THE RATIONALE FOR ASSESSMENT OF UNDISCOVERED, ECONOMICALLY RECOVERABLE OIL AND GAS IN CENTRAL AND NORTHERN ARIZONA: PLAY ANALYSES OF SEVEN FAVORABLE AREAS

by

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

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ABSTRACT

Seven oil and gas plays, totalling about 12,750 square miles, have been identified in the northern Arizona assessment province of the U.S. Geological Survey. This province is roughly north of 34°15′ N. lat. in its western half and north of 33°15′ N. lat. in its eastern half. These seven plays have good potential for the future discovery of economic oil and gas accumulations in reservoirs of middle and late Paleozoic age. Assessments are based on favorable attributes of potential source and reservoir rocks plus geothermal maturity, trap development, migration and timing. Arizona's only petroleum production occurs in the northeast corner of Apache County where the first oil field was discovered in 1954. Currently, Arizona's oil and flammable gas are extracted from Pennsylvanian rocks with minor production from Mississippian and Devonian rocks.

Six plays are outlined in the Colorado Plateau physiographic province and one in the Cordilleran overthrust belt in the Basin and Range province of extreme northwestern Arizona. Plays are: 1) Devonian, Mississippian, and Pennsylvanian reservoirs in the Cordilleran overthrust structures; 2) Devonian through Permian reservoirs in primarily structural traps of the Hurricane Fault - Uinkaret Plateau area of northwestern Arizona; 3) Devonian reservoirs in both structural and stratigraphic traps in the greater Black Mesa basin of northeastern Arizona; 4) Pennsylvanian bioherm and carbonate mound reservoirs along the southern margin of the Paradox basin in extreme northeastern Arizona; 5) Pennsylvanian reservoirs along the northern, western, and southern flanks of the Defiance uplift in northeastern Arizona; 6) Pennsylvanian and Permian reservoirs in the Holbrook anticline region of the southwestern Holbrook basin of east-central Arizona; and, 7) Pennsylvanian and Permian reservoirs in anticlines and updip stratigraphic pinchouts within the northeastern Holbrook basin of east-central Arizona.

All Arizona plays are speculative except for: 1) the extreme northeastern part of the greater Black Mesa basin which has very minor oil production, 2) the Paradox basin (Blanding basin subprovince) which has minor Pennsylvanian oil and gas production in seven fields, and 3) the northern flank of the Defiance uplift which contains Arizona's largest producing field, Dineh-bi-Keyah. The latter is a 20-million-barrel (ultimate recovery) field discovered in 1967. It produces from a fractured igneous sill of Oligocene age within the Pennsylvanian section.

Regional anisotropy of basement rock and paleotopography have strongly influenced the growth of younger tectonic features and depositional patterns and are expressed in northwest-northeast geophysical trends. Continued analyses of these trends may provide one of the keys to finding more oil and gas in northern Arizona.

Northern Arizona is a frontier exploration area with inviting targets and favorable potential. There are approximately 800 boreholes in the assessment province; almost half of these were drilled for oil and gas. The remainder were drilled exploring for geothermal, helium, and mineral resources, and as stratigraphic tests. About 130, or 35 percent, of the oil and gas boreholes are between 5,000 and 8,500 feet deep with none being deeper than 8,500 feet. Excluding development wells in existing oil, gas, and helium fields, drilling has been geographically uneven with an overall average drilling density of about one borehole per 140 square miles. In many instances drilling has been too shallow to reach the best potential reservoirs, and strategies have not always been based on modern exploration principles. Very few boreholes have tested the sedimentary section beneath the volcanic rock cover. Over 26,000 square miles (40 percent) of the study area is Indian reservation lands; unfavorable leasing policies have sometimes discouraged exploration in these areas (Peirce, 1982).

INTRODUCTION

General Statement and Purpose

This report has been prepared for the U.S. Geological Survey's National and Federal Lands Appraisal Program (FLAP province #91). The area investigated roughly includes the state of Arizona north of latitude 34°15' in the western part and north of latitude 33°15' in the eastern half. This includes the counties of Mohave, Coconino, Yavapai, Navajo, Apache, and Gila, and the northern third of Graham and Greenlee counties. Figures 1 and 2 are index maps locating the area assessed, political boundaries, and tectonic elements. Figure 3 defines the geographic boundaries for seven areas having the highest petroleum potential. All plays are limited to northern Arizona by definition of the program's province boundaries.

