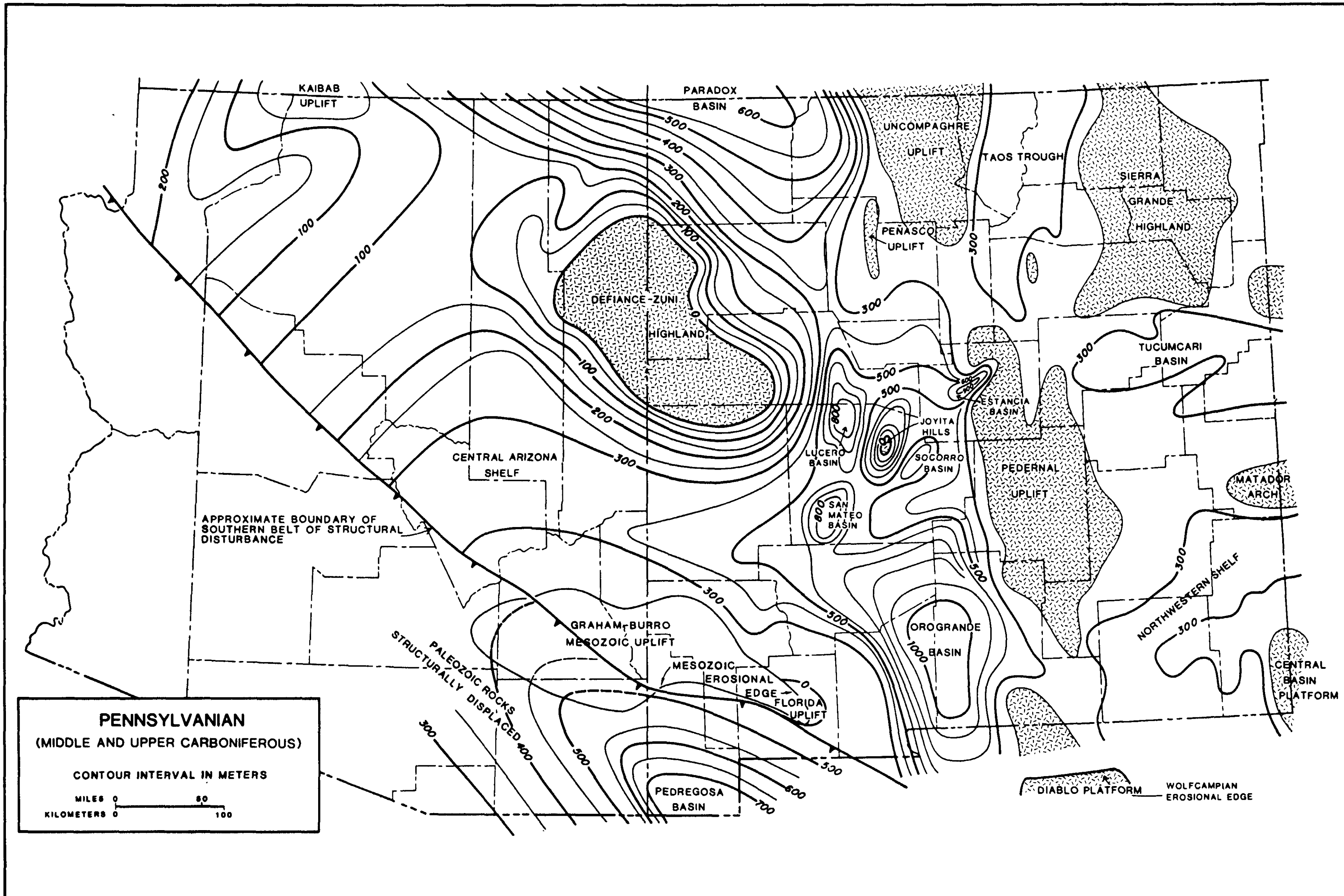


Figure 20--Distribution of Pennsylvanian strata in Arizona and New Mexico. (From Ross and Ross, 1986).

The Naco Group carbonates of central and east-central Arizona are essentially equivalent to the silty bioclastic Black Prince Limestone, Horquilla Limestone, and lower Earp Formation of southeastern Arizona. In southwestern Arizona the Pennsylvanian paleogeography is poorly understood.

In southeastern Arizona five conformable Permian formations (Wolfcampian through Guadalupian age) up to 4,000-4,500 ft thick (fig. 21) conformably overlie the Earp Formation (Butler, 1969 and 1972). The lagoonal to supratidal (sabkha) stromatolitic carbonates, limy mudstones, marls, siltstones, argillaceous and carbonaceous dolomites, and gypsum of the Colina Limestone and Epitaph Dolomite complexly intertongue as facies equivalents, and have a combined thickness of up to 2,000 ft in Cochise County and about 2,500 ft in southeastern Hidalgo County (Butler, 1971). In New Mexico the equivalent of this interval is the Yeso Formation, and in east-central Arizona its equivalent is the middle and upper Supai Formation consisting of red beds, limey clastics, and evaporites. Large lobes of quartz sand splayed southward into the Pedregosa basin where 200-700 ft accumululated as the Scherrer Formation in Cochise County. These cross-bedded sandstones (orthoquartzites) are predominately intertidal and beach deposits and are separated by dolomite beds. Transgressive, open-marine (subtidal), cherty, fossiliferous carbonates of the Concha Limestone were deposited during gradual subsidence of the basin. The superjacent Rainvalley Formation is a mixed carbonate-sandstone lithology of subtidal to intertidal origin. Total thickness of the latter two formations has been reduced by erosion to a maximum of about 800-900 ft. The Glorieta Sandstone and San Andres Limestone of southwestern New Mexico are essentially equivalent to to the Scherrer, Concha, and Rainvalley formations. Regional uplift and erosion began in the middle Permian.

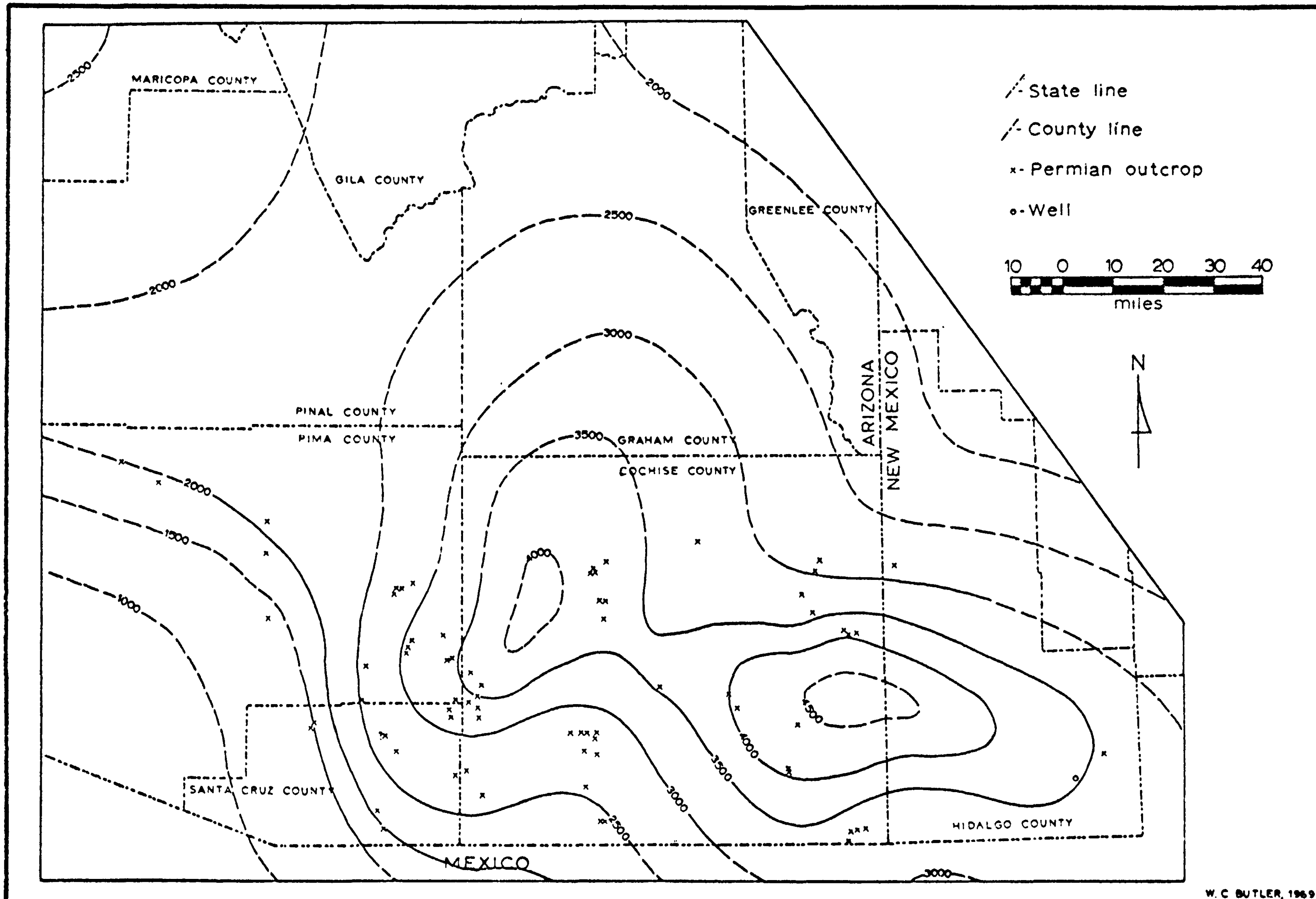


Figure 21--Permian isopach map of the eastern assessment area. Contour interval 500 ft.

MESOZOIC ERA AND EARLY TERTIARY

Triassic sedimentary rocks, deposited in an expansive, unusually-emergent, alluvial-fluvial plain covering nearly all of Arizona, are poorly represented in southeastern Arizona as erosional remnants and isolated outcrops of red bed siltstones. None are known to occur in Hidalgo County (Greenwood and others, 1970). The Triassic-Jurassic interval in Cochise County is marked by strong crustal deformation and plutonism (Gilluly, 1956; Wilson, 1962). A wide variety of pyroclastic volcanic rocks has been documented in southeastern Arizona. Unmetamorphosed Jurassic sedimentary strata are unknown in the assessment area.

In the Little Harquahala Mountains area of west-central Arizona, about 2,500 ft of undifferentiated and intensely deformed Mesozoic clastic rocks and 3,300 ft of volcanic rocks are known (Richard, 1982). The tectonic framework of this area is poorly understood. Harding (1978) has described the Jurassic Livingston Hills Formation of west-central to southwestern Arizona as a sequence of shallow-water to subaerial conglomerates, greywacke sandstones, and mudstones 19,000-20,000 ft thick which were possibly deposited in an intra-arc basin. As much as 24,000 ft of interbedded Jurassic volcanic rocks and mildly metamorphosed clastic strata (including the Livingston Hills Formation) have also been studied in southwestern Arizona and southeastern California (Harding and others, 1983). Deformation of this sequence during the Jurassic occurred between the edge of the North American craton and an outlying allochthonous terrane (Harding and others, 1983).

Figure 22 depicts the Jurassic paleotectonic setting of the southern Cordillera. The present-day central transition zone of Arizona was uplifted during the Jurassic (Mogollon Highlands) and became a major source of clastics which were transported northeastward. South-central to

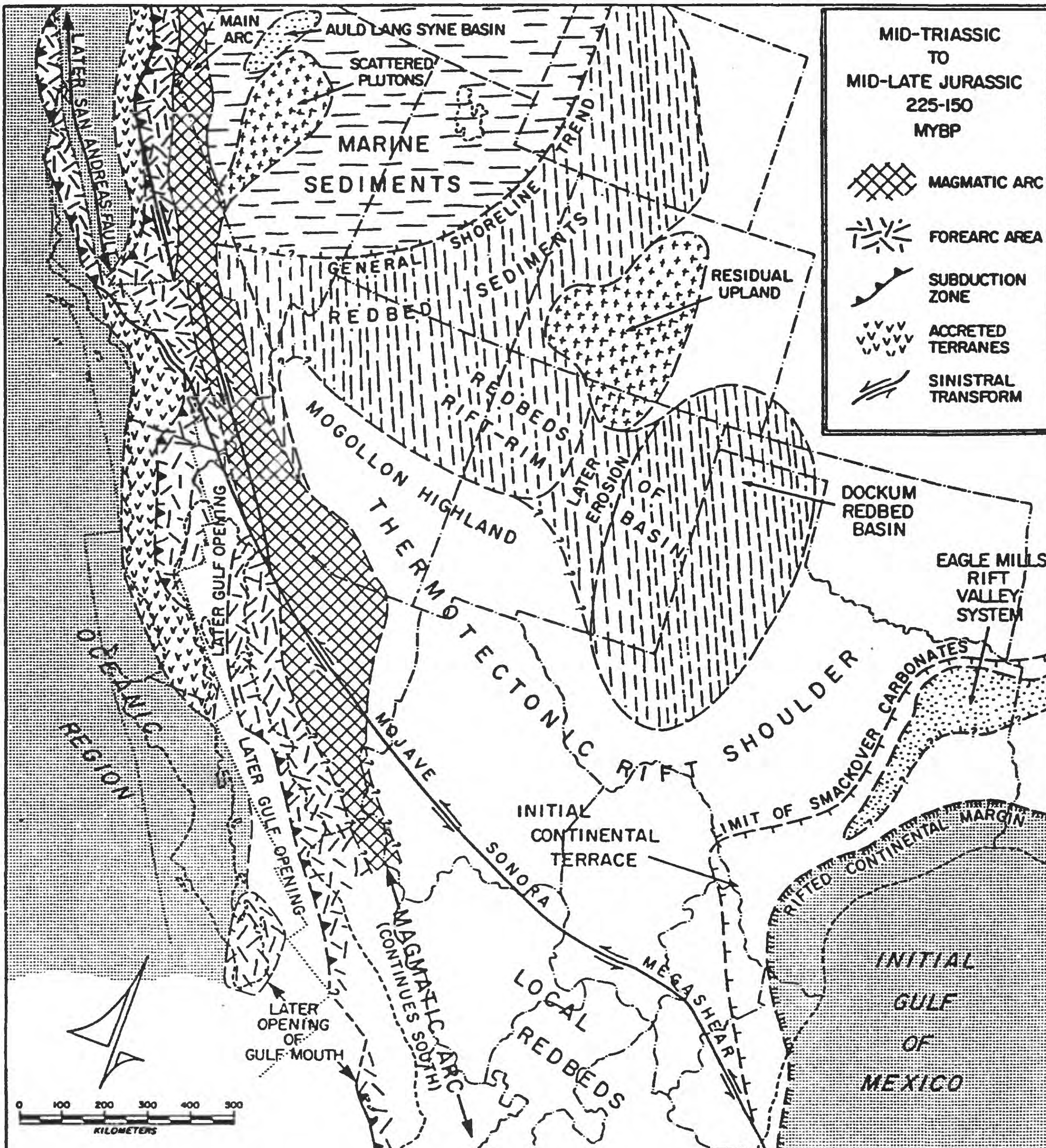


Figure 22 —Paleotectonic map of southern Cordillera, mid-Triassic (end of Middle Triassic) to mid-Late Jurassic time, 225-150 myBP. In Texas, rift-valley clastics overlain by Upper Jurassic carbonates form basal horizons of Gulf Coast sediment prism whose deposition along rifted continental margin was 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).

southwestern Arizona was part of a northwest-trending zone of magmatism (the Maricopa Arch). Continental-scale left-lateral mega-shearing (Mojave-Sonoran megashear), which had formed along the southwestern craton due to convergent plate interaction and subduction (Coney, 1978a; Dickinson, 1981), continued to be active producing major lateral offsets during the Jurassic.

During the Early Cretaceous, magmatic arc volcanism in southwestern Arizona migrated northeasterly, and by Late Cretaceous time had affected half of Arizona west of a diagonal line from the state's southeastern to northwestern corners (fig. 23). Incursion of the sea was from the southeast into southeastern Arizona; thus, the southeastern half of the assessment area became a major depocenter during the Early Cretaceous (fig. 24, 25, and 26). Lower Cretaceous transgressive strata, assigned to the Bisbee Group in southeastern Arizona (fig. 9 and 13), are a thick sequence of up to 15,000 ft of back-arc (? aulocogen) siliciclastics, with interbedded volcaniclastics, a basal limestone breccia, and minor carbonate beds with patch reefs near Bisbee, AZ. Scott and Brinckle (1977), Scott (1979 and 1981), Roybal (1981), and Schreiber (1986) have described these reefs in outcrops. Highly variegated lithologies include a monotonous sequence of alternating marine/non-marine coarse conglomerates, arkoses, greywackes, red beds, siltstones, shales, calcarenites, and black lacustrine limestones. Deposition, initially on a rugged surface and probably in a rift basin, occurred proximally as alluvial fans in or near a coastal plain (Enos, 1983) and distally as a fluvial-marine delta system; the basin deepened to the southeast into the Chihuahua trough (Bilodeau, 1982). The axis of the Early Cretaceous depocenter (Bisbee basin rift) was coincident with the northwest-trending Texas lineament zone.

From oldest to youngest the potentially-productive Bisbee Group

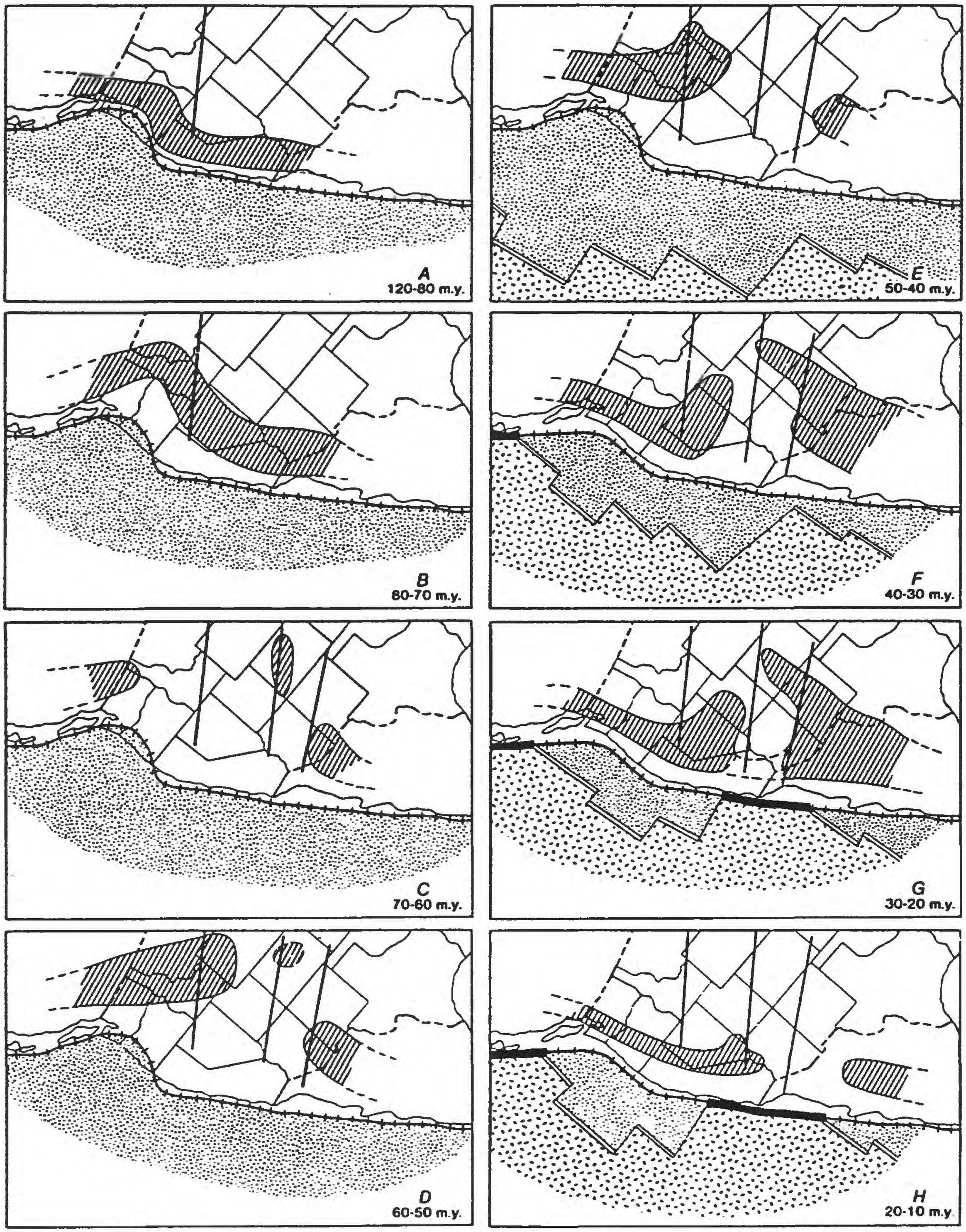


FIGURE 23 – Generalized distribution in the western United States of predominantly andesitic volcanic suites, inferred to be related to subduction. Distributions are based on compilations (Lipman *et al.*, 1972; Snyder *et al.*, 1976; Stewart and Carlson, 1976; Armstrong *et al.*, 1977; Cross and Pilger, 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).

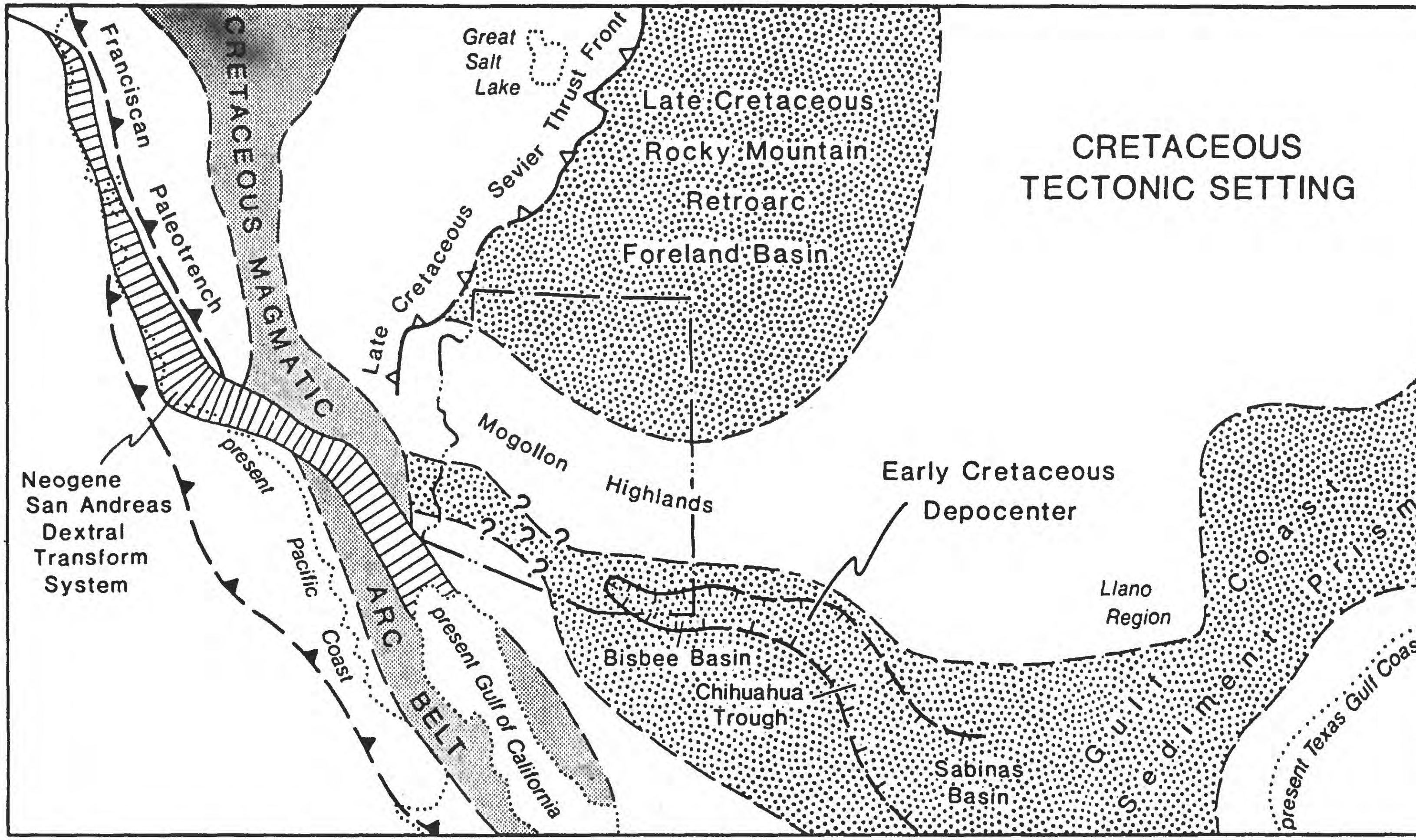


Figure 24--Cretaceous tectonic setting of southwestern United States. (From Dickinson and Klute, 1987).

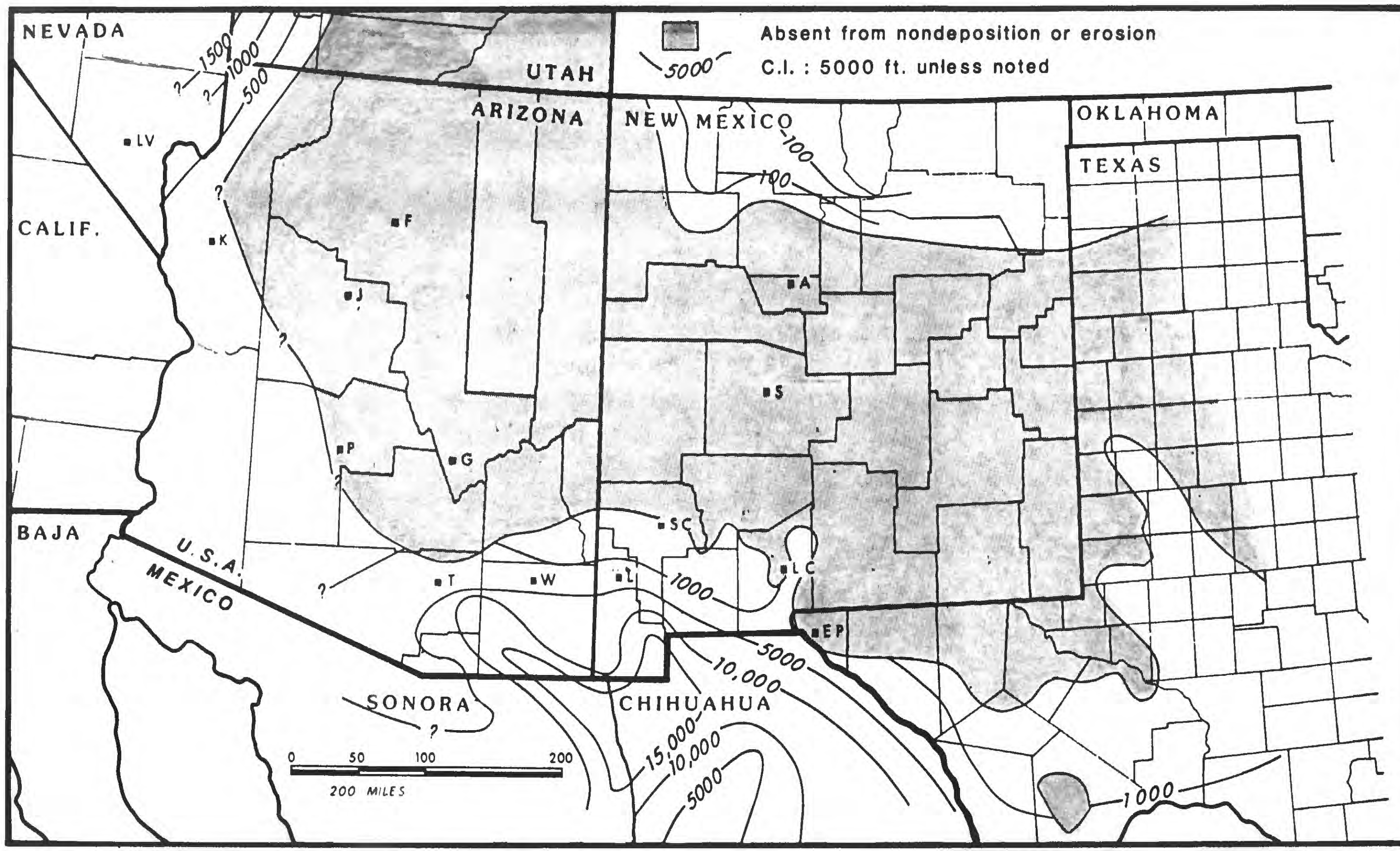


Figure 25--Lower Cretaceous (Bisbee Group) isopach map for southeastern Arizona and southwestern New Mexico. (From Nydegger, 1982).

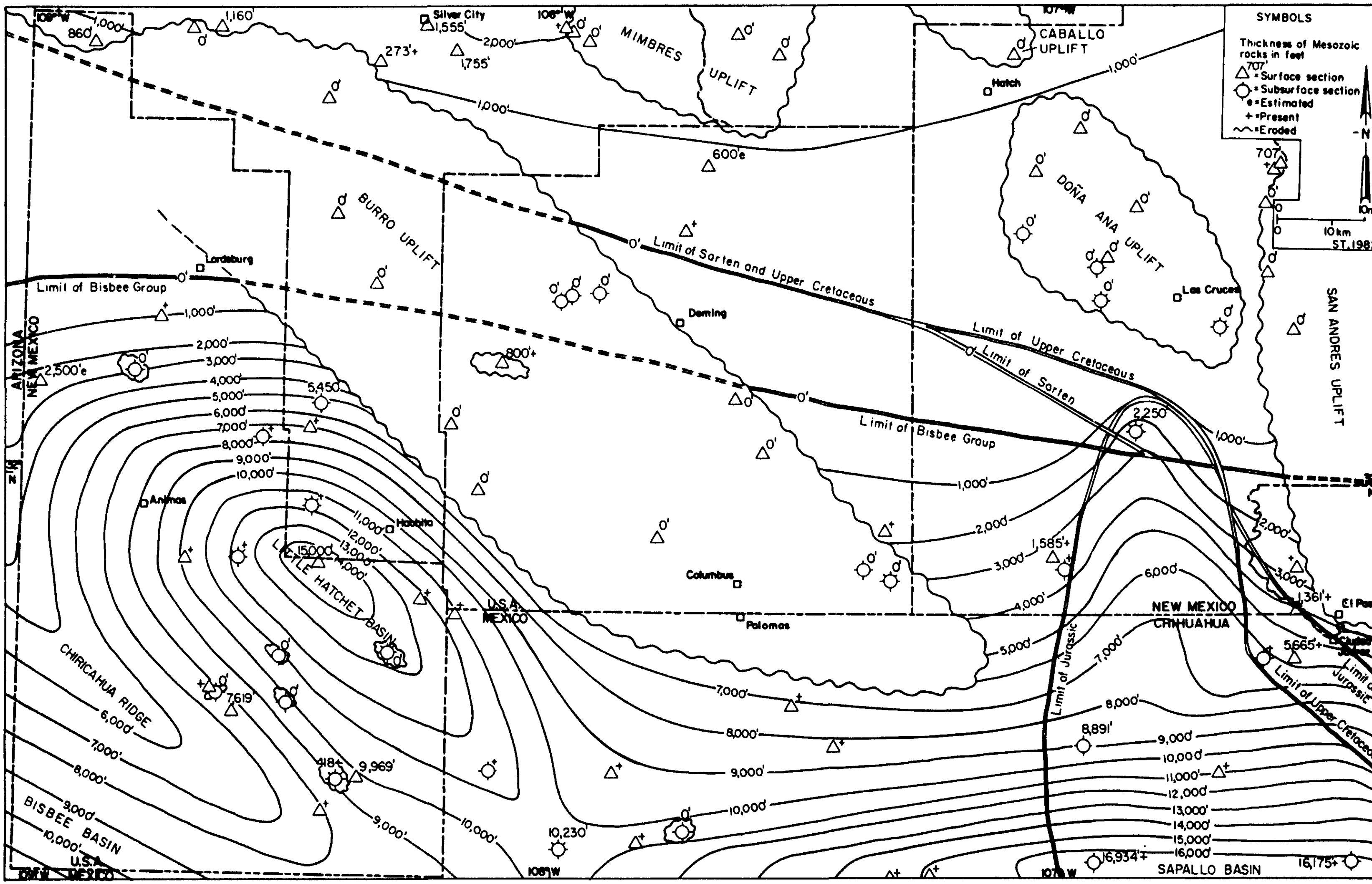


Figure 26-- **Mesozoic isopach map of southwestern New Mexico (includes the total thickness of units between the Laramide and basal Mesozoic unconformities).** (From Thompson, 1982b).

includes these formations: the Glance Conglomerate, Morita Formation, Mural Limestone, and Cintura Formation. Terminology used for Lower Cretaceous formations in the Empire and Whetstone Mountains is: Willow Canyon, Apache Canyon, Shelleburg Canyon, and Turney Ranch (Tyrrell, 1957; Finnell, 1970a). In southwestern New Mexico the Lower Cretaceous units are the Hell-to-Finish, U-Bar, and Mojado formations (Zeller, 1965) commonly 10,000-15,000 ft thick and possibly 20,000 ft thick. See Greenwood and others (1970) for more detailed data on these strata.

Late Cretaceous seas regressed northeastward and southeastward from southeastern Arizona and southwestern New Mexico leaving actively rising and eroding mountains (McGookey, 1972; Cumella, 1983) and the resultant Fort Crittenden Formation. The latter is a non-marine clastic unit nearly 5,500 ft thick occurring locally in the Santa Rita Mountains of Pima and Santa Cruz Counties (Schafroth, 1968); its equivalent in the Empire Mountains is the Hilton Ranch Conglomerate. These two Upper Cretaceous units rest with angular unconformity on Lower Cretaceous rocks. Other Upper Cretaceous formations of southeastern Arizona were deposited near a coastal plain as red beds and arkosic debris from rising and eroding mountains; they include the Pinkard Formation, Amole Arkose, Silverbell and Salero Formations, and various undifferentiated andesites, tuffs, and rhyolites (Hayes and Drewes, 1968; Nations and Stump, 1981). In southwestern Hidalgo County about 7,000 ft of mostly coarse to fine clastics are assigned to the Ringbone Formation of Late Cretaceous and Paleocene age; elswhere in southwestern New Mexico, some of the commonly described Cretaceous units are the Sarten Sandstone, Beartooth Formation, Colorado Shale, and Lobo Formation (Greenwood and others, 1970).

In southwestern Arizona, thrust faulting, magmatism, and clastic rock deposition characterize the major Late Cretaceous geologic events. Uplift during the Paleocene resulted in extensive erosion during the Eocene Epoch. For additional comments on the tectonics of this western area, see the discussion under "Precambrian - General Statement and Overview".

The Laramide Orogeny and Possible Regional Overthrusting

A dramatic change from extensional to northeast-directed compressional stress initiated the Laramide orogeny (Late Cretaceous through Early Eocene) in Arizona and western New Mexico (Woodward and Callender, 1977). Consequently, some Late Paleozoic positive areas, such as the Burro uplift, were rejuvenated. In the assessment area Laramide features and events become younger west to east (Keith and Wilt, 1986) and include local basement-cored uplifts (Davis, 1979; Brown and Clemons, 1983; Seager, 1983), emplacement of plutons and ore bodies, intense folding, left- and right-lateral movement along the Texas lineament, and local thrust faults dipping southwest and northeast. The regional structure, however, as affected by the Laramide orogeny, is enigmatic and controversial to say the least.

Three major schools of thought about Laramide tectonism invoke: 1) overthrusting of several "lobes" and plates of Precambrian, Paleozoic, and Mesozoic terrane about 60 mi or more to the north and northeast and involving the entire southwestern half of Arizona and parts of southwestern New Mexico (fig. 27, 28, 29), 2) eastward-subducting underthrusting (southwestward overthrusting), and 3) gravity sliding (Jones, 1963; Davis, 1979). Subduction models of Coney (1978a), Dickinson (1981), and others serve well to explain the observed tectonic (including local thrust faults), magmatic, and volcanic framework, in time and space in the simplest, most plausible manner. Keith (1978, 1982) has shown that the subduction geometries of the northeastward-subducting Farallon plate beneath southern California and southern Arizona flattened during the Laramide orogeny; steepening of this over-ridden slab during the Oligocene

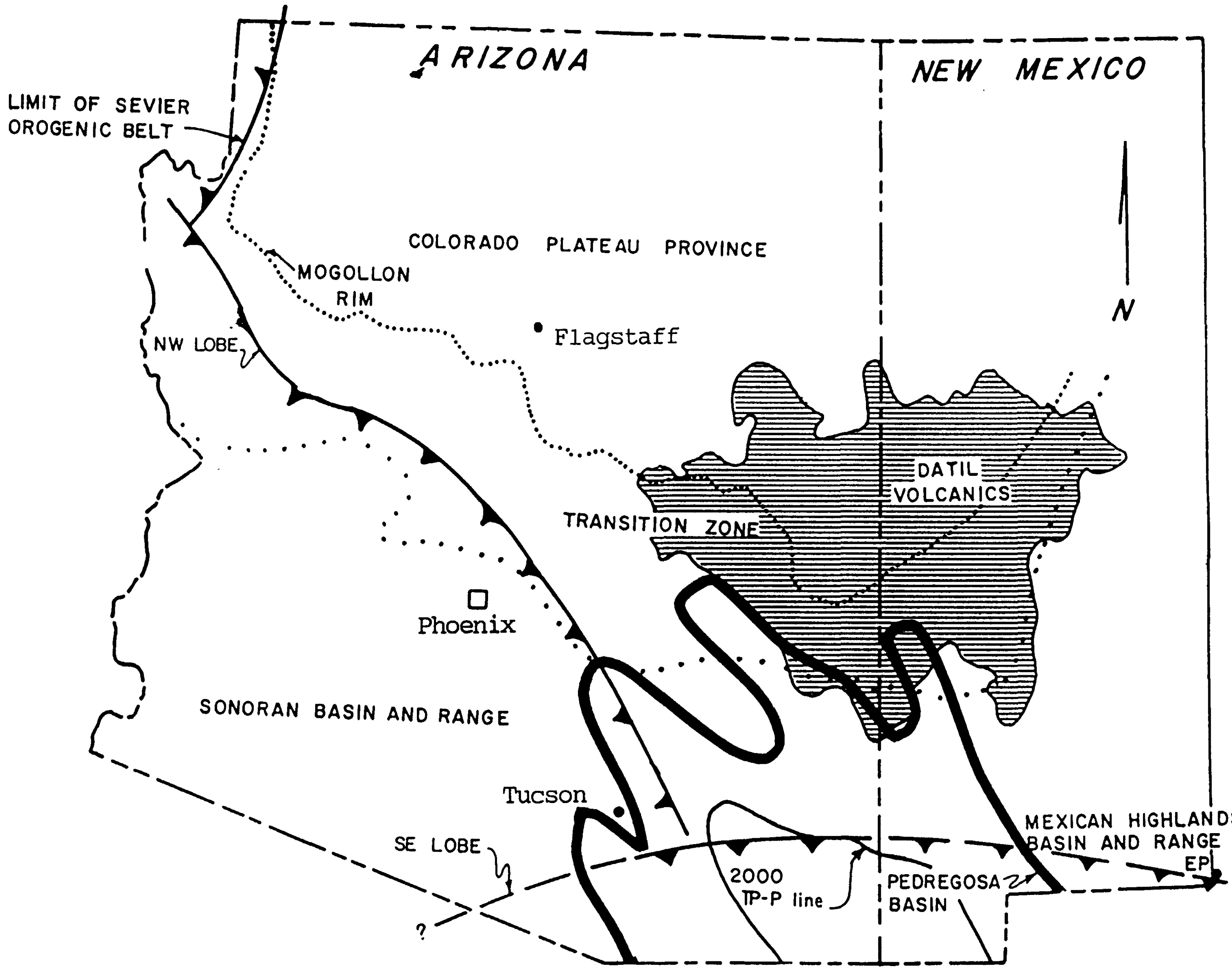


Figure 27--Physiographic and geologic setting of Arizona and western New Mexico. (From Nydegger, 1982).