Information presented herein is the qualitative component of quantitative estimates presented to the U.S. Geological Survey's assessment project. A tectonic framework, including history, has been synthesized for the assessment area to allow the reader to draw deductions about causal relationships. Basic information concerning the surface geology, e.g. state geologic maps, has been taken from the following: Dane and Bachman (1965), Longwell and others (1965), King (1969), Wilson and others (1969), Grose (1972), Hintze (1975), and Steward and Carlson (1978). Formation names and thicknesses specific to each play are presented in appendix A. The land status of each play is presented in appendix B.

Scope and Depth of Report

This generalized report is a condensation of seven detailed play analyses by the author. Although hundreds of additional references in my data base were used, particularly in documenting stratigraphy, only the essential or most representative ones have been cited in order to provide the basic rationale, with balance among disciplines, consistent with

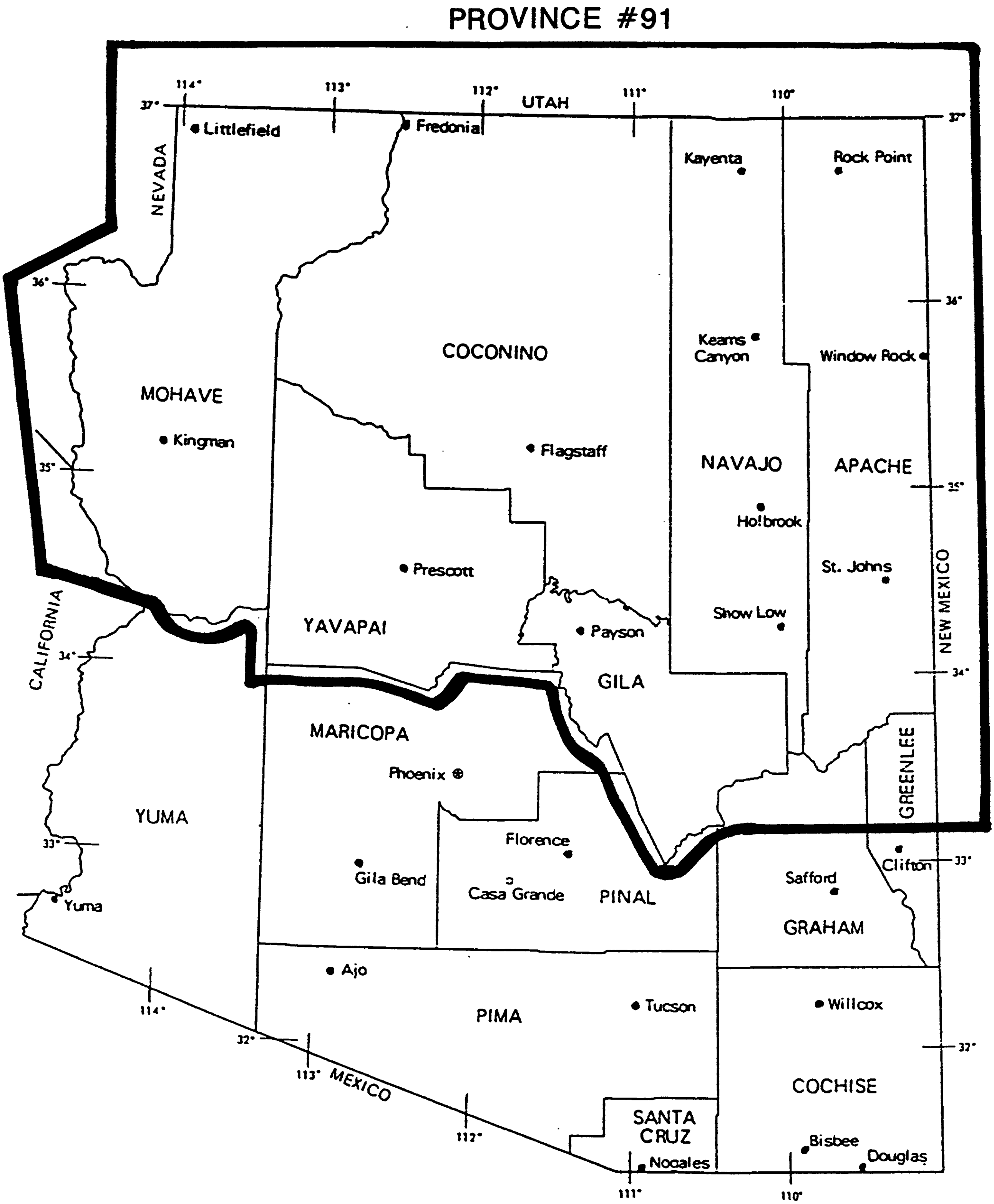


Fig. 1--Index map of Arizona. Area assessed inside heavy line.