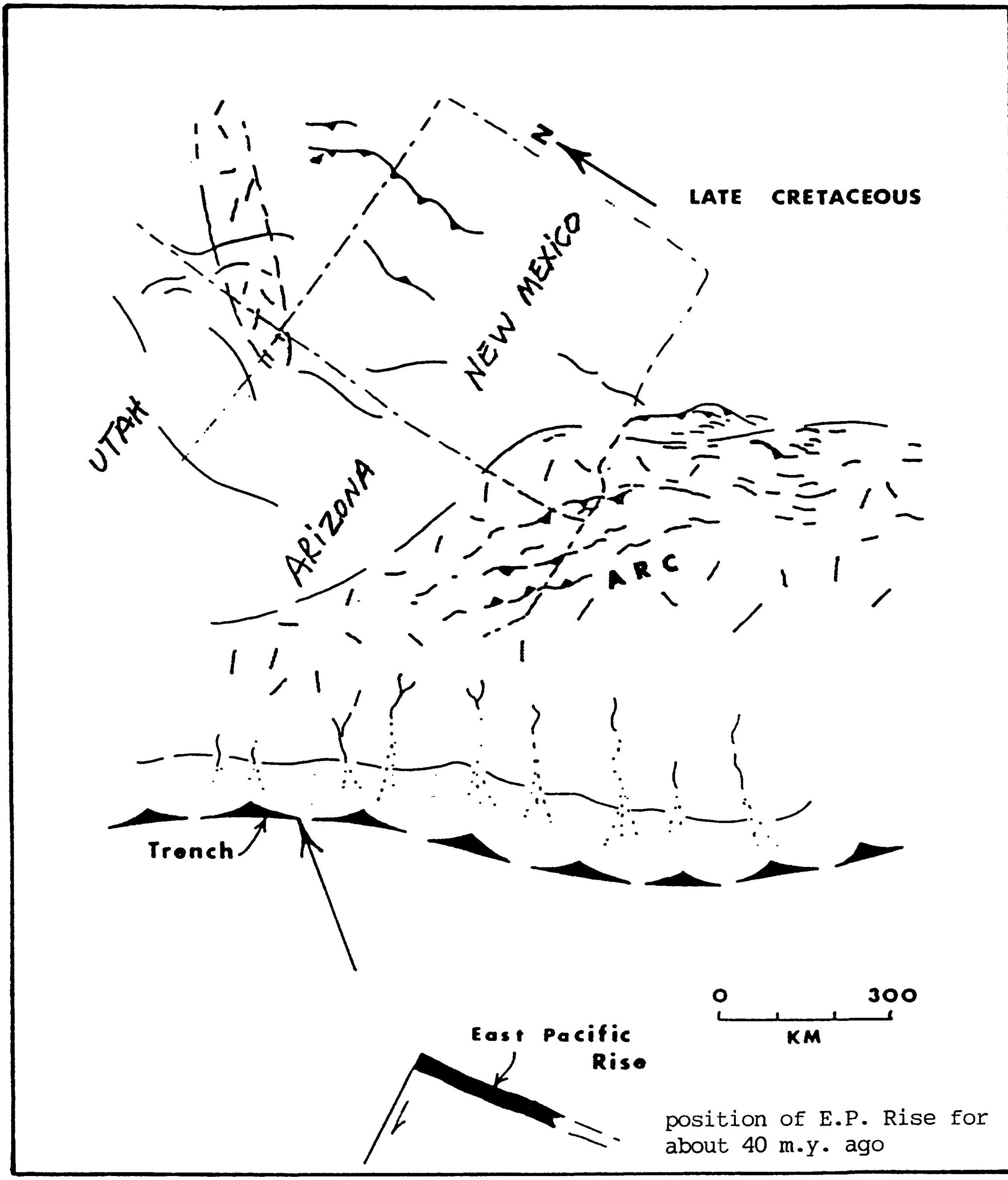


Figure 28--Map showing Late Cretaceous regional tectonic setting of Arizona and western New Mexico. (From Nydegger, 1982).

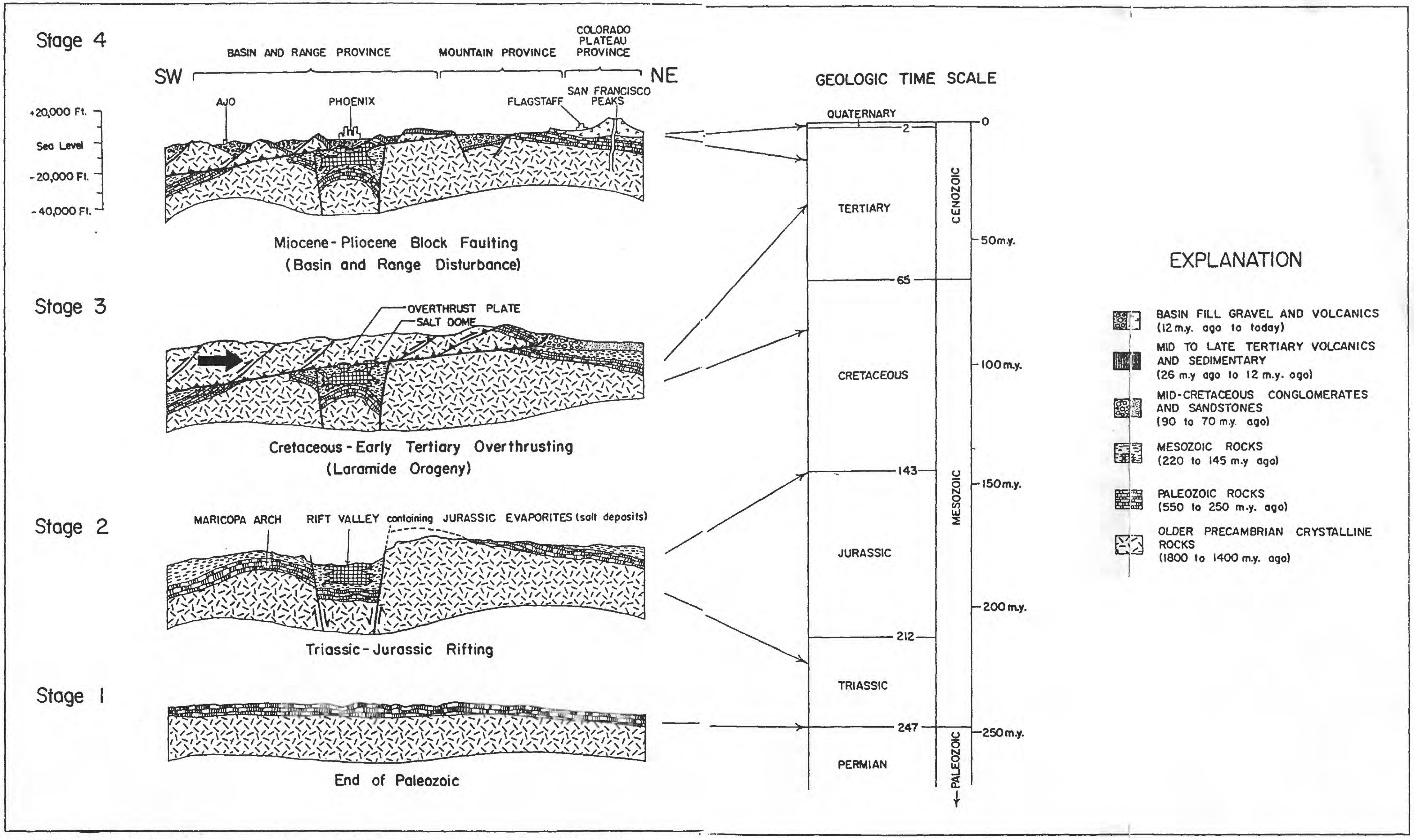


Figure 29--Interpretative cross-sections illustrating regional overthrust concepts in southern Arizona. (From Keith, 1979).

caused the eastward-sweeping volcanism to be reversed in the Mid-Tertiary.

Advocates of a major northwest-trending overthrust belt running either continuously or intermittently from Guatamala to Alaska cutting diagonally through Arizona between the Colorado Plateau and the Basin and Range provinces include: Drewes (1976), Hansen (1976), Woodward and Callender (1977), Drewes (1978, 1981, 1982), Moulton and others (1978), Ross (1979b), Anschutz (1980), Hansen and others (1980a,b), Reynolds and others (1980), Woodward and Duchene (1981, 1982), Moulton (1982), Nydegger (1982), Drewes (1983), Ross and Ross (1986).

If regional overthrusting has occurred in the Pedregosa basin, much paleogeographical data that currently makes sense for Paleozoic systems will need to be re-interpreted. Jones (1963) stated that overthrusting had been over-emphasized due to a failure to discriminate thrusts from gravity slide blocks. Some faults, mapped as major thrusts by the regional-overthrust advocates, have subsequently been reinterpreted as low-angle normal faults and thus, "cast doubt on the concept that coherent subhorizontal thrust sheets of Laramide age actually exist in southern Arizona" (Dickinson, 1984). In regard to Laramide tectonics of southwestern New Mexico, Seager and Mack (1986) concluded both northeast compression and wrench faulting produced transpressional thrusts, and the overall deformation of the area was not due to regional overthrusting.

In order to test the overthrust hypothesis in Pinal County, a 18,013-foot well (No. 1-A State) was drilled in 1980-81 by Anschutz Corp. and Phillips Petroleum. Location of the site near Florence, AZ. (fig. 4, Sec. 2, T7S, R10E) was based on seismic cross-sections (Keith, 1980). Dry and abandoned, the borehole encountered a metamorphic core complex (Robinson and Reif, 1981) which proved to be an inconclusive if not a negative overthrust test (Reif and Robinson, 1981; Nations and others, 1983). The seismic reflectors were probably layered gneisses. Subsequently, six other boreholes were drilled as stratigraphic tests by Phillips Petroleum in the Basin and Range province of southern Arizona; depths ranged from about 4,000 to 9,000 ft. Five of the six boreholes did not encounter "the great southwestern Arizona overthrust", and the sixth near Tombstone may have drilled through a thrust sheet of unknown magnitude. None of this drilling penetrated Paleozoic strata.

CENOZOIC ERA (POST-LARAMIDE)

General Statement and Overview

In brief, following the Laramide events of the assessment province, the Eocene was a time of widespread erosion (Dickinson, 1986) and of tectonic quiescence. Depositionally, fluvial-alluvial fans and other coarse continental sediments (gravels) accumulated in local downwarps. During the late Paleogene, Neogene, and Quaternary, regional uplift, crustal extension and collapse, and erosional dissection predominated. Thick continental sediments, including lake beds, with intercalated volcanic rocks accumulated locally. Surficial Quaternary basalts are common in the assessment province. A total of about 5,000-6,000 ft of regional uplift occurred during the Cenozoic Era. Jones (1963), however, calculated that uplift may have exceeded 20,000 ft.

History

The Oligocene Epoch is characterized by extensive calc-alkaline volcanism in the present-day Great Basin Province (fig. 23). West of Arizona, transcurrent right-lateral movement began along the ancestral San Andreas transform fault (Atwater, 1970; Atwater and Molnar, 1973; Stewart, 1978), thereby accomodating convergent motion between the Pacific and North American plates. Subduction and accompanying arc magmatism beneath Arizona ceased 10-20 m.y.a. (Miocene) due to this transform faulting; as a result, thermal upwelling in the no-slab (subducted plate) area may have contributed to uplift with fragmentation and development of the Basin and Range Province.

Crustal tension, leading to development of the Cordilleran metamorphic core complexes in southern Arizona (fig. 30), is also an early to middle Tertiary phenomenon (Coney, 1979; Davis and Coney, 1979; Banks, 1980; Crittenden and others, 1980; Davis, G.H., 1980; Rehrig and Reynolds, 1980; Rehrig, 1982 and 1986; Davis, 1983). These cores, or tectonically denuded domes, or mid-crust lenses with cataclastic carapaces (Hamilton, 1981a), are found where extensive stretching or doming and gravity sliding, flowage, and metamorphism of the basement has occurred akin to mega-boudinage (Davis and Coney, 1979). The Paleozoic and Mesozoic cover is separated from the basement by a decollement zone and undergoes ductile growth faulting (low-angle, listric, normal type) during core evolution. Keith and Wilt (1986), on the other hand, have suggested that these complexes are really "pseudo-cores" representing fensters showing parts of a regional crystalline plate, "deformed, plutonized, and tectonized by thrust faulting in the latest Laramide." An accurate assessment of the tectonic development of core complexes is cogent to the localization, or non-localization, of oil and gas in the Pedregosa basin of the Texas lineament zone.

Generally speaking, regional tensional forces, possibly beginning during the late Oligocene or early Miocene, resulted in block-faulting. Similarly, low-angle, normal, detachment faulting characterizes the Miocene to Holocene (Lucchitta and Suneson, 1979, 1981; Davis, G.A., 1980; Davis and others, 1980; Davis and Hardy, 1981; Wernicke, 1981; Frost and Martin, 1982; Garner and others, 1982; Mueller and others, 1982; Pridmore and Craig, 1982). Accordingly, the Basin and Range physiographic province came into being through back-arc spreading, and has continued at

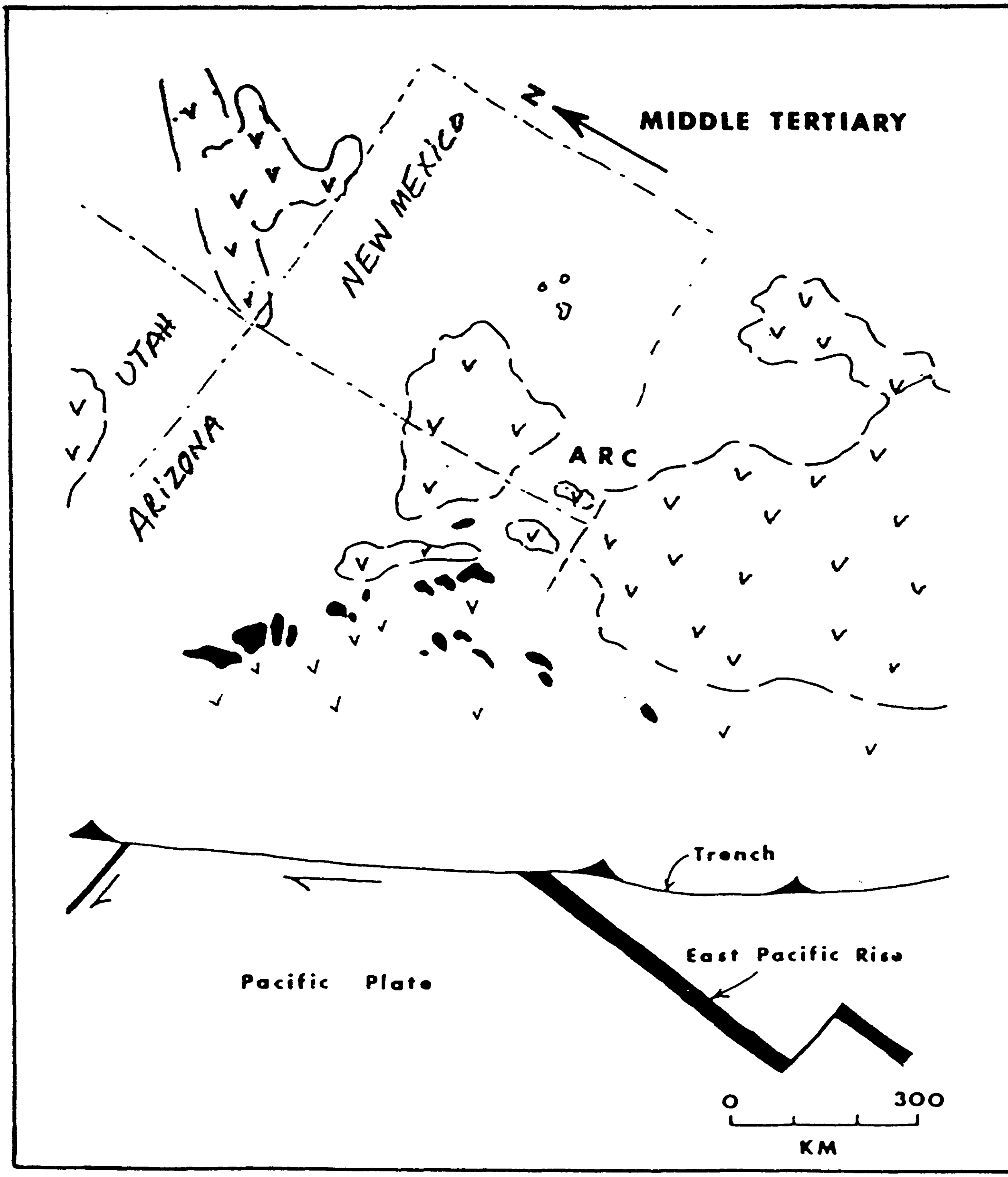


Fig. 30-- Middle Tertiary-Major features of middle Tertiary magmatism and development of metamorphic core complexes. Larger caldera complexes outlined by V-stipple pattern. Location of presently identified domal uplifts of Tertiary cataclastic gneiss in core complexes shown by solid black. Position of East Pacific Rise approximately 20 m.y. ago. (From Nydegger, 1982).

least into the Pleistocene. Existing structures were thus overprinted with these faults plus the deformation associated with rotated crustal blocks. Cumulative stratigraphic displacements on Basin-and-Range normal faults may exceed 11,000 ft. They may possibly be 20,000 ft or even 30,000 ft according to Scarborough and Peirce (1978). The structural valleys show major longitudinal ridges on seismic cross-sections and are more than simple grabens.

During the Oligocene-Miocene, eroding horsts began filling the grabens, or half grabens, with thick alluvial fans of sands and gravels (e.g. the Helmet and Locomotive fanglomerates) and other fluvial and lacustrine sediments (Heindl, 1952; Feth, 1964; Pederson and Royse, 1970; McDonald, 1976). This basin-fill is interbedded with volcanic flows and ash-falls (Blackwell, 1978; Stewart and Carlson, 1978; Luedke and Smith, 1978). In some shallow saline lakes of south-central Arizona (Picacho and Luke salt domes), unusually thick deposits (an estimated 6,000 to 10,000 ft, respectively) of evaporites accumulated (Scarborough and Peirce, 1978; Peirce, 1980). The origin and age of these salt masses are problematic. Although a hypothesis advanced by Hansen (1976), and related to regional overthrusting, suggested the salt is Jurassic of marine origin, the salt is most likely Miocene in age as noted by Eberly and Stanley (1978).

In the north-central assessment area, the nonmarine Verde Formation consists of over 3,000 ft of shale, clay, limestone, evaporites, and volcaniclastics. It is an extensive Miocene to Pliocene (Amer. Assoc. Petrol. Geol., 1983) lacustrine unit that crops out in several valleys of central Arizona (Nations, 1974; Nations and others, 1981). Similar units may be present in the subsurface to the south and have oil and gas potential. Other nonmarine Cenozoic formations of the assessment area, each several thousands of feet thick, have been described by Wilson (1962) and Nations and Stump (1981), and are noted in the TERTIARY BASINS PLAYS section.

In the western-most assessment area, marine and estuarine limestone and fine clastics of Miocene and Pliocene age were deposited in downwarps as seas encroached into the ancestral northern Gulf of California (Mattick and others, 1973; Olmstead and others, 1973; Eberly and Stanley, 1978; Blair and others, 1979; Lucchitta, 1979). This area is the present-day lower Colorado River drainage of southwestern to northwestern Arizona. Miocene magmatism, volcanism, and structural unrest was extensive (Lucchitta, 1979). Block-fault basins formed and were also filled with fluvial and lacustrine sediments. The Pliocene Bouse Formation (fig. 8) is mostly silt and clay 950-2,165 ft thick. It rests on interbedded fine clastics of marine origin and volcanics of Miocene age and on subaerial, basin-fill fanglomerates. Late Pliocene uplift was followed by subsidence in the Yuma area, presumedly due to rifting related to the San Andreas-Salton Sea trough fault system (Lucchitta, 1979).

GEOPHYSICAL STUDIES

An integrated synthesis of gravity, magnetic, magnetotelluric, and other geophysical studies is beyond the scope of this report. However, because of their importance to the understanding of such a complex region, the reader is encouraged to consult these references selected for their general treatment: Sauk and Sumner, 1971; Sumner, 1972; Vozoff, 1972; Mattick and others, 1973; West and Sumner, 1973; Thompson and Burke, 1974; Sumner, 1975; Aiken, 1976 and 1978; Sumner and others, 1976; U.S. Geol. Survey, 1977; Aiken and others, 1978; Eaton, 1979a, 1980, 1982; Lysonski and others, 1980; Aiken and Ander, 1981a; Hildenbrand and others, 1982; Klein, 1982; Lance and others, 1982; Zietz, 1982; Keller and Cordell, 1983; Keller and others, 1984; Jachens and others, 1985; Mayer, 1986; Simpson and others, 1986; DeAngelo and Keller, 1988.

PETROLEUM PLAY IDENTIFICATION

PEDREGOSA BASIN PLAYS

Big and Little Hatchet Mountains Area, Southwest New Mexico

Some geologists who have recognized a highly favorable oil and gas setting of this area, including northern Chihuahua, Mexico, are Kottlowski (1959, 1962b, 1965a), Wengerd (1962, 1969, 1970), Diaz and Navarro (1969), Greenwood (1970a), Zeller (1970c), Thompson (1976, 1980, 1981a,b, 1982a,b), Greenwood and others (1977), Thompson and others (1978), Thompson and Jacka (1981), and Nydegger (1982). Foster and Grant (1974) and Kottlowski (1977) included the area as one of the highest petroleum-potential areas (fig. 31) in New Mexico outside of the highly productive San Juan and Delaware basins. Information about source and reservoir rocks of this play has been drawn heavily from Thompson and others (1978) and Thompson (1982b).

The Alamo Hueco basin (fig. 32), i.e. inner part of the Pedregosa basin, may contain up to 15,000 feet of Paleozoic strata. Based on paleogeographic reconstruction, the play is upslope from a deep Pennsylvanian basin where oil and associated gas were presumably generated and subsequently expelled into porous carbonate rocks at the basin margin (Thompson and Jacka, 1981). Figure 32 shows the approximate shelf-basin facies break. The best targets include Pennsylvanian strata (Thompson and others, 1978) which are 2,000-2,500 feet thick (Kottlowski, 1962a; Ross and Ross, 1986) and Lower Permian strata which are 4,000-5,500 feet thick. A composite section of Lower Cretaceous strata may be from 10,000 to 15,000 feet thick of predominately deltaic mudstones and arkosic sandstones. About 2,500 feet of ash flow tuffs, thin basaltic andesites of Miocene age, and up to 2,000 feet of younger fanglomerates are common rocks covering portions of the play.

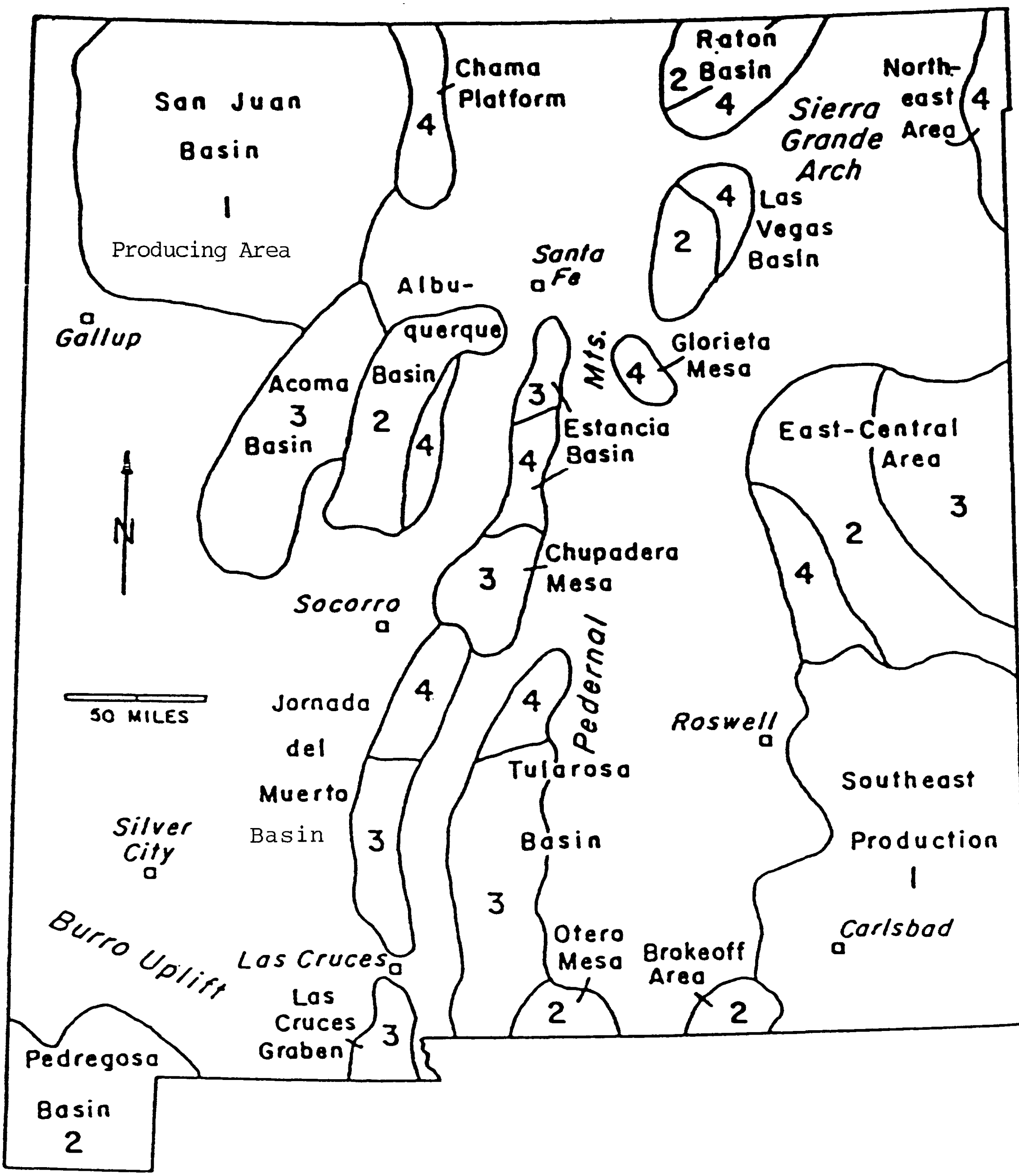


Figure 31--Petroleum potential map of New Mexico. Areas of #1 are petroleum provinces and areas #2-4 have exploration potential with #2 being highest. (From Kottlowski, 1977).

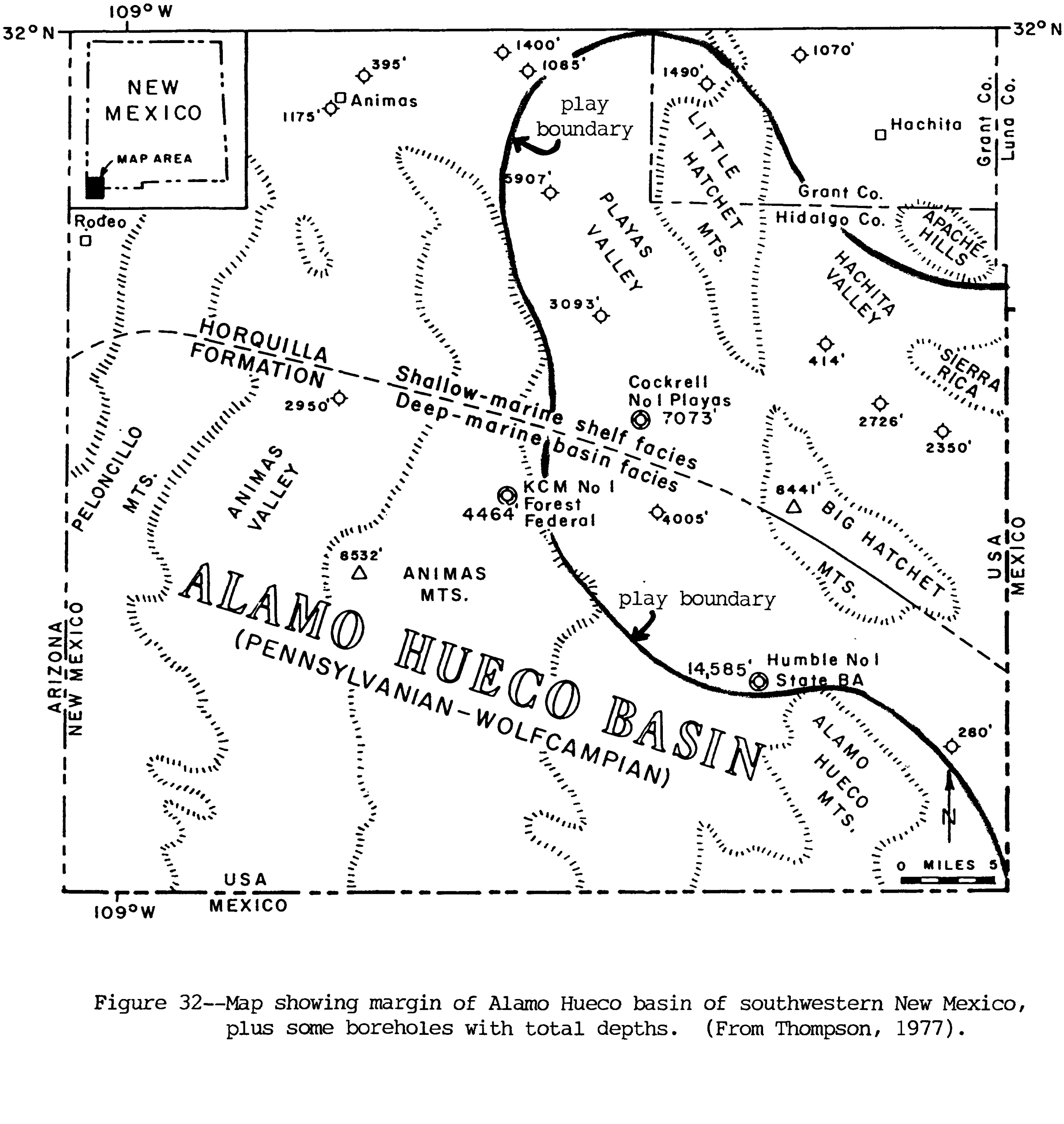


Figure 32--Map showing margin of Alamo Hueco basin of southwestern New Mexico, plus some boreholes with total depths. (From Thompson, 1977).

Location, Size, and Land Status

The play, about 570 mi^2 in size, is in the southern Basin and Range physiographic province of southwestern New Mexico. Eighty-seven to 88 percent of the area is in southeastern Hidalgo County with the remainder in extreme southern Grant County. Most of the play area encompasses the Little Hatchet and Big Hatchet Mountains plus the Hachita Valley and Playas Valley (fig. 2 and 32). Land status includes 57 percent Bureau of Land Management, 30 percent private, and 13 percent state owned.

Potential Source Rocks and Geothermal Maturity

The most promising source beds are black, 2,500-3,500-foot thick shales, mudstones, and reef carbonates of the Pennsylvanian Horquilla Limestone (fig. 9, 10, 11 plus table 1). The basinal mudstones probably have sufficient TOC (total organic carbon) of type II kerogen to provide economic accumulations of petroleum. Other less important potential source beds include: 1) Ordovician carbonates of the El Paso Group (Hayes, 1975); 2) dark mudstones of the Devonian Percha Shale (TOC of 0.7 percent); 3) Mississippian shale and carbonates (Thompson, 1982b); and, 4) black Lower Cretaceous algal limestone associated with reefs.

The thermal maturity of Paleozoic outcrops in the area ranges from about 0.6 to 1.8 percent R_o, generally increasing southeastwardly (Butler, 1988a). Oil, associated gas, condensate, and dry gas are the types of hydrocarbons expected to be generated and preserved in Upper Paleozoic strata. Although both oil and gas shows have been found in all parts of the geologic section, the effects of migration in a structurally complex area are unknown. Kerogen types being equal, the Lower Paleozoic strata, having a history of deeper burial, probably have generated more thermal or dry gas, as evidenced by their numerous shows.

The Lightning Dock known geothermal resource area (KGRA) is about 10

Table 1--Stratigraphic units of southwestern New Mexico with their depositional environments and petroleum potential. (From Thompson, 1982b).

Chronostratigraphic units		Pedregosa basin Hidalgo-Grant Counties	Burro uplift Luna County	Orogrande basin Doña Ana County	Main rock type	Depositional environment	Petroleum evaluation source	Petroleum evaluation reservoir
Quaternary		--------bolson, fluvial, and other deposits--------			sand	nonmarine	none	poor
Quaternary-Upper Tertiary		Gila	Gila	Santa Fe	conglomerate	nonmarine	none	fair
Middle Tertiary		--------volcanic and local intrusive rocks--------			rhyolite, etc.	nonmarine	none	none
Lower Tertiary-Uppermost Cretaceous		Hidalgo	Rubio Peak	Palm Park	andesite, etc.	nonmarine	none	none
		Ringbone	Lobo	Love Ranch	cgl., redbeds	nonmarine	none	poor
		absent	absent	unnamed	sandst.,mudst.	nonmarine	poor	poor
--------Laramide unconformity--------								
Upper Cretaceous		absent	upper Colorado	absent	sandst.,mudst.	nonmarine	poor	poor
		absent	lower Colorado	Mancos	mudstone	shallow marine	good	very poor
		absent	Beartooth	Dakota	sandstone	deltaic	poor	fair
Lower Cretaceous	Bisbee	Mojado	Sarten	Sarten	sandst.,mudst.	deltaic	poor,fair	fair,poor
	Bisbee	U-Bar	absent	absent	limestone	shallow marine	fair	fair
	Bisbee	Hell-to-Finish	absent	absent	cgl., redbeds	nonmarine	none	very poor
Jurassic		absent	absent	unnamed	sandst.,mudst.	marine	poor,fair	fair,poor
Triassic		absent	absent	absent	--	--	--	--
--------basal Mesozoic unconformity--------								
Permian	Guadalupian	Concha	absent	San Andres	limest.,dolost.	shallow marine	fair	poor,fair
		Scherrer	absent	Glorieta	sandstone	shallow marine	very poor	poor
	Leonardian	Epitaph	absent	Yeso (Hueco?)	dolostone	shallow marine	fair-good	fair
		Colina	absent		limestone	shallow marine	fair	very poor
	Wolfcampian	Earp	Abo	Abo-Hueco	redbeds-limest.	non.-shall.mar.	poor-fair	poor-fair
		upper Horquilla	absent	Magdalena: Bursum	limest., dolost., mudst. / limest.	shallow to deep marine	fair to good	fair to good
Pennsylvanian	Virgilian	limestone-shelf	absent	Magdalena: Panther Seep	sandst.			
	Missourian	dolostone-margin	Magdalena	Magdalena: Lead Camp	limest.			
	Desmoinesian	mudstone-basin						
	Derryan	lower Horquilla	absent		limestone	shallow marine	fair	poor
	Morrowan		absent					
Mississippian	Chesterian	Paradise	absent	Helms	limest.,mudst.	shallow marine	fair-good	poor
	Meramecian,etc.	Escabrosa	Lake Valley	Lake Valley-Rancheria	limest.,chert	shall.-deep mar.	fair	poor
Devonian		Percha	Percha	Percha	dark mudstone	shallow marine	poor-fair	poor
Silurian		Fusselman	Fusselman	Fusselman	dolostone	shallow marine	poor	fair-good
Upper Ordovician		Montoya	Montoya	Montoya	dolost.,sandst.	shallow marine	fair,poor	fair,poor
Middle Ordovician		absent	Simpson	absent	mudst.,sandst.	shallow marine	fair	poor
Lower Ordovician		El Paso	El Paso	El Paso	limest.,dolost.	shallow marine	fair	poor,fair
Lowermost Ordovician-Upper Cambrian		Bliss	Bliss	Bliss	sandstone	shallow marine	poor	poor
Middle and Lower Cambrian		absent	absent	absent	--	--	--	--
--------basal Paleozoic unconformity--------								
Precambrian		--------basement complex--------			granite,met.	nonmarine	none	none

miles northwest of this play (Grim, 1977; Swanberg, 1978). Present-day thermal gradients in southern Hidalgo County are 1.7-2.2^{o}F/100 ft (31-40^{o}C/km) (DeFord and Kehle, 1976; Kron and Stix, 1982), but increase to 3.2-3.7^{o}F/100 ft (58-67^{o}C/km) in the more mineralized spots closely surrounding the play. Present-day heat flow has been measured at 2.0-2.7 HFU (see Sass and others, 1971; Reiter and others, 1975; Sass and others, 1976; Lachenbruch and Sass, 1977; Swanberg and others, 1977; Blackwell, 1978; Grant, 1978; Grim and Berry, 1979; Sass and others, 1981; U.S. Geol. Survey and New Mex. Bur. Mines Min. Res., 1981; Kron and Stix, 1982; Reiter and Tovar, 1982). Figures 33 and 34 show the highest present-day heat flow is in the eastern part of the play area.

Thompson (1976) has weighed both the positive and negative effects of heat on petroleum generation in southwestern New Mexico. A major constraint to finding hydrocarbon accumulations is of course their thermal destruction by widespread Laramide plutonism, and to a lesser extent by Tertiary volcanism and relatively high present-day heat flow (hot hydrothermal convection systems). However, the effects of the relatively "cold" intrusive and extrusive processes of the area are very localized and may not have significantly detracted from the area's potential. The surface Winkler Anticline (Zeller and Alper, 1965) was drilled to 4,464 ft to test a possible intrusive dome in central Hidalgo County. This well proved disappointing with respect to high bottom hole temperature, i.e. a gradient of 3.7^{o}F/100ft (68^{o}C/km) (Thompson, 1977). This well encountered good source and reservoir rocks in the Horquilla Formation but bottomed in a Tertiary pluton. Elston (1978) has characterized the cauldrons which border the outline of this petroleum play. Elston and others (1979) noted that in the Winkler Anticline well the severe thermal effects were limited to within about 2,300 ft of the intrusive igneous contact, whereas the more

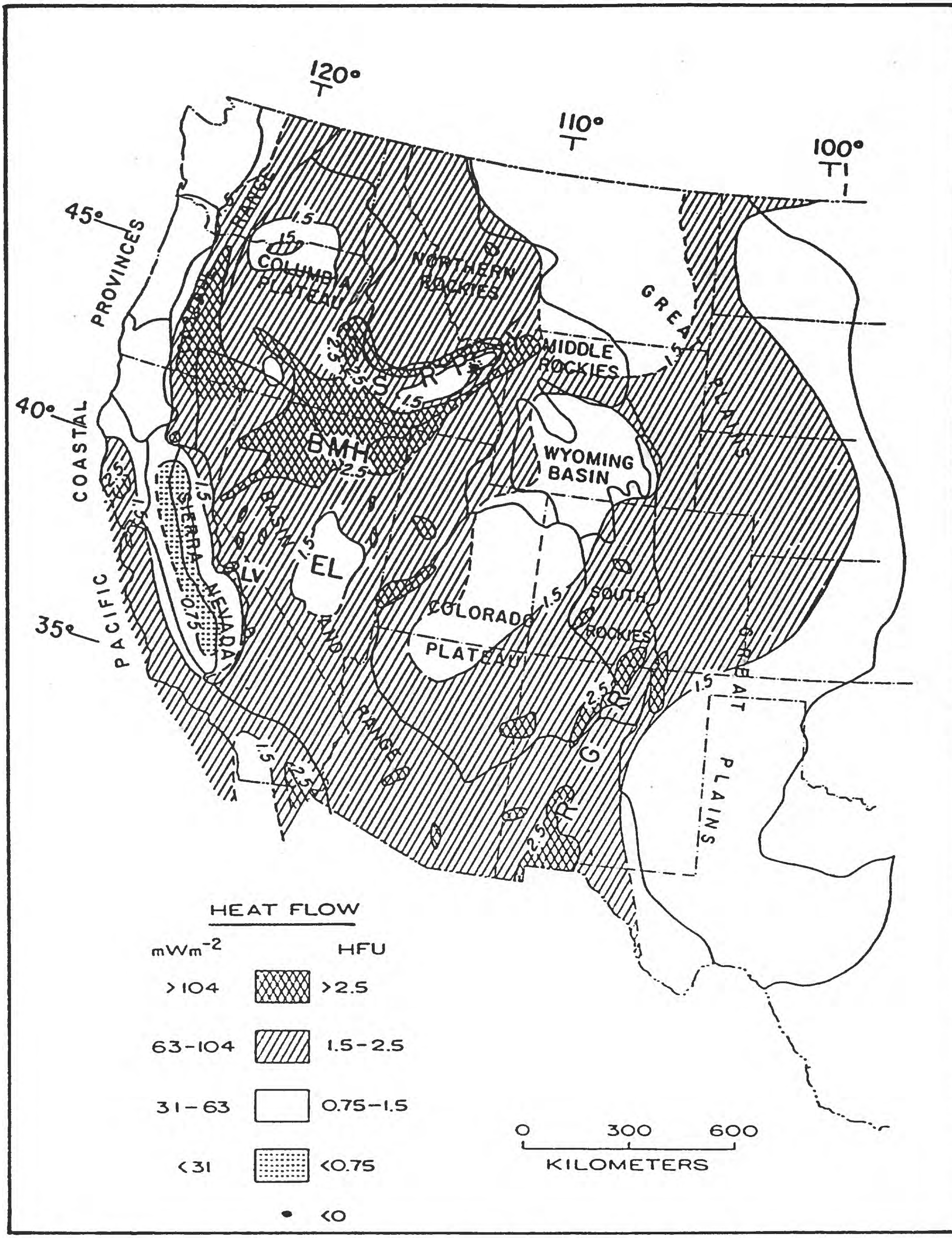


Figure 33 -- Map of the western United States showing heat-flow contours (in heat-flow units, HFU, 1 HFU = 41.8 mWm^{-2}), heat-flow provinces, and major physiographic divisions (SRP: Snake River Plain; BMH: Battle Mountain High; EL: Eureka Low; RGR: Rio Grande Rift Zone; Y: Yellowstone; LV: Long Valley). (From Sass and others, 1981).