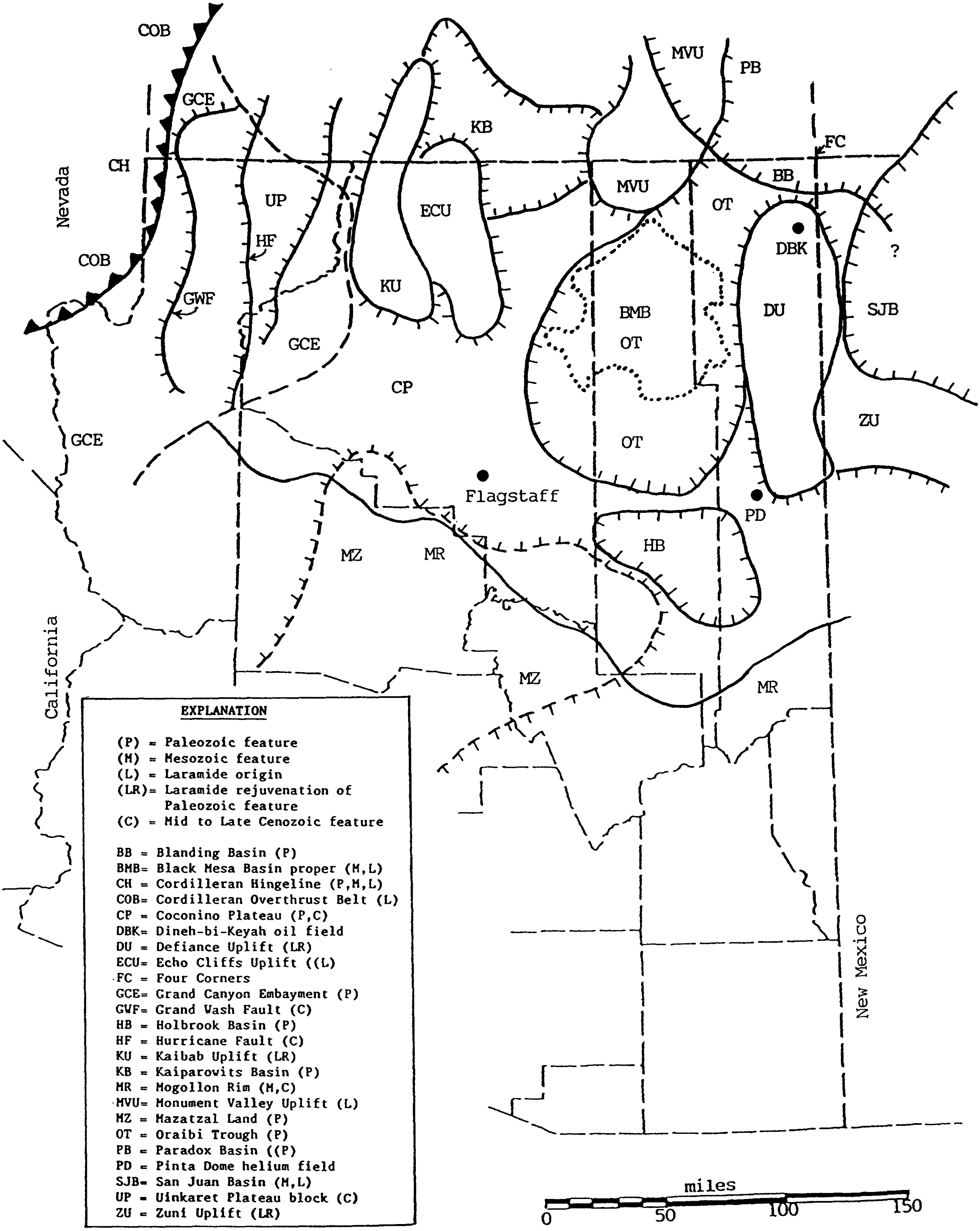


Fig. 2--Generalized tectonic map of central and northern Arizona.