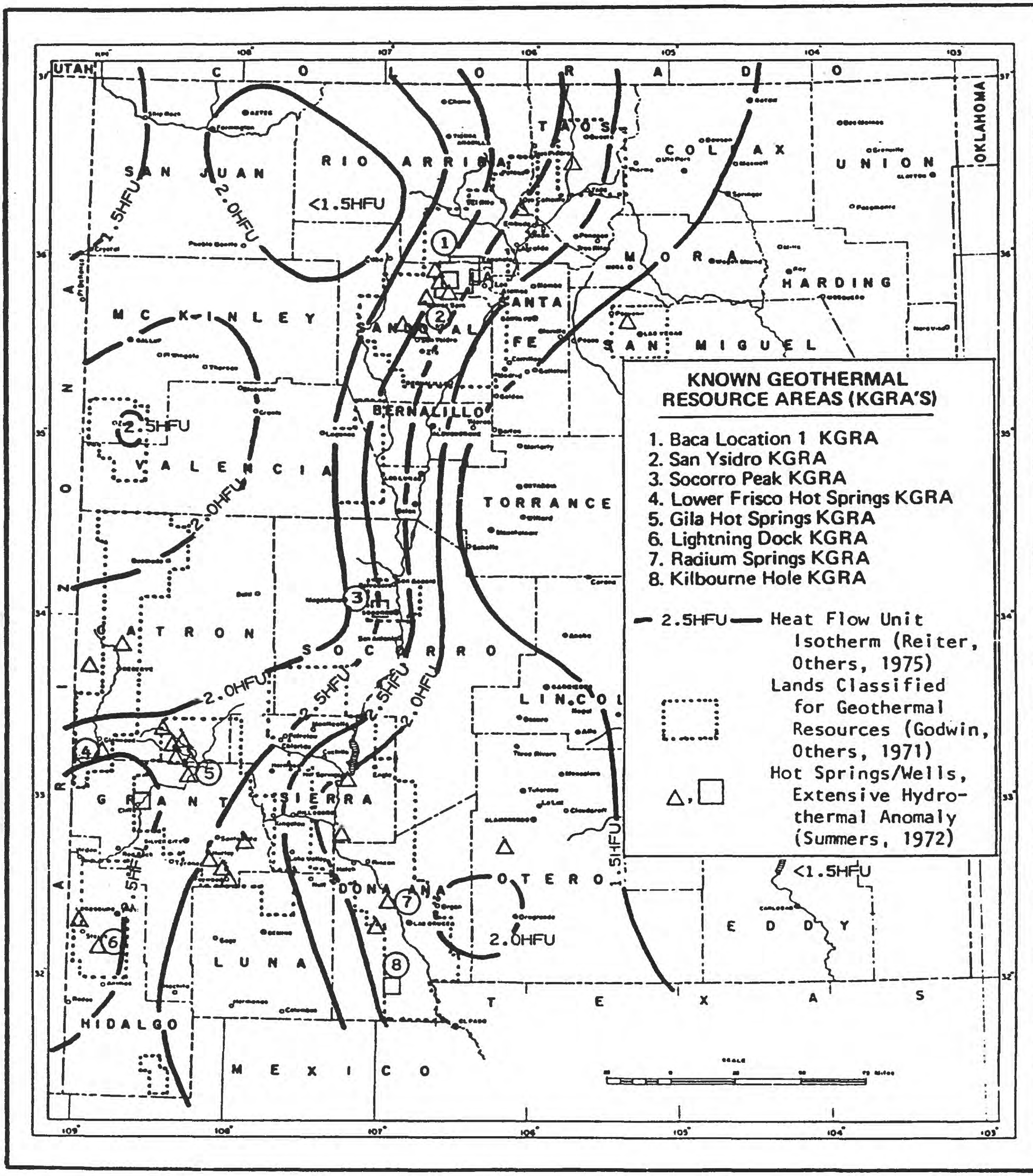


Figure 34--Index map of New Mexico showing geothermal resource areas and heat-flow unit isotherms. (From Grant, 1978).

distant areas may actually have had their petroleum potential enhanced. Exploration should not be prohibitive outside the narrow sphere of high thermal influence associated with these calderas.

Potential Reservoir Rocks

According to Kottlowski (1962b), all Paleozoic strata, excluding the Devonian, are favorable targets. Wengerd (1970) identified both major and minor potential reservoir rocks in the Big Hatchet Mountains as follows: Major carbonate reservoirs occur in formations of Ordovician, Mississippian, Pennsylvanian, Permian, and Early Cretaceous age. Figure 35 represents the stratigraphic section in the southern play area, whereas figure 36 is a section a few miles north of the play. The Paleozoic reservoirs are mostly porous or fractured shelf to shelf-margin dolomites. Figure 37 shows location of porous shelf-margin carbonate mounds (phylloid algae) up-dip from potential Horquilla source rocks. Lower Cretaceous carbonates of the U-Bar Formation are rudistid reefs (Weise and LeMone, 1981).

Regardless of this optimism, in this play the Pennsylvanian and Lower Permian carbonates are considered to have the best potential to contain petroleum, particularly the approximately 500- to 1,200-foot-thick, porous, dolomitic, phylloid algal reefs (bioherms of Zeller, 1965) of the Horquilla Formation. This formation is about 2,500-4,500 ft thick and contains intercalated source and reservoir rocks. Porosity is low (3-4 percent), but is 10 percent in the carbonate mounds/reefs. However, Greenwood and others (1970) noted excellent secondary porosity where exposed to weathering. They also drew a favorable analogy between the productive Permian rocks of southeastern New Mexico and the potential Permian rocks of southwestern New Mexico. Based on limited and extrapolated geochemical data of Morgan and others (1983), the Cenozoic basins overlying the reservoirs do not appear to be completely flushed by meteoric water.

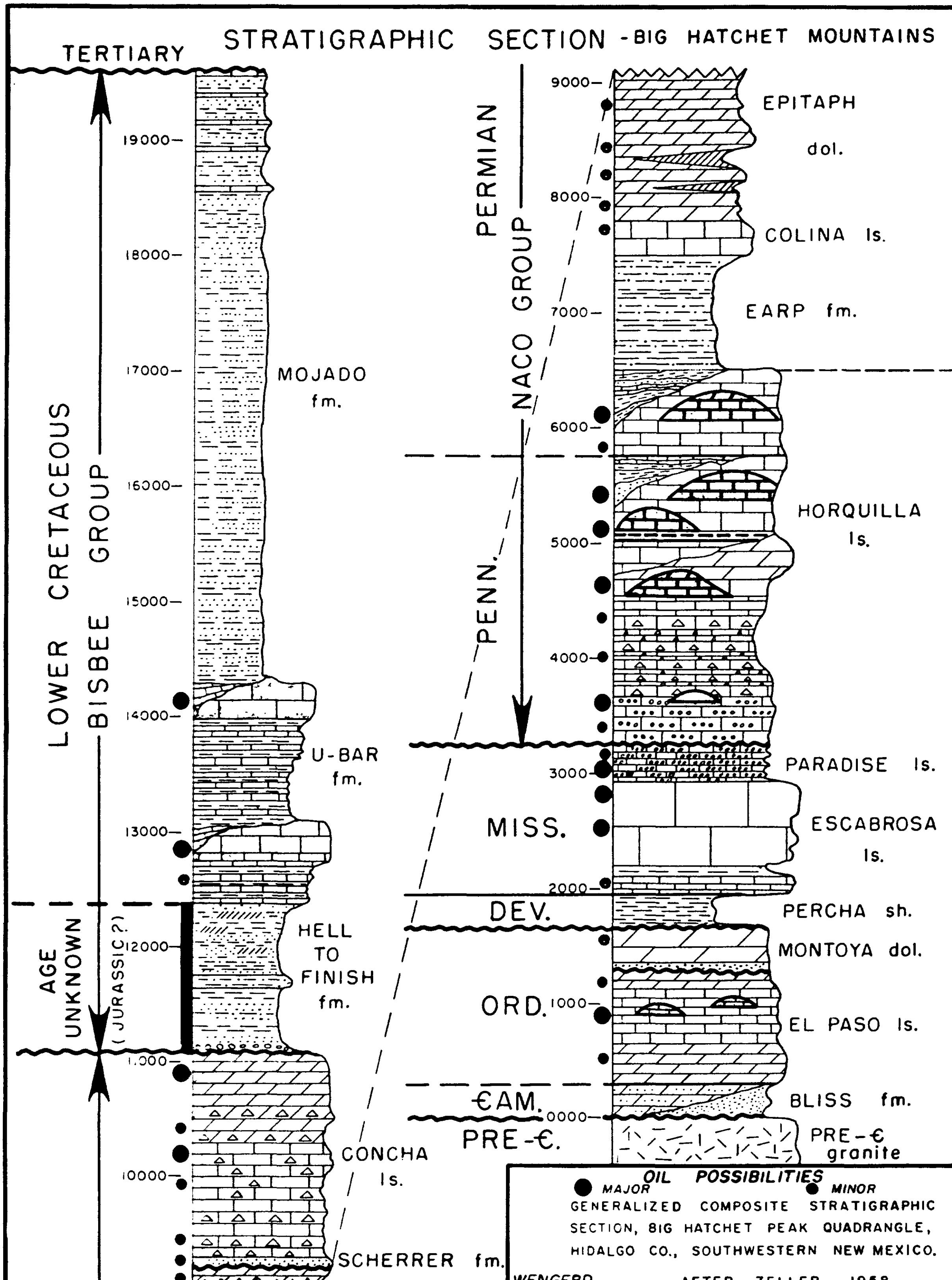


Fig. 35—Stratigraphic Section (composite)—Big Hatchet Mountains (after Zeller 1958, and later commercial work). This section shows those strata which may have major and minor oil possibilities in southwesternmost New Mexico. The Hell-to-Finish Formation is now considered to be of Cretaceous age. The thickness of reefs in the Horquilla is vertically exaggerated. (From Wengerd, 1970).

ERA	SYSTEM	SERIES	STRATIGRAPHIC UNITS		
CENOZOIC	TERTIARY			RHYOLITIC-LATITIC VOLCANICS	
				HIDALGO FM	5,500'
				RINGBONE FM	7,500'
MESOZOIC	CRETACEOUS	UPPER			
		LOWER		MOJADO FM	5,000'
				U-BAR FM	4,000'
				HELL-TO-FINISH FM	6,000'
PALEOZOIC	PERMIAN	LEONARD	NACO GROUP	CONCHA LS	1,376'
		LEONARD OR WOLFCAMP		SCHERRER FM	20'
				EPITAPH DOL	1,519'
				COLINA LS	505'
				EARP FM	997'
		WOLFCAMP		HORQUILLA LS	3,530'
	PENN.	UPPER			
		MIDDLE			
		LOWER			
	MISS.	UPPER		PARADISE FM	318'
		LOWER	ESCABROSA GROUP 1,261'	HATCHITA FM	
				KEATING FM	
	DEVONIAN	UPPER		PERCHA SHALE	280'
	SILURIAN				
	ORDOVICIAN	UPPER		MONTOYA DOL	385'
		MIDDLE			
		LOWER		EL PASO FM	1,070'
	CAMBRIAN	UPPER		BLISS FM	327'
PRECAMBRIAN				GRANITE, QUARTZITE	

Figure 36--Stratigraphy of Brockman Hills area, southwestern New Mexico. Thicknesses are in feet. (From Corbitt and others, 1977).

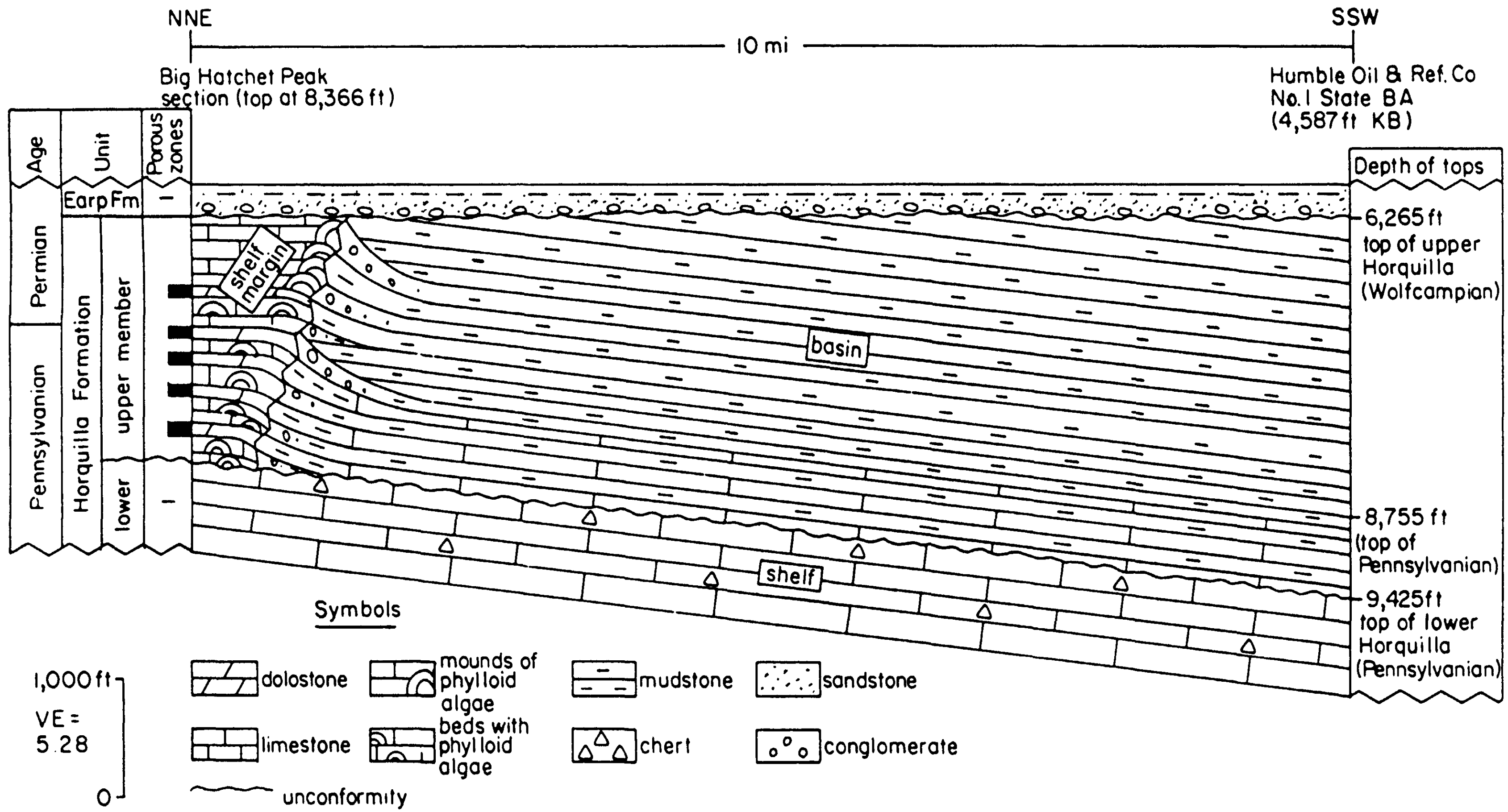


FIGURE 37–NORTH-NORTHEAST-SOUTH-SOUTHWEST STRATIGRAPHIC CROSS SECTION FROM THE BIG HATCHET PEAK SECTION TO THE HUMBLE NO. 1 STATE BA WELL. (From Thompson and Jacka, 1981).

Potential Traps

Faults, anticlines, and combinations of these structures are the common traps of the play (Wengerd, 1970). Basement-cored uplifts, southwest- and northeast-directed Laramide overthrusts, high-angle reverse and normal faults, right-lateral strike-slip faults, and major northwest-trending folds, are the types of structures exposed in the Little Hatchet and Big Hatchet Mountains (Corbitt and Woodward, 1970; Elston, 1970; Zeller, 1975; Drewes and Thorman, 1978; Seager, 1981 and 1983; Ryder, 1983a; Seager and Mack, 1986). These structures are portrayed in the cross-sections of figures 38 and 39. Porosity pinchouts associated with reef facies, and updip facies changes at the basin margin all provide trapping mechanisms. Other potential trapping structures are also noted in the "Texas Lineament" section of this report. If primary migration of petroleum occurred during the Cretaceous Period, plenty of older traps should have been in place and filled; secondary migration may have redistributed this oil consequential to the generally southward tilting during Laramide deformation.

The greatest detriments to accumulation are the possible flushing of reservoirs by meteoric water, and the rupturing of reservoirs by multiple episodes of post-migration block faulting, particularly during the Miocene. Effective seals for good clastic reservoirs are lacking in the Cretaceous section (Woodward and Duchene, 1981).

Estimated Depth of Occurrence

Lower Permian and Pennsylvanian strata crop out in the Big Hatchet Mountains uplift. In the down-faulted areas of the play, as much as 20,000 ft of rock overlies the Horquilla Limestone (about 5,000 ft of Cenozoic, 10,000 ft of Cretaceous, and 5,000 ft of Permian strata).

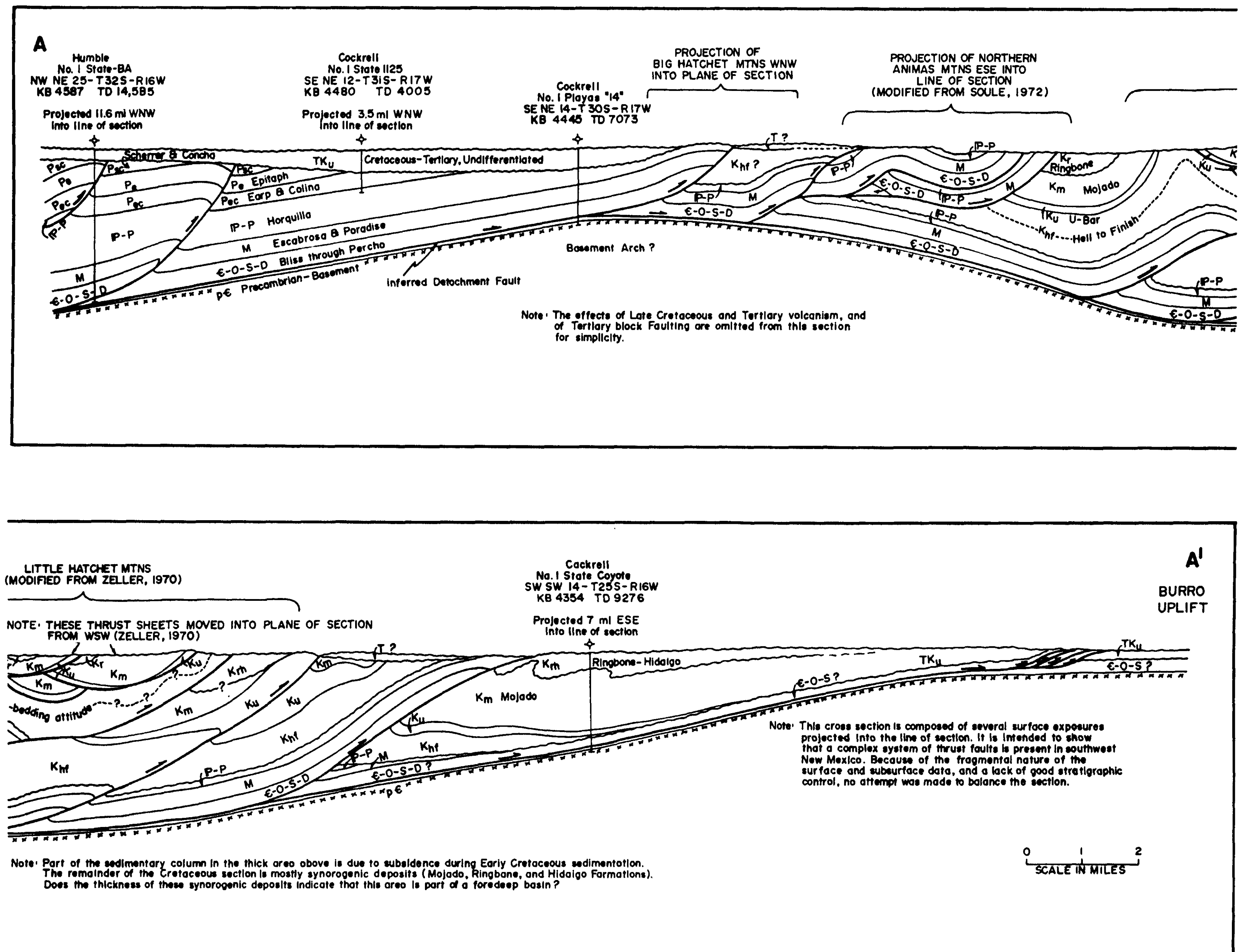


Figure 38-- **Generalized cross section across thrust and fold belt of southwestern New Mexico.** Location of cross-section on figure 40. (From Woodward and Duchene, 1982).