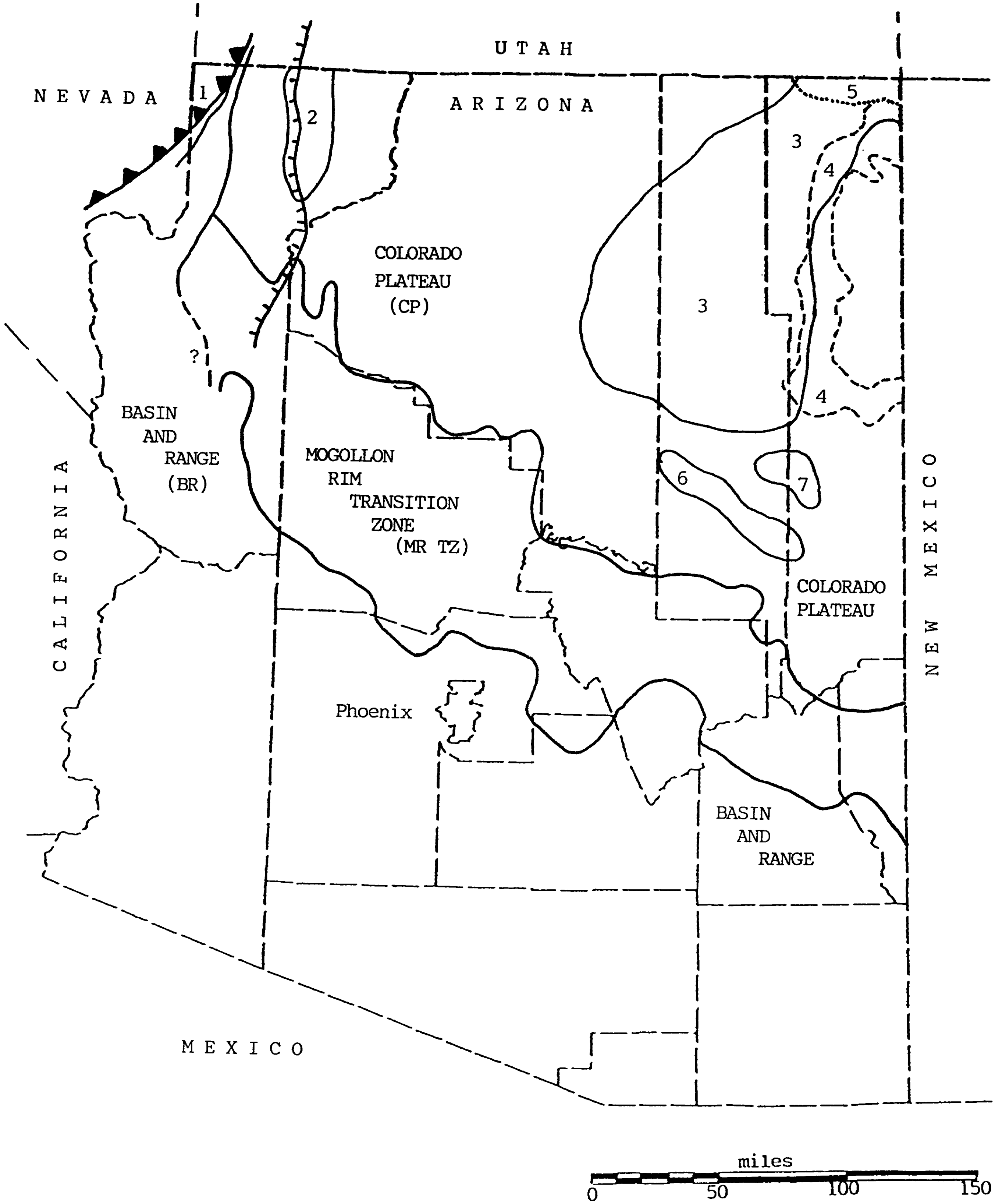


Fig. 3--Location of seven petroleum plays relative to the physiographic provinces of Arizona. #1= Cordilleran Overthrust Belt; #2= Hurricane Cliffs - Uinkaret Plateau; #3= Greater Black Mesa Basin; #4 = Western Flank of the Defiance Uplift; #5= Southern Margin of the Paradox Basin; #6= Holbrook Anticline; #7= Petrified Forest of Holbrook Basin.

resource assessment on a national scale. Given the large assessment area, local geologic relationships have only briefly been addressed. Geophysical studies supporting assessment rationale, comparative hypotheses on tectonic evolution, local structural complexities, and stratigraphic nomenclature problems have been either treated superficially or omitted.

Acknowledgments

The author expresses appreciation to C.W. Spencer and C.M. Molenaar for their helpful discussions regarding the petroleum geology of northern Arizona. D.K. Higley and J.W. Schmoker made valuable editorial comments.

GENERAL TECTONIC AND DEPOSITIONAL SETTINGS

Arizona is divided physiographically into two main provinces (Fenneman, 1928; Eardley, 1951; Bayer, 1983), 1) the Basin and Range (BR) about 51,000 square miles, and 2) the Colorado Plateau (CP) about 45,000 square miles. A third subprovince, the Transition Zone (TZ), also called the Mexican Highlands, is about 18,000 square miles and occupies the central Arizona mountains (fig. 3). The CP-TZ boundary is marked by the Mogollon Rim (MR) escarpment. The TZ lies between the other two provinces, possessing features of each (Peirce, 1985). It becomes less well defined in northwestern Arizona and abruptly terminates at the Grand Wash fault (GWF). The northern Arizona assessment province of the U.S. Geological Survey includes the CP, TZ, and small segments of the BR around the western and southern margins. Peirce and others (1970) have summarized the significant geologic events of Arizona's plateau history in figure 4. Figures 5 and 6 summarize the stratigraphy of northern Arizona and adjacent areas.

Precambrian

Two groups of Precambrian rocks are recognized: the "older

ERAS	Periods and Epochs		Age-millions of years	Geologic Highlights of Plateau Region of Arizona	
CENOZOIC	Quaternary	Recent		Alluvial sediments; volcanics.	Volcanism. Uplift and erosion.
		Pleistocene	.011	Stream, river, and lake deposits; volcanics; glaciation on San Francisco Peaks near Flagstaff and in White mountains.	Local sedimentation.
	Tertiary	Pliocene	1	Continental sedimentation: Bidahochi and Verde Formations. Uranium occurrences.	Mogollon Rim faulting.
		Miocene	12	Unconformity	Regional uplift of large magnitude. Volcanism and erosion.
		Oligocene	23	Chuska Sandstone, "Rim" gravels, Datil Formation.	
		Eocene	40 (Unconformity)	Rock units not generally recognized.	Laramide Revolution. Folding, monoclinal flexuring. Formation of Kaibab, Monument, and Defiance uplifts, and Black Mesa basin. General uplift.
		Paleocene			
MESOZOIC	Cretaceous		70 (Unconformity)	Up to 2,000 feet upper cretaceous marine and non-marine sediments, principally sandstones and shales; important coal deposits in Black Mesa; local uranium occurrences.	
	Jurassic		135 (Unconformity)	Up to 2,000 feet largely non-marine sediments, principally sandstones. Morrison Formation important uranium host rocks.	Northward tilting of Black Mesa basin region-erosion. (Nevadan?)
	Triassic		180	Up to 1,500 feet non-marine sediments, principally shales and sandstones. Contains host rocks for major Arizona uranium deposits and reservoir rocks for helium. A Black Mesa basin objective.	
PALEOZOIC	Permian		220 (Unconformity)	Up to 2,000-3,000 feet marine and non-marine sediments. Contains principal reservoir rock for helium at Pinta. Local petroleum, natural gas, and helium potential. A Black Mesa basin objective. Locally, a host for important uranium deposits. Minor coaly occurrences.	General uplift and erosion. Local basining.
	Pennsylvanian		270	Up to 2,000 feet of marine sediments, principally carbonates and shales. Important reserves and objectives for oil and gas in Black Mesa basin area.	Local basining.
	Mississippian		320 (Unconformity)	Up to 800 feet marine sediments, principally carbonates. Local petroleum, natural gas, and helium production in Black Mesa basin area A drilling objective throughout N. Arizona.	Regional erosion.
	Devonian		350	Up to 600 feet marine sediments, principally carbonates with locally important sandstones. Local petroleum production and helium occurrences. A drilling objective in Black Mesa basin area.	Local erosion.
	Silurian		400	Not recognized.	General emergence.
	Ordovician			Marine sediments in extreme NW. Arizona.	
	Cambrian		490 (Unconformity)	Up to 1,500 feet marine sediments, principally sandstones, shales, and carbonates. Limited drilling objective in NW. Arizona. Sandstone beneath Devonian to SE is a local objective.	
YOUNGER PRECAMBRIAN			600 (Unconformity)	About 10,000 feet quartzite, shale, and limestone.	Grand Canyon disturbance.
OLDER PRECAMBRIAN			1600 (Unconformity) – 2000+	Granitic and metamorphic rocks constitute basement rocks of region. Local outcrops in Defiance and Grand Canyon regions.	Mazatzal Revolution.