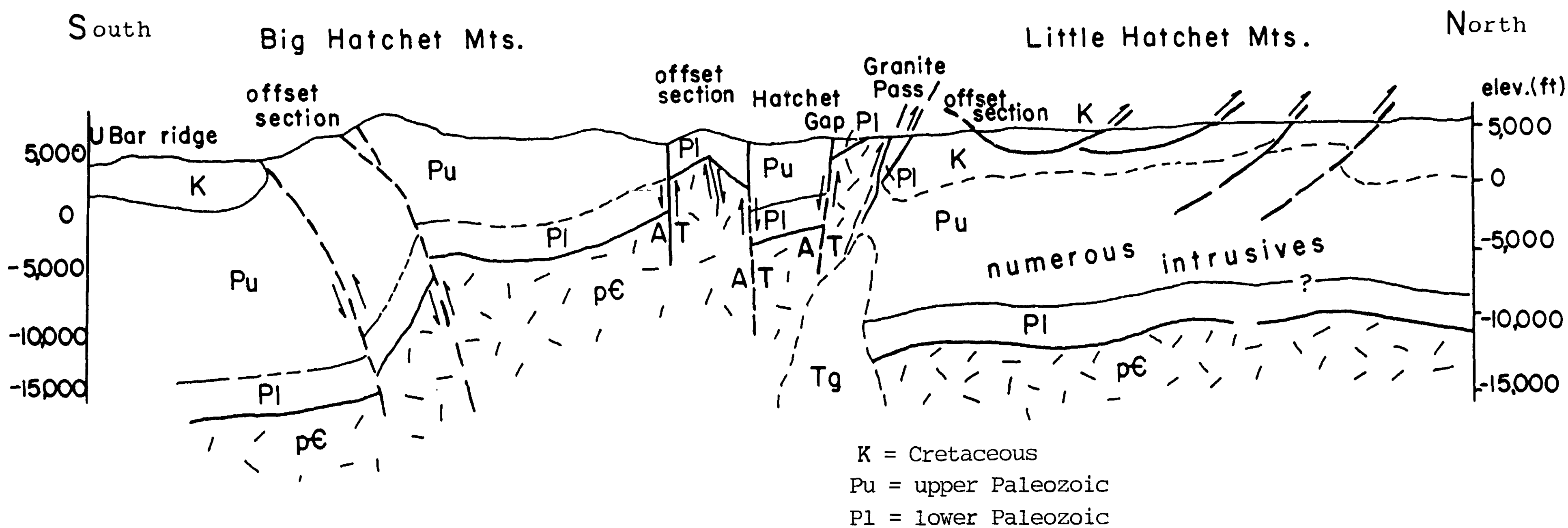


Figure 39--Diagrammatic section through the Little Hatchet - Big Hatchet Mountains. (From Seager, 1983).

Exploration Status

The play is in frontier exploration territory; Laramide thrusts, Cenozoic volcanism, and block faulting make it extremely difficult to explore for hydrocarbons (Woodward, 1981). Hidalgo County has a drilling density of 101 to 250 mi^2 per borehole (Stark and Gordon, 1982). The play itself has a drilling density of about 40 mi^2 per borehole. Thompson (1981b) has noted that in the entire Pedregosa basin (49,500 mi^2), the drilling density of petroleum-exploration wells (37) penetrating Paleozoic and/or Precambrian strata is 1,338 mi^2 per borehole.

Although much of the play area is concealed by alluvium, the surface expression of the geologic structure is on-trend with the northwest-southeast Big Hatchet Mountains and Little Hatchet Mountains (fig. 40) where good sections of Paleozoic and Cretaceous strata, respectively, are well exposed and described (notably Lasky, 1947; Zeller, 1965, 1970a and b, 1975; Thompson and Jacka, 1981).

Promising oil and gas shows have been recorded in the New Mexico part of the Pedregosa basin . Some of these shows are located in figure 38, and are listed below (table 2); the farthest show from the play area in this list is about 50 miles. Data are taken from Sandeen (1953), Dixon and others (1954), Wengerd (1962), Kottlowski and others (1969), Greenwood (1970a), Foster and Grant (1974), Thompson and others (1978), Thompson (1982b), Woodward and Duchene (1982), Brady (1984), and Howland (1985).

Table 2--Some oil and gas shows in the vicinity of the Big Hatchet Mountains play area, southwestern New Mexico.

WELL NAME & COMPLETION DATE	LOCATION	TOTAL DEPTH (ft)	SYSTEM AGE at TOTAL DEPTH; [DEPTH, AGE & SHOW TYPE]
		Southern Grant County	
Cockrell No.1 Coyote State 1969	sec. 14 T25S R16W	9,282	Precambrian [4,140 - Cret. oil]
Winiger and Berry No.1 State 1943	sec. 16 T27S R16W	1,500	Cretaceous [1,415-1,430 - Cret. gas; 610-620; 1,270-1330 - Cret. oil]
Wininger Bros. Berry & Mike No.1 State, 1947	sec. 16 T27S R16W	?	? Ordovician [950 - Ord. gas; 1,495-1500 - Ord. oil & gas]
		Hidalgo Coounty	
Hachita Dome No.1 Tidball-Berry Fed. 1957	sec. 12 T30S R15W	2,726	Precambrian [1,500; 2,310; 2,430 - Ord. gas; 2,590 - Camb./Ord.? oil]
Graham No.1 Hatchet Fed. 1978	sec. 12 T30S R15W	2,455	Ordovician [? - Ord. gas]
Humble No.1 State BA 1958; 1968	sec. 25 T32S R16W	14,585	Ordovician [1,753-1,758 - Perm. dead oil; 4,190-4,219 - Perm. gas]
Cockrell No.1 Playa State 1970	sec. 14 T30S R17W	7,086	Precambrian ? [5,780 - Ord. oil]
KCM No. 1 Cochise State A 1975	sec. 18 T28S R17W	5,916	Precambrian [2,050; 2,220; 2,650 - Cret. gas]
Long & Beck No.1 State 1942	sec. 14 T22S R20W	?	unknown [790-848 - unknown age, oil]
		Luna County	
Sycor Newton No.1 St. L-6,350 1974	sec. 10 T23S R5W	10,090	Precambrian [6,670-6,720; 7,612-7,632 - Ord. oil]
Sunray No. 1 Fed. R 1962	sec. 27 T28S R5W	6,626	Precambrian [5,582-5,619 - Ord. gas]
		Chihuahua, Mexico	
Pemex No. 1 Espia 1972	20 mi N Ascension $(108^{o}\ 00', 31^{o}\ 21')$	18,566	Permian [18,538 - Perm. gas]

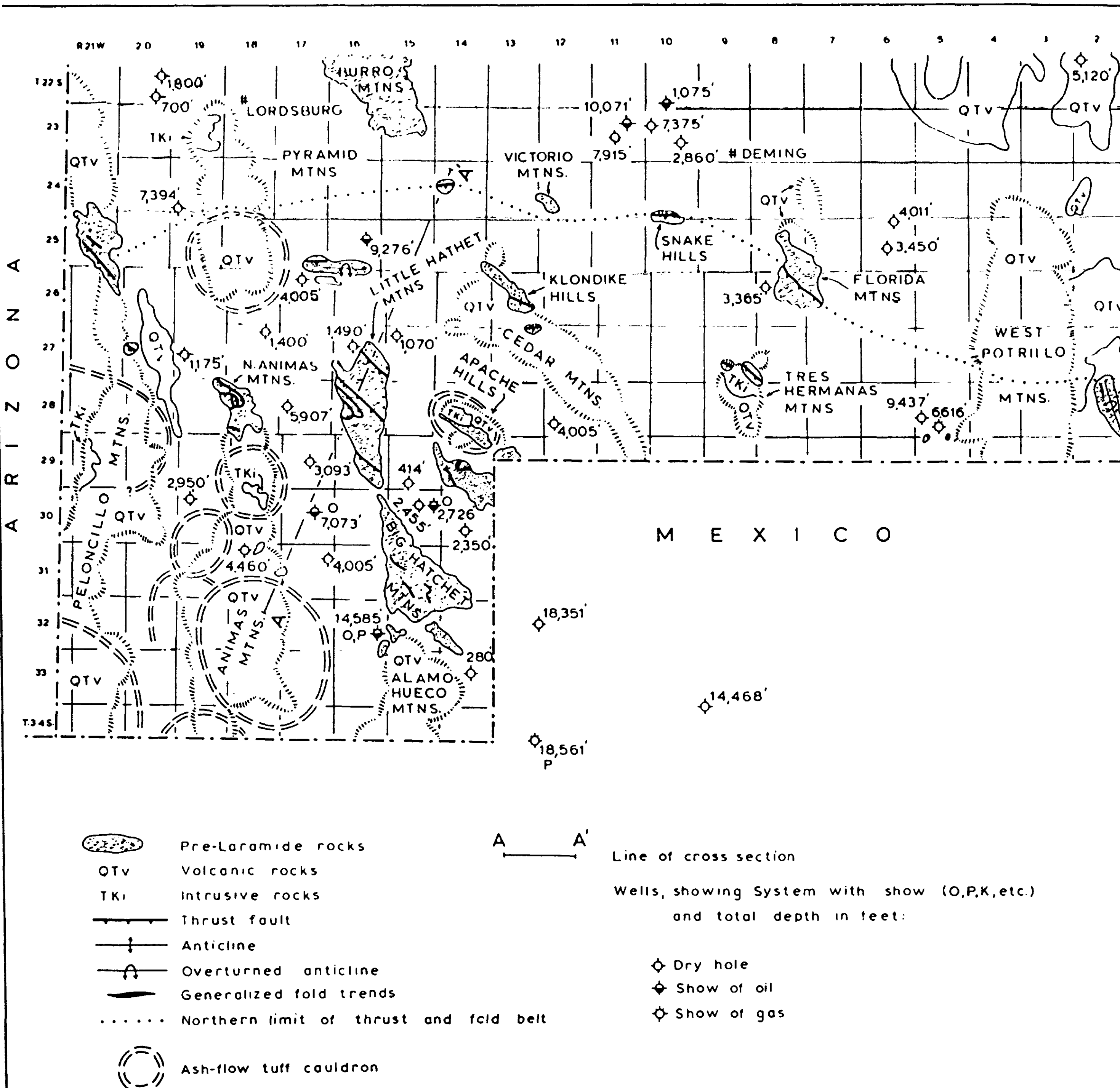


Figure 40--Location of calderas and other structural features of southwestern New Mexico. (From Woodward and Duchene, 1982). See figure 38 for A-A' cross-section.

No exploration wells have tested the best reservoir objectives in the deeper parts of the graben valleys (Thompson, 1982a). Based on the few test boreholes drilled to date, every geologic system present (except the Devonian and maybe Cambrian) has yielded petroliferous odors or shows. A key well, the Humble No. 1 BA State, was drilled on the Alamo Hueco anticline (Thompson, 1976). In a drill stem test at 4,190-4,219 feet, gas flow was measured at 10.3 MCFPD from the Colina-Epitaph interval. In 1968 this reworked well tested 86 MCFPD before being abandoned. Greenwood (1970a) noted a higher 500-MCFPD flow, but the hole was "lost" during acid fracturing. Dead oil and oil staining were also encountered (Wengerd, 1962).

Southwestern and South-central Cochise County, Arizona

Identification of this play is based primarily on outcrops of Paleozoic strata (6,000-9,000 ft, composite thickness) that are thermally within the oil window of occurrence, i.e. about 1.3 percent or less vitrinite reflectance (R_o) or its equivalent conodont alteration index (CAI). Secondly, the thick Upper Paleozoic strata have good source and reservoir potential. Thirdly, the large number of major unconformities and other local folds and thrusts provide potential traps. These factors necesitate continued study and evaluation of this area by industry.

Location, Size, and Land Status

The play occupies about 1,470 mi^2 of south-central and southwestern Cochise County in the southern Basin and Range Province of southeastern Arizona (fig. 2). Land status includes about 91.5 percent combined state and private, 5.5 percent Bureau of Land Management, and 3 percent military.

Potential Source Rocks and Geothermal Maturity

Nydegger (1982) indicated the source rocks of the Pedregosa basin include Devonian Percha (Woodford) shales, Mississippian to Permian limestones and shales, Jurassic shales, and lower Cretaceous limestones and shales. Hayes (1975) considered the lower shale member of the Abrigo Formation to have good source-rock potential. However, in the U.S. part of the basin, there does not seem to be convincing evidence for adequate Cambrian, Devonian, Mississippian, Jurassic, and Cretaceous source rocks. This may be due only to insufficient drilling data. Devonian rocks are characterized by having a fetid odor, but this occurs principally in the Mogollon Rim area of east-central Arizona (Ball Associates, 1965; Teichert, 1965; Curtis, 1972). Although the Mississippian Escabrosa carbonates (500-900 ft thick) have oil shows, the Mississippian Paradise Formation shale and black biostromal limestone is relatively thin, i.e. probably less than 150 ft. The questionable hypothesis of regional overthrusting (see THE LARAMIDE OROGENY section of this report) is required to preserve a Triassic-Jurassic rift system (proto-Gulf of Mexico) with source rocks and thick evaporites south of the Colorado Plateau in the assessment province (see Hansen, 1976). Fetid black shale of Early Cretaceous age is known (Robinson, 1982; Bilodeau and Lindberg, 1983), but it is of limited occurrence. Patch reefs of the Mural Limestone (fig. 9) are also limited in geographical occurrence; they are composed mainly of scleractinians, corals, algal stromatolites, rudistid bivalves, and molluscan debris.

On the other hand, many of the Upper Paleozoic formations, predominately carbonates, are dark and biostromal and may have had sufficient organic carbon to have generated oil and gas. Peirce and others (1970) have mapped the Pennsylvanian-Permian section to be about 4,000 to over 4,500 ft thick in the play area (fig. 41). These formations (with thicknesses) include the Black Prince dark oolitic limestone, siltstone, and shale (120-280 ft), Horquilla, (600-1,750 ft), Earp (400-1,000 ft), Colina (400-920 ft), Epitaph (900-1,700 ft), middle carbonate member of the Scherrer (100-125 ft), Concha (500-575 ft), and Rainvalley (300-400 ft).

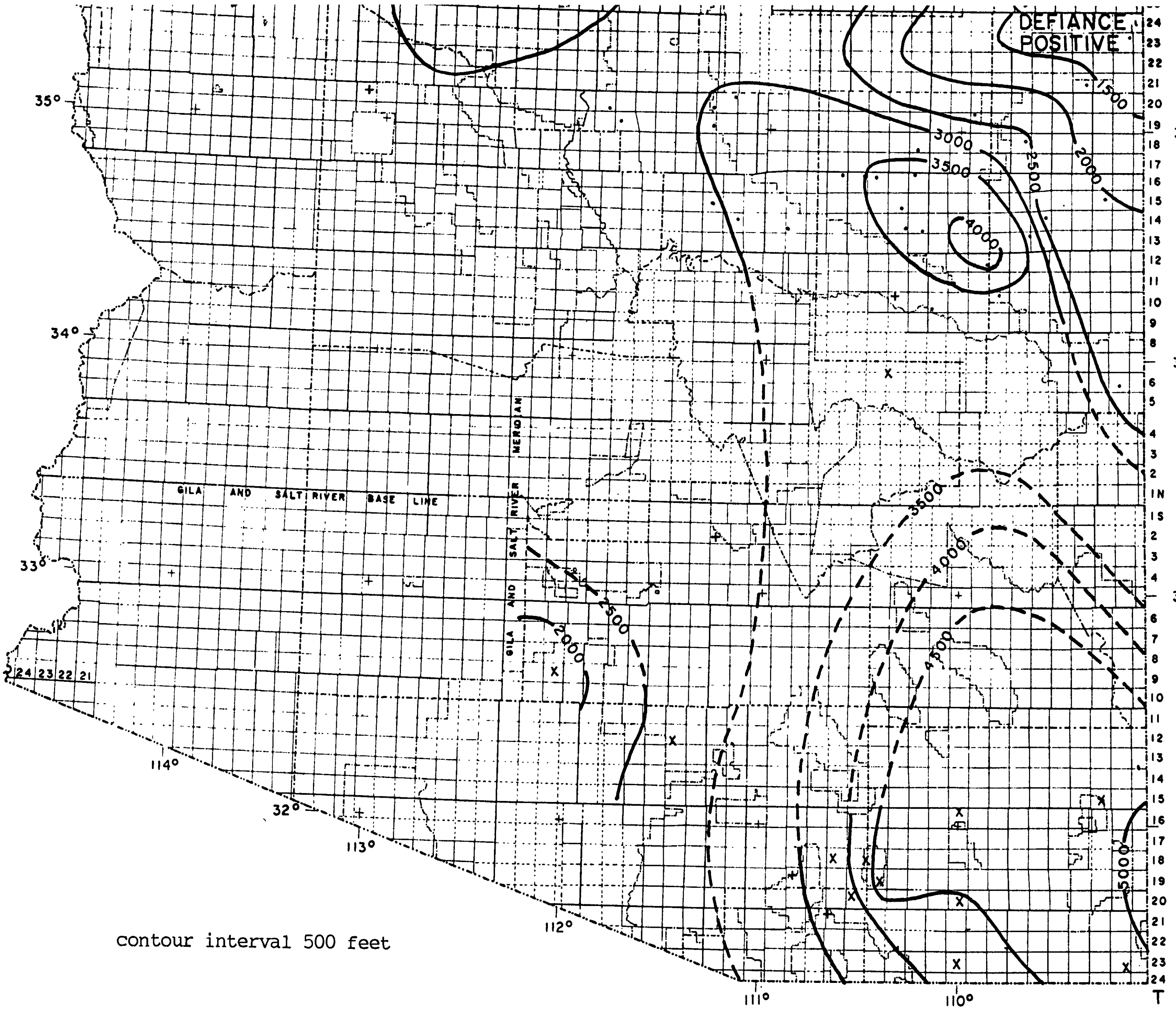


Figure 41--Pennsylvanian - Permian isopach map of southern Arizona. (From Peirce and others, 1970).

When selective samples of such rocks are dissolved in acetic acid, a thick carbonaceous residue remains. Figure 42 shows that the Colina-Epitaph interval is about 1,600-2,200 ft thick in the play area. Thompson (1982b) has ranked the entire stratigraphic section in southwestern New Mexico with respect to source rock potential. He found the Paradise, Horquilla, and Epitaph formations the only ones achieving a "good" rank.

Geothermal maturity values for Paleozoic outcrops within the play outline are ≤ 1.2 percent R_o and its CAI equivalents. Other values in Cochise County are commonly 3.0-4.8 percent R_o, i.e. in the thermal gas to completely metamorphosed window. CAI values of Wardlaw and others (1983) and Wardlaw and Harris (1984) show a similar geothermal maturity pattern and indicate the play area has oil and gas potential. No areas of potential geothermal resources have been identified within the play area (Grim, 1977; Grim and Berry, 1979). Present-day geothermal temperature gradients within the play area range from 1.05 to 1.89^{o}F/100ft (19-35^{o}C/km) according to DeFord and Kehle (1976); heat flow units, shown generally in figure 33, are between 1.45 and 2.40 (Grim and Berry, 1979; Nathenson and others, 1983). For comparison, the median HFU value for the Basin and Range Province is 2.0 (Grose and Keller, 1979) and about 1.9-2.0 for southeastern Arizona (Shearer, 1979). The reader should also consult the geothermal references cited in the previous play.