Fig. 4--Time scale with geologic highlights of the Arizona Plateau region. (From Peirce and others, 1970).

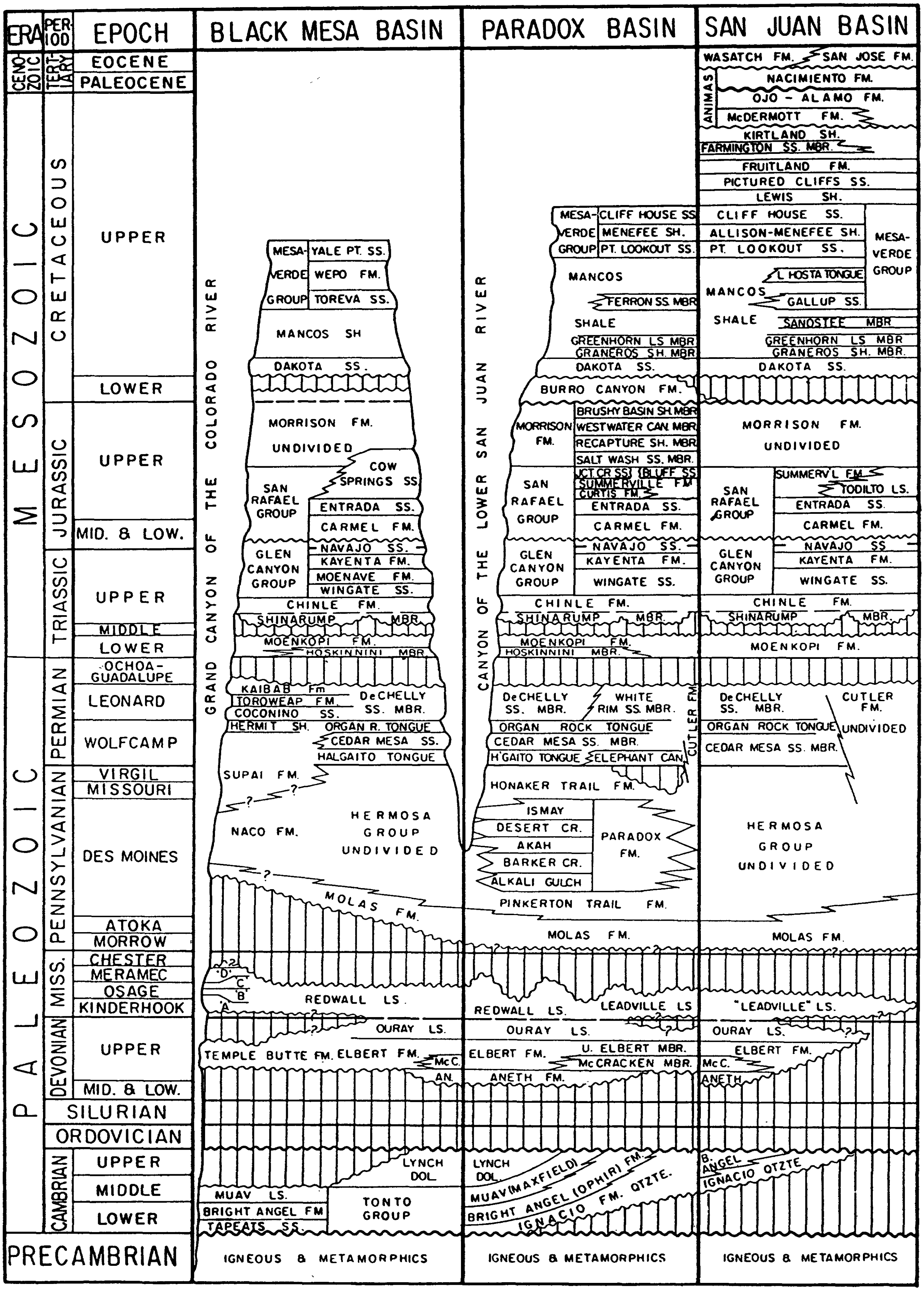


Figure 5.--Stratigraphic column of the Four Corners region. (From See, 1963).