Potential Reservoir Rocks

Pennsylvanian-Permian shelf-margin carbonate rocks, including carbonate buildups and bioherms, have the greatest reservoir potential. Primarily they include formations of Permian age, such as the entire Colina-Epitaph interval, possibly the middle member (carbonate) of the Scherrer, and the Concha-Rainvalley interval. A stratigraphic section in the Whetstone Mountains (fig. 43), near the northwest edge of this play, is

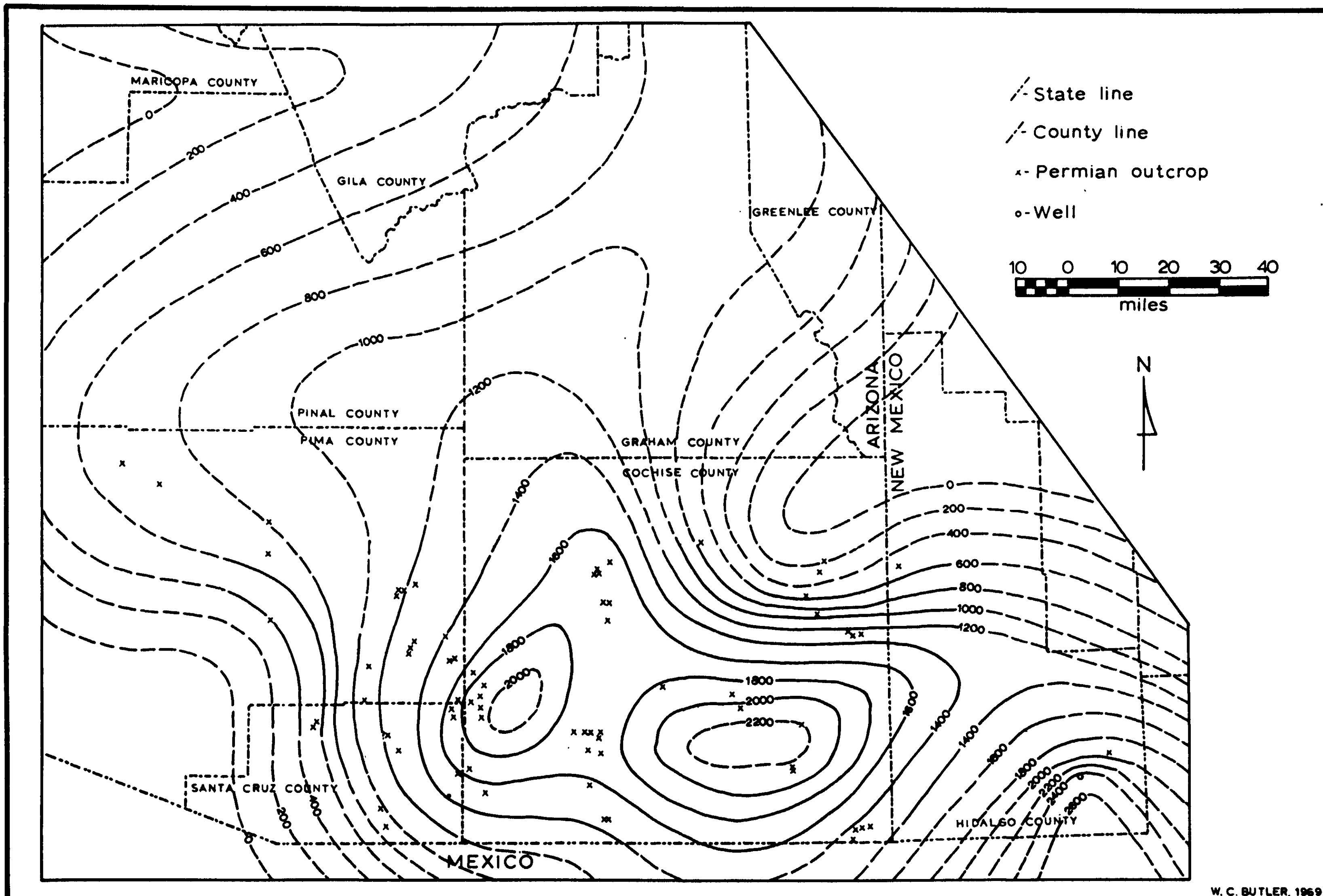


Figure 42--Isopach map of the Colina Limestone plus the Epitaph Dolomite source rocks in the eastern assessment area. Contour interval is 200 feet.

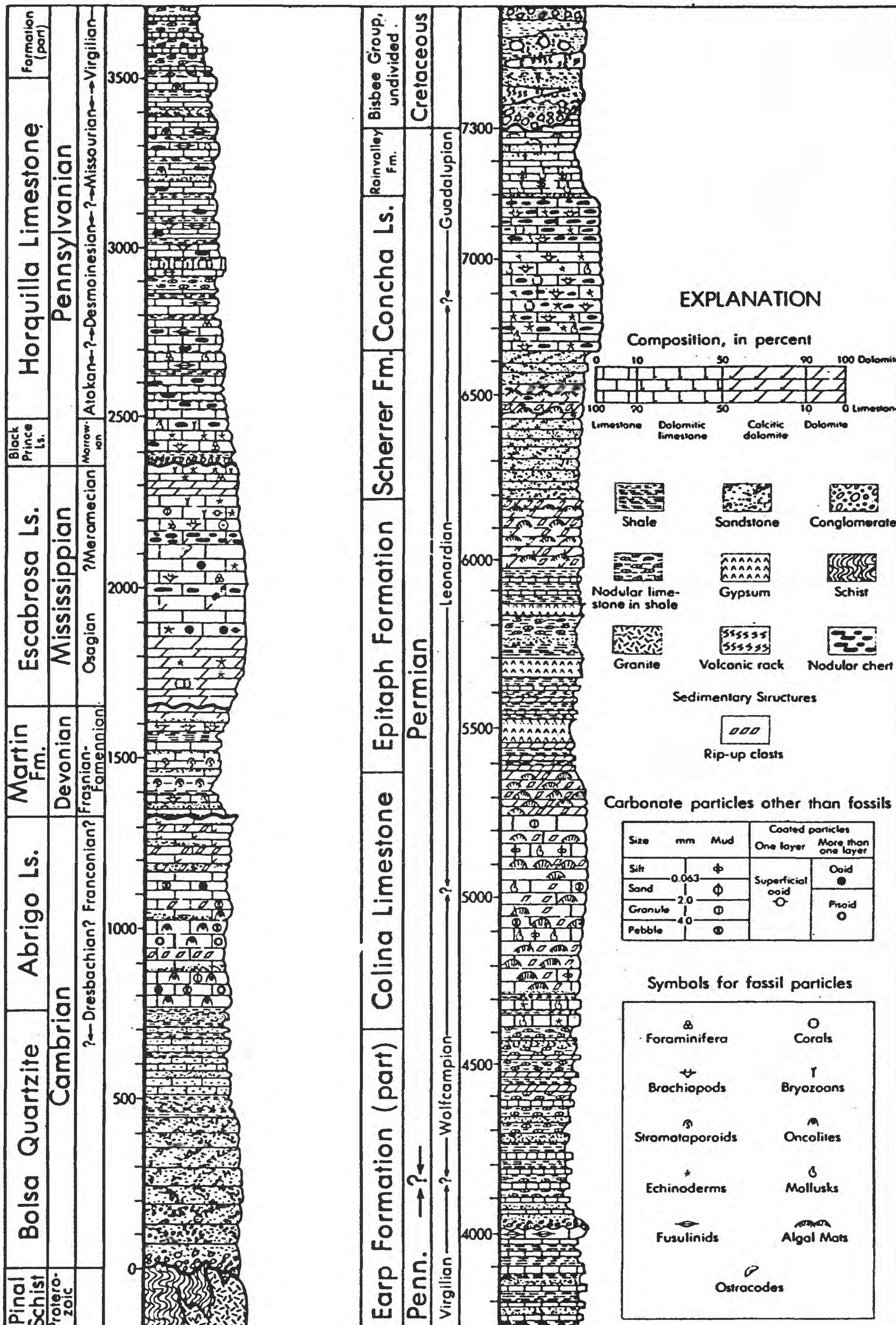


Fig. 43– **Idealized and diagrammatic columnar section of Proterozoic, Paleozoic, and Cretaceous rocks in the Whetstone Mountains.** (From Wrucke and Armstrong, 1987).

representative of the Paleozoic rocks of the Pedregosa basin in Arizona.

Reefoid carbonates of the Early Cretaceous Mural Limestone (up to 800 ft thick) are potential reservoirs but would require complicated migration routes to fill with oil in view of the lack of good, widespread Cretaceous source rocks.

Potential Traps

Trap types are diversified and ubiquitous. They include stratigraphic pinch-outs (fig. 44) and Laramide folds and faults. Porosity wedge-outs should be found in the transition between the inner shelf to the southwest and the outer shelf to the northeast; Ross (1978) has depicted such facies. See the general comments concerning structural traps under the "Texas Lineament" section of this report. Several beds of evaporites, mostly gypsum, up to 150 ft thick, within the Epitaph Dolomite are good seals. Regional dip, established in the Late Paleozoic, is to the south. Because the deepest part of the Pedregosa basin was in northeastern Sonora and northwestern Chihuahua, Mexico, updip migration of petroleum may have resulted in entrapment in the U.S part of the basin.

The seismic time cross-section published by Keith (1980) and Robinson (1982), showed large anticlinal arches in Paleozoic strata beneath one or two overthrust plates of south-central Arizona. Local folded blocks of Paleozoic rocks, such as in the Tombstone Hills area of Cochise County, either were thrust or slid (Jones, 1963 and 1966) over the Cretaceous Bisbee Group and some allochthonous Paleozoics. Surface mapping has identified at least one large fold (2,500 acres) in the play area near Tombstone with a closure of about 1,200 ft.

Estimated Depth of Occurrence

Various targets of this structurally complicated area can be expected at drilling depths from about 6,000-17,000 ft. If the regional overthrust

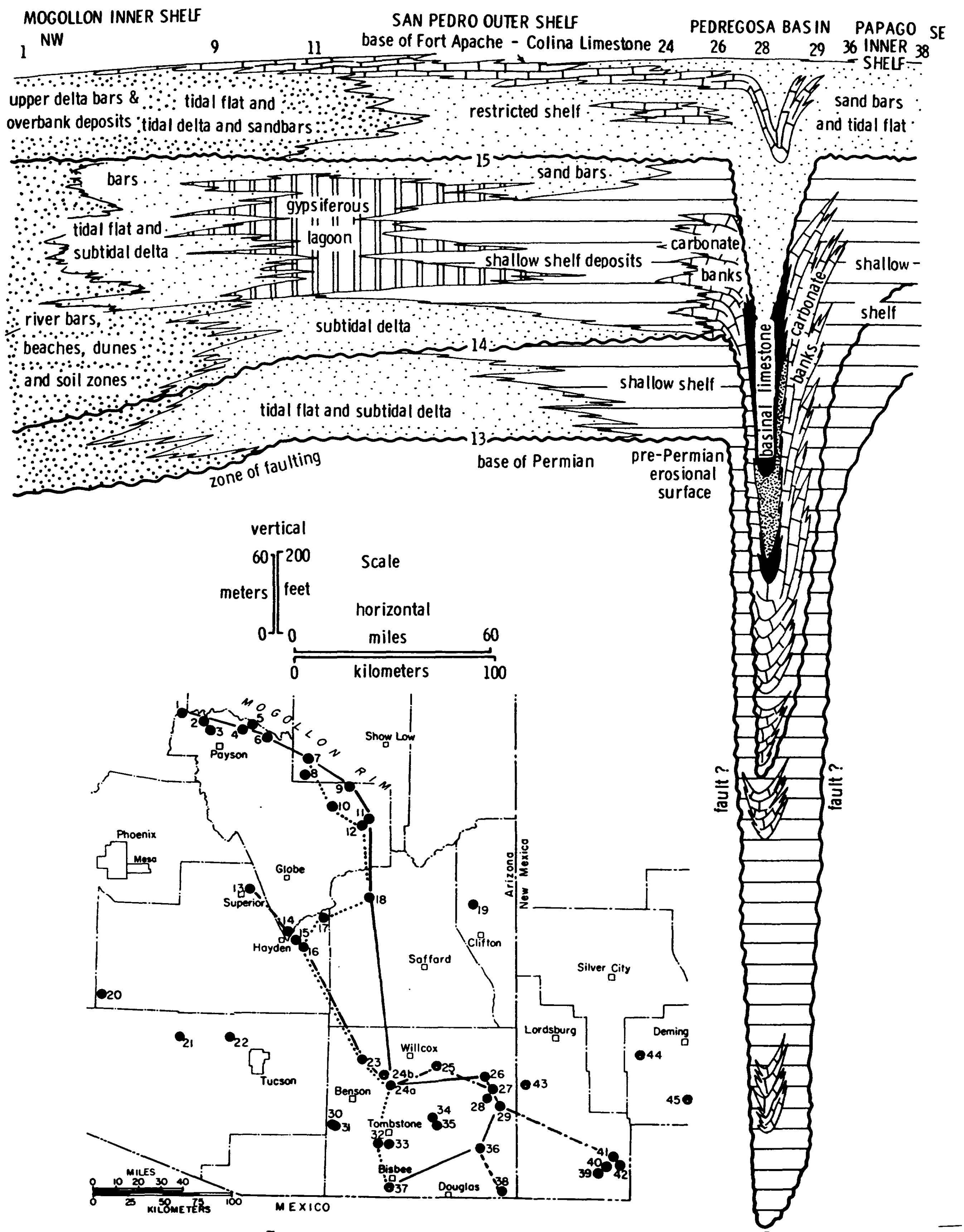


Figure 44--Reconstructed cross-section of part of the Earp, Horquilla and Supai formations in the Pedregosa basin. (From Ross, 1978).

plates exist as illustrated by Drewes (1978) and Keith (1979, 1980), then in the Tombstone Hills area (near the center of this play) about 1,500 ft of Cretaceous strata, 2,000 ft of Upper Paleozoic carbonates, and 2,500 ft of Precambrian Pinal Schist will be encountered above 6,000 ft in the upper plate (Betton, 1982), and the Paleozoic and Cretaceous sections will be repeated below it. The Cretaceous Mural Limestone (patch reefs) might be expected between 11,000 and 12,000 ft. Depth to Permian strata in the lower plate is estimated to be 14,000-15,000 ft.

Exploration Status

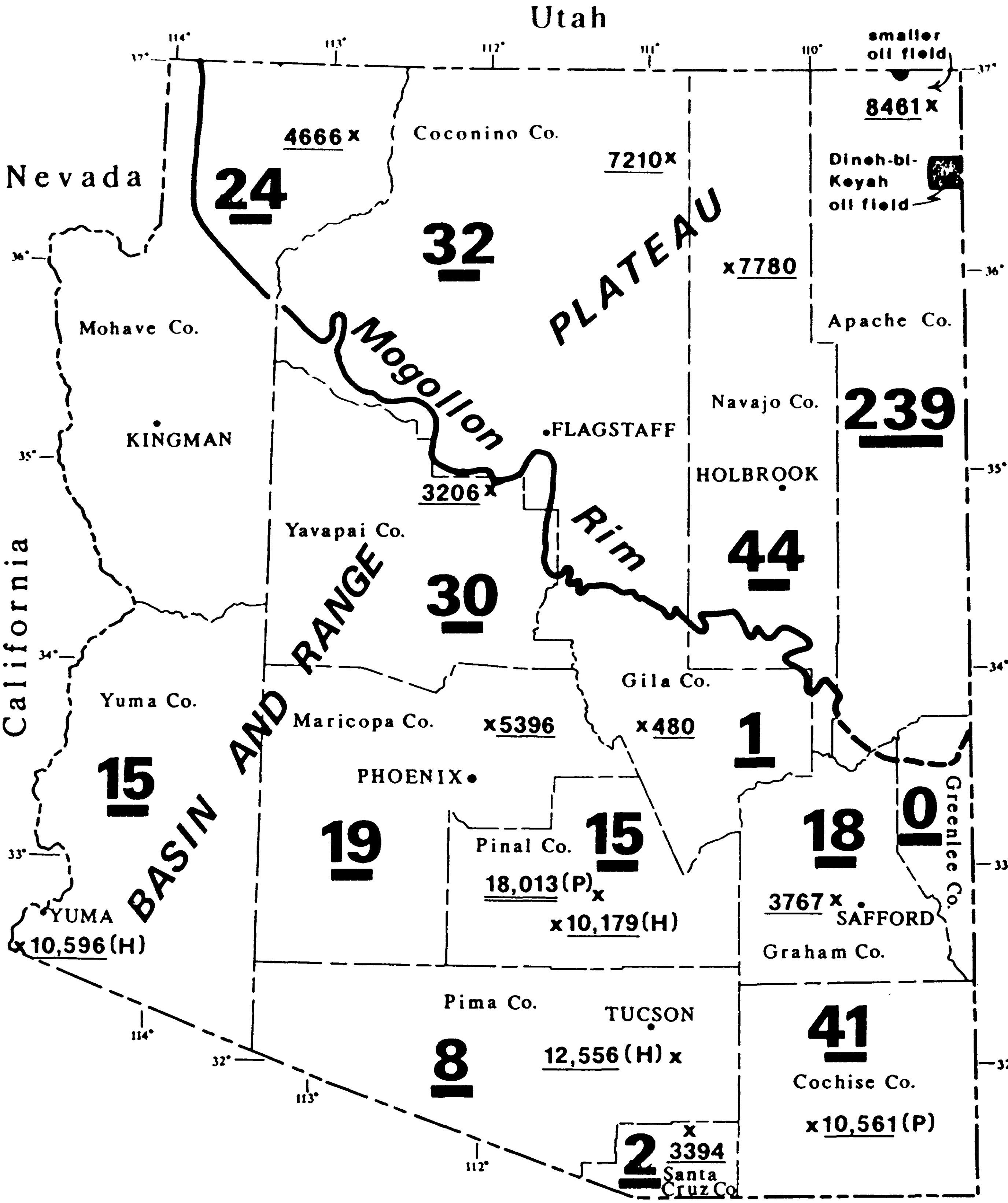
Nydegger (1982) noted that in the U.S. part of the Pedregosa basin less than 50 wells in approximately 7,500 mi^2 have been drilled to Cretaceous or older strata , and he relegated the basin's level of exploration to an infancy stage. In Cochise County, only nine boreholes have been drilled between 5,000 and 10,000 ft and only one borehole is deeper than 10,000 ft. Figure 45 shows the distribution of drilling by county in the assessment province. Drilling density in the play area has been about 130 mi^2 per borehole; in Cochise County it has been between 51 and 100 mi^2 per borehole according to Stark and Gordon (1982) and about 150 mi^2 per borehole as figured from data by Peirce (1982) who considered only petroleum tests.

All Paleozoic rocks of southeastern Arizona, plus the Cretaceous System, have had reported shows of oil and/or gas. Stark and Gordon (1982) also documented that the ratio of number of total shows to dry holes is equal to or greater than 1.00 for Cochise County (valid for two depth intervals of 0-5,000 ft and 5,000-10,000 ft). Some of the wells with significant oil and gas shows in Cochise County are listed below (table 3); data is from Peirce and Scurlock (1972), Aiken and Sumner (1974), Thompson and others (1978), and Ariz. Oil and Gas Conserv. Comm. (1984?).

Table 3. Some oil and gas shows in the Arizona portion of the Pedregosa basin play area.

WELL NAME & COMPLETION DATE	LOCATION	TOTAL DEPTH (ft)	SYSTEM AGE at TOTAL DEPTH; [DEPTH, AGE & SHOW TYPE]
Moncrief No.1 State 1963	sec. 17 T21S R23E	2,446	Mississippian [1,600-1,640; 1,840-1,884 - Penn. gas]
Fraser No.1 State 1968	sec. 19 T21S R23E	1,903	Pennsylvanian [1,409-1,449 - Penn. oil & gas]
Moncrief No.1 Davis-Clark 1963	sec. 5 T21S R24E	3,525	? Cambrian [1,950-1,970 - Penn. oil]
Southwest No.1 Davis-Clark 1967	sec. 5 T21S R24E	3,570	Devonian [2,570-2,590 - Miss. or Penn. oil]
Waddell-Duncan No. 1 Murray 1952	sec. 5 T22S R27E	4,400	Precambrian [1,950-1,960 - Penn. oil; 2,980-2,990; 3,345-3,350 - Camb. oil]
Waddell-Duncan No. 1 McComb 1951	sec. 23 T13S R24E	6,865	? Cretaceous [unknown depth, age, or type]
Thomson No.2 State 1961	sec. 2 T24S R31E	802	Permian [458 - Perm. gas]

Drilling for oil and gas in Arizona's Basin and Range Province has not only been disappointing but also slow. In the Arizona part of this assessment province (nearly 47,200 mi^2), the drilling density is 395 mi^2 per borehole (some drilling data taken from Peirce, 1982). As is commonly the situation in frontier areas, not enough deep boreholes have been drilled to adequately test the potential of this province. Drilling risks are accordingly high given the lack of information about the subsurface geology.



x	Drill hole	5396	Deepest petroleum test in county (feet)
15	Number of holes in county	18,013	Deepest petroleum test in state (feet)
H	Humble Oil (currently Exxon)	P	Philips Petroleum

Figure 45--Map showing number of petroleum tests by county and the deepest test in each county and the state. (From Peirce, 1982).

Comparisons of stratigraphic/tectonic settings among the Orogande and Pedregosa basins and petroliferous Delaware basin of southeastern New Mexico have been made by Greenwood (1970a), Bachman (1975), Greenwood and Kottlowski (1975), Horak (1975), Greenwood and others (1977), Thompson (1977), and by many of the workers already cited who recognized the potential of this play area. The highly productive shelf-margin carbonates deposited in the Permian seas of West Texas and southeastern New Mexico should provide inspiration to find hydrocarbons in similar strata of the Pedregosa basin.

TERTIARY BASINS PLAYS

San Simon, Sulphur Springs, San Pedro, and Other Basins of Southeastern Arizona

The basis of this play is the analogy with Tertiary oil production, and less significantly with Paleozoic oil production, in the Basin and Range Province of Nye County, southern Nevada, and Eureka County, north-central Nevada (Bortz and Murray, 1979; Duey, 1979; French and Freeman, 1979; Nations and others, 1983; Suek and Krazan, 1983). The six Nevada fields with their years of discovery are: Eagle Springs (1954), Trap Spring (1976), Currant (1979), Bacon Flat (1981), Blackburn (1982), and Grant Canyon (1983) fields. These six fields produced in aggregate 14.0 million barrels of oil through 1984. The Arizona Tertiary basins selected for inclusion are in areas where lacustrine deposits have been documented (examples include: White, 1963; Feth, 1964; Gray, 1967; McDonald, 1973 and 1976; Cole and Armentrout, 1979; Wilt and Scarborough, 1981; Lindsay, 1984). Although not required, lake beds may have acted as potential source rocks. Some southern Arizona Tertiary basins were interconnected with internal regional drainage. Correlation of Tertiary units from basin to basin has proven difficult and most stratigraphic nomenclature remains tentative.

Location, Size, and Land Status

The seven structural valleys that constitute this play have a total area of about 3,650 mi^2. They are in the southern Basin and Range province of Cochise, Pima, Santa Cruz, and Graham Counties of southeastern Arizona (fig. 2). The valleys, some in two sections, include the Tucson Basin (Santa Cruz Valley), Sonoita-Cienega Basin, San Pedro Basin, Teran Basin (San Pedro Valley), Sulphur Springs Basin, and San Simon (Safford) Basin. Land status percentages include the following: private 49, state 26.5, Bureau of Land Management 17.5, military 3, National Forest 1.5, City of Tucson 1.5, and Indian reservation 1.0.

Potential Source Rocks and Geothermal Maturity

Carbonates, marly limestones, evaporites, and mudstones, deposited as part of the swampy-lacustrine facies of the subsiding and rapidly-filling Mid-Tertiary to Late Cenozoic basins, may have preserved sufficient organic matter to be source rocks. Interior drainage from the eroding highlands concentrated fine clastics over organic-rich lake sediments. High salinity in lakes is known to be a factor in preserving organic matter (Kirkland and Evans, 1981). In addition to containing coarse alluvial fan and braided stream sediments, the Mineta Formation of Miocene and probably older age (within the Pantano Group, fig. 46) is a petroliferous (Heylmun, 1978) pisolitic, stromatolitic limestone, sandstone, siltstone and mudstone (Chew, 1962; Clay, 1970; Grimm, 1978; Grover, 1984). This potential source rock is roughly 450 to 4,600 ft thick (Grover, 1982). In the Teran Basin (San Pedro River Valley) in northwestern Cochise County, it is about 725 feet thick with about half of this section being fine-grained clastics and limestone (Grover, 1984). The entire Pantano Group has been documented to be in excess of 13,700 ft in the eastern play area (Brennan, 1962).

GENERALIZED CENOZOIC STRATIGRAPHIC CHART OF SOUTHEASTERN ARIZONA

(many units noted below are very localized; age assignments are tentative and bounding contacts are usually unconformable)

AGE	CENTRAL TRANSITION ZONE	PEDREGROSA BASIN AREA
Quaternary Holocene	alluvium (talus, gravels, fluvial deposits, etc.)	alluvium (fluvial, terrace, etc.); basalt flows
Pleistocene	alluvium	alluvium; basalt St. David Fm.
Tertiary Pliocene late	Verde Fm.; basalt flows	St. David Fm.; alluvium; Gila Conglomerate Group
early		Quiburis Fm.; Gila Conglomerate
Miocene late	Verde Fm.; gravels	? Gila Conglomerate Group; Quiburis Fm.; Whitetail Conglomerate; Pantano Group (Mineta Fm.); rhyolitic volcanics
	Hickey Fm.	thick salt masses
early	Hickey Fm; Sandtrap Fm.; Artillery Fm. (west); gravels	Helmet Fanglomerate; ? Locomotive Fanglomerate; various volcanics; Pantano Group; Rillito Fm.
Oligocene	alluvium; lake beds; minor volcanics; rim gravels; Artillery Fm.	various volcanics; Pantano Group (conglom., mudstone, lake beds, evaporites, etc.)
Eocene late	Artillery Fm.; ? Baca Fm. (north); rim gravels	? andesitic volcanics; ? Pantano Group
early	? Artillery Fm.	
Paleocene		volcanics

Figure 46--Some Cenozoic rock units of the eastern assessment province.

As with the Tertiary basin oil fields of Nevada, Paleozoic strata may not only source oil but may also produce it; i.e., some oil may have migrated through the extensive fault system into Tertiary reservoirs. In southeastern Arizona, the Pennsylvanian and more probably the Permian carbonates of the Pedregosa basin may fulfill this source-rock requirement (see the previous play description). Local heating by intrusive rocks may have caused oil to be generated in the Railroad Valley, Nevada, fields (Duey, 1984), and may have accomplished the same in the otherwise less mature strata of the southeastern Arizona Tertiary basins.

Present-day heat flow in the play area is between 1.4 and 2.4 HFU (Grim and Berry, 1979; Reiter and Shearer, 1979). Giardina and Conley (1978) have mapped all southern Arizona Tertiary basins as having anomalous temperature gradients, i.e. $\geq$ 3.3°F/100ft (60°C/km). However, according to Witcher (1979), the average temperature gradient is about 2.2°F/100ft (40°C/km) in Arizona's alluvial basins -- a normal gradient in an area of high heat flow (1.92 HFUs). Also, a considerable number of thermal springs, caused by forced convection and deeply circulating water, occur in the play area (Witcher, 1981).

Potential Reservoir Rocks

Tertiary basin sediments are highly variable in texture, lithology, and thickness. Various depositional facies represented include gravels of pediment surface origin, alluvial fan, floodplain, fluvial, terrace, playa, lacustrine, subaerial dune, delta, and evaporating pan. The medium to coarse clastic rocks of fluvial origin and interbedded porous volcanic rocks (e.g., tuffs, rhyolites, ash flows) and fresh-water carbonates have the best reservoir potential (Nations and others, 1983).

Potential Traps

A diversity of stratigraphic pinchouts, unconformities, and structural traps are possible. With up-dip migration toward the horst blocks, oil could be trapped within the complexly and rapidly interfingering reservoir beds. Impermeable layers of claystones or mudstones and evaporites of the ancient playas should contain pockets of hydrocarbons. Whether indigenous or intrusive, there are gypsum, halite, and anhydrite masses at least 3,300 ft thick in at least three Basin and Range grabens of Arizona (Koester, 1971; Eaton and others, 1972; Peirce, 1972, 1974, 1981; Mytton, 1973). The evaporite mass in the Picacho Basin between Phoenix and Tucson is 6,000 ft thick (Nations and others, 1983). Rising salt masses would not only contort the surrounding sedimentary layers and form traps, they would also provide good seals to migrating hydrocarbons. The many very shallow oil and gas shows described by Heylmun (1978), however, may indicate a situation similar to Railroad Valley where imperfect seals have allowed traps to leak; if so, hydrocarbons are thus dispersed throughout the valley fill. Active Late Cenozoic faulting is a serious drawback to trap integrity.

Estimated Depth of Occurrence

No part of the stratigraphic sections of the Teriary basins can be slighted for potentiality. Drilling depths range from a few hundred feet (Heylmun, 1978) to over 12,500 ft, and all basins of this play have depths-to-bedrock of at least 5,000 ft (Giardina, 1979; Oppenheimer and Sumner, 1980). Several of the deepest and largest block-faulted basins in southeastern Arizona are the San Simon (Safford) Basin, Sulphur Springs Basin, and the Tucson Basin where at least 4,000 ft of basin-fill (Whitetail and superjacent Gila Conglomerates plus Quaternary alluvium) occurs over potential source rocks. In these grabens, Oligocene to Pliocene beds could be as deep as 8,000 to 11,000 ft in the area of their long axis.

Exploration Status

Oil was first discovered in the Basin and Range of Nevada within the Railroad Valley graben at Eagle Springs in 1954. Trapping has been described as a truncation fault where oil was preserved in a present-day structural low. Successful exploration techniques included mapping surface fault patterns and geomorphic anomalies (Foster, 1979). Although the source rocks may be both Paleozoic and Tertiary (Suek and Krazan, 1983; Duey, 1984), the best reservoirs to date in Railroad Valley are Eocene lake deposits and Oligocene volcanics; for example, at Trap Spring oil is produced from fractured Oligocene ash-flow tuffs (French and Freeman, 1979).

Exploration in the Tertiary basins of southern Arizona has been primarily focused on geophysics to better understand basin evolution and geometry as related to the search for water resources. The full vertical and horizontal extent of these basins remains to to be tested. Drilling density in the seven valleys of this play is about 72 mi^2 per borehole. There remains much room for productive exploration for oil and gas, considering that over half of the boreholes were drilled in the San Simon (Safford) Basin and include all types of wells - geothermal, water, stratigraphic test, and petroleum. See Johnson (1959), Peirce and Scurlock (1972), Heylmun (1978), Scarborough and Peirce (1978), and Arizona Oil and Gas Conserv. Comm. (1984?) for drilling information and specific locations of oil seeps, oil and gas shows, and petroliferous rocks.

Altar (San Luis) Basin, Southwestern Arizona

Location, Size, and Land Status

About 400 mi^2 in the Basin and Range physiographic province in southwestern Yuma County of southwestern-most Arizona (fig. 2) have oil and gas potential. The play's name originates with the Altar Desert of Mexico but could also be termed the San Luis Basin beneath the Yuma Desert. About

40 percent is military land, 30 percent private land, 17 percent Bureau of Land Management, and 13 percent state land.

Potential Source Rocks and Geothermal Maturity

Miocene to Pliocene marine rocks, particularly the shales and secondarily the carbonates, could generate gas and oil if a sufficiently high level of maturity were reached through both depth of burial and/or high heat flow of the area. These rocks were deposited in the deep, euxinic, and narrow proto-Gulf of California embayment (Blair, 1978; Cole and Armentrout, 1979; Guzman, 1981). Detailed descriptions of the stratigraphic units are not available for inclusion in this report. A high total organic carbon content (up to 10 percent) has been hypothesized by Guzman (1981) for Neogene rocks of this play.

Geothermal maturity may be adequate because onshore oil and gas has already been discovered about 5 miles (8 km) south of Yuma and about 62 miles (100 km) north of Pemex's offshore gas field (Petroconsultants, 1983). Temperature gradients in the play area range from 0.83 to 1.17^{o}F/100ft (15-21.5^{o}C/km) according to DeFord and Kehle (1976), but are in the range of 1.85-2.25^{o}F/100ft (34-41^{o}C/km) according to Kron and Stix (1982) and Nathenson and others (1983). Most thermal water wells in the play area are of two types: 1) discharge temperature <125^{o}F (50^{o}C) with gradient of >2.8^{o}F/100ft (50^{o}C/km); and, 2) discharge temperature >125^{o}F (50^{o}C) with gradient of <2.8^{o}F/100ft (50^{o}C/km) according to Witcher and others (1982). The present-day heat flow ranges from 1.92-2.4 HFU (Grim and Berry, 1979; Kron and Stix, 1982). Gradients increase by a factor of about three just a few miles to the west in southernmost California where there are several KGRAs, such as the East Mesa and Salton Sea fields, and where reservoir temperatures exceed 200^{o}F (90^{o}C) (Muffler, 1979). Figure 33 shows heat flow exceeding 2.5 HFU in this Salton Sea trough/Imperial

Valley area (Sass and others, 1981; Nathenson and others, 1983).

Potential Reservoir Rocks

The general Precambrian to Recent stratigraphy of southwestern Arizona (fig. 8) has been described by McCarthy (1961) who documents at least 1,300 feet of marine and brackish water deposits of Pliocene age in the Yuma area. Although the Miocene-Pliocene package of admixed conglomerates, sandstones, siltstones, shales, and carbonates, interbedded with volcanic beds, is the full stratigraphic range of reservoir targets, the principal reservoir is the Pliocene Bouse Formation; the several thousand feet of Miocene clastics is the secondary target.

Potential Traps

The pre-Tertiary geologic history of this area is sketchy and hence the limits of speculation are much wider than for the other plays described herein. The structural grain of southern Yuma County (south of 33° N. lat.) trends northwest (Mattick and others, 1973), e.g. the Gila-Tinajas Altas Mountains, and is inherited from an allochthonous terrane deformed by Laramide compression and complex overprinting by Cenozoic transcurrent faulting (San Andreas-Imperial-San Jacinto-Algodones fault system, fig. 3 and 7) and extension. Guzman (1981) suggested that the Altar Basin is genetically related to the oil-rich Los Angeles and other Miocene basins of southern California, but offset by right-lateral movement along the San Andreas fault zone. Drag folding along the strike-slip fault system may have created hydrocarbon traps.

Rapid facies changes, and hence porosity pinch-outs, are to be expected in this narrow trough which received a rapid accumulation of sediments. Also, mid-Tertiary tilting has created angular unconformities. Erosional unconformities, such as between the Miocene and Pliocene (Rusnak and Fisher, 1964), increase the potential for entrapment of hydrocarbons.

Estimated Depth of Occurrence

Seismic refraction in the northern Gulf of California (Phillips, 1964) indicated a possibly total thickness of unconsolidated sediments (? Pliocene and Pleistocene) of 5,000 ft, and semi-consolidated sediments (? Miocene and Paleogene) of 6,500 ft. Gravity studies by Biehler and others (1964) have revealed that Neogene sediments may be 10,000-15,000 ft deep between the Salton Sea of Southernmost California and the northern Gulf of California. Mattick and others (1973) have shown that except for a north-south basement high in the Yuma area, northwest-trending structural contours on top of the Bouse Formation decrease in elevation southwestward. These contours decrease from +500 ft on the southwest side of the Gila Mountains to -3,300 ft near 114°45′ W. long. and 32°30′ N. lat. in the southwestern-most play area. Corresponding topographic elevations of this area range from approximately 200-1,000 ft, thereby indicating minimum drilling depths of about 500 to 3,500 ft. Oppenheimer and Sumner (1980) have mapped the maximum depth-to-bedrock in the Altar Basin south of Yuma and southwest of the Gila Mountains to be between 11,200 and 12,800 ft. The latter data suggest that the top of Neogene targets probably occur no deeper than about 5,000 ft. Based on the Exxon 1 Yuma Fed. well (sec. 8, T11S, R24W, TD=11,444 ft), Guzman (1981) placed the top of the marine Pliocene strata at about 4,100 ft in the Yuma area.

Deltaic sediments of the Colorado River in the northern Gulf yielded a gas discovery in a Pliocene-Pleistocene section 13,000-19,700 ft thick (Oil and Gas Journal, 1982). In southwestern Yuma County, two dry holes with Miocene objectives (permitted to 10,000 ft) were drilled in late 1987 to at least 7,000 ft by Petroleum Technical Services of Midland, TX.

Exploration Status

Miocene gas was discovered in 1981 by Pemex in the northern Gulf of California (offshore northwestern Sonora, Mexico) according to Nations and others (1983). Very little is known about this discovery and discrepancies occur in the meager published literature. The Oil and Gas Journal (1982) reported gas plus condensate was discovered by Pemex in Pleistocene sediments and flowed at 6 million CFG per day and 30 BB oil per day. Petroconsultants (1983) reported another oil and gas discovery by Pemex in early 1983 8 miles south of Yuma County and about 60-65 miles north of the 1981 discovery. Hydrocarbon shows as deep as Eocene strata in the play are noted by Guzman (1981). Recent shows were found in a 5,000-ft well of the play area (sec. 34 T10S, R23W). About 50 mi northeast of this play, gas shows were detected in the Desert Drilling No.1 State well (Peirce and Scurlock, 1972). The 6,770-foot well was drilled in 1963; the gas was reported at 6,550 feet in ? Cenozoic sediments. Figure 45 shows that only 15 boreholes had been drilled for petroleum (32 drilled for other reasons) in Yuma County (now, Yuma plus LaPaz Counties) as of 1982; most of these holes are in the play area. Three boreholes were drilled between 5,000 and 10,000 ft, and the deepest well in the county is also here in the play and is 10,595 ft. Exploration activity in southwestern-most Arizona is as high as anywhere in the state at present.

SUMMARY

During the "older" Precambrian Era (Early to Middle Proterozoic) of central and southern Arizona, plate collision caused continental accretion and mountain-building. Subsequent peneplanation separates this tectonism from "younger" Precambrian (Middle to Late Proterozic) block-faulting, intrusion, metamorphism, and wrench faulting. Precambrian events controlled succeeding Phanerozoic sedimentary rock deposition, plutonic and volcanic foci, structural trends, and presumably fluid migration routes. A major zone (Texas Lineament) trending northwest through the province, considered by some to represent northeast-directed thrust-faulting, is more likely a combined result of regional underthrusting, local overthrusting, basement uplift, and wrench (transform) faulting.

Paleozoic and Mesozoic strata of west-central and southwestern Arizona have virtually no petroleum potential based on their intense thermal history, i.e. they are super-mature to metamorphosed in outcrops. However, locally in the Pedregosa basin of southeastern Arizona and southwestern New Mexico, there is higher potential in unmetamorphosed interbedded organic-rich carbonates and clastics of Pennsylvanian and Permian age. Abundant traps, including stratigraphic (facies) types, unconformities, and Laramide folds and thrust faults, occur throughout the basin. The petroleum potential of the Cretaceous System, consisting of mostly clastic reservoir rocks many thousands of feet thick and local bioherms, has a down-graded potential because of the sparcity of source rocks and seals.

Stratigraphic pinch-outs in numerous mid-Tertiary grabens offer a multitude of targets associated with petroliferous lacustrine deposits. Freshwater carbonates, evaporites, and mudstones are closely associated with intercalated volcaniclastics and fine-to-coarse siliciclastic basin-fill. Paleozoic oil could also be structurally trapped near the bounding faults of these grabens, such as found in Railroad Valley, Nevada.

The accumulation of and search for petroleum in this assessment province have encountered major obstacles. Multiple episodes of deformation and plutonism have obscured the geologic record and have made geophysical exploration difficult. Relatively late events include the evolution of scattered metamorphic core complexes and the overprinting of Paleozoic and Mesozoic sedimentary rocks by Miocene and younger horsts and grabens -- including some low-angle detachment faults. Alluvial valleys grew as uplifted fault blocks were eroded and buried in their own debris. This thick, widespread alluvial cover is a detriment to exploration for Paleozoic hydrocarbons deep within the structural valleys. Block-faulting and fresh-water flushing of potential reservoirs by deep-circulating convective hydrothermal systems are other detriments to oil and gas accumulation. Although an abundance of volcanic rocks and local calderas unfortunately limits the sizes of the petroleum plays, the associated effects of high heat on source rocks have had minimal impact without condemning the regional potential.

In Arizona's portion of the assessment province, drilling density for all types of wells (including mineral, stratigraphic test, and geothermal) is 180 mi^2 per borehole. Nineteen of these wells are between 5,000 and 10,000 ft deep, and five are over 10,000 ft deep. Drilling density for strictly petroleum tests in the same area is 395 mi^2 per borehole. Most targets of the four plays are between 5,000 and 20,000 ft deep.

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