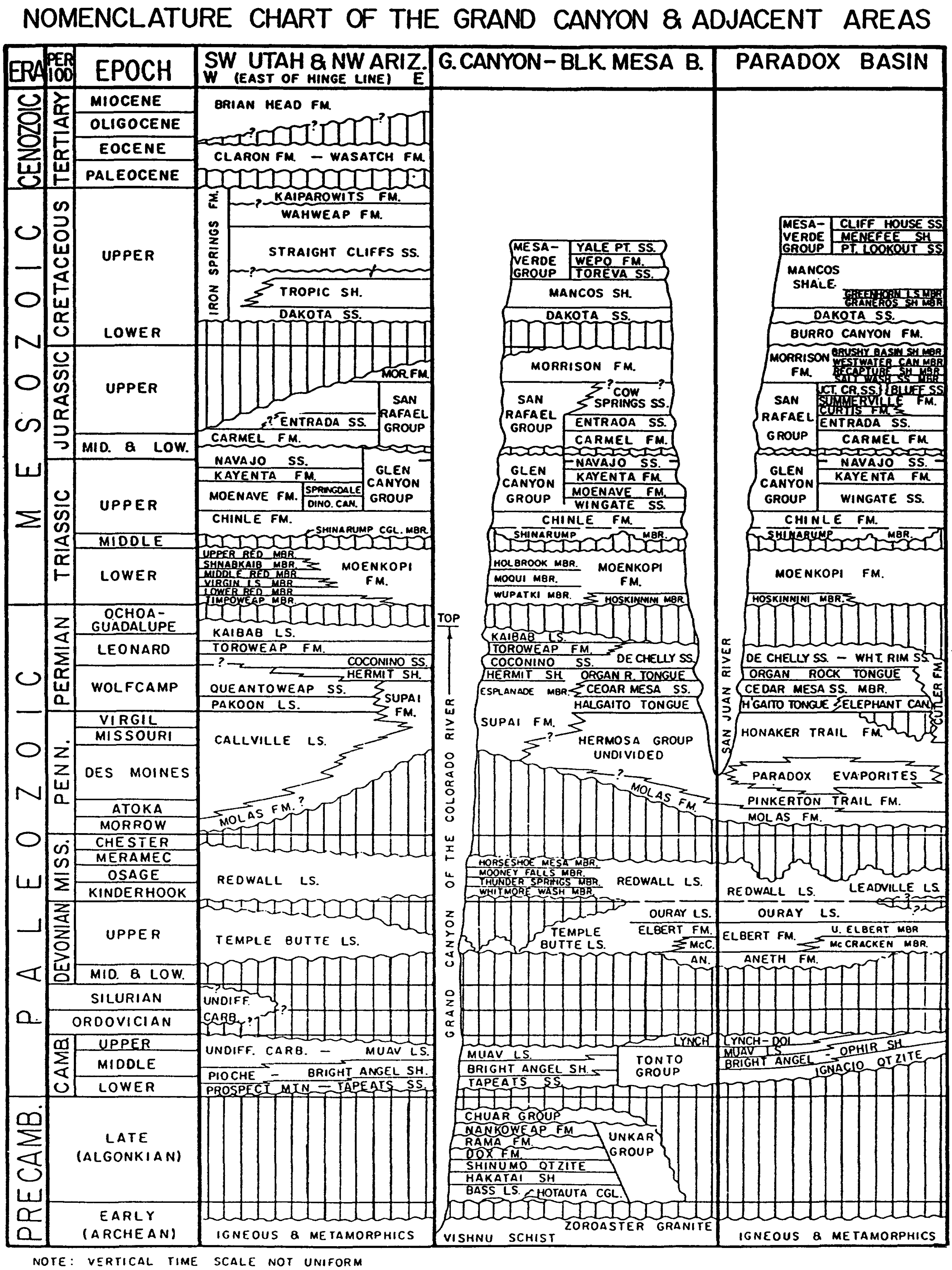


Fig. 6--East-west correlation chart of northern Arizona and adjacent areas. (From Molenaar and Halverson, 1969).

Precambrian" or Early Proterozoic and the "younger Precambrian" or Middle and Late Proterozoic. Early Proterozoic rocks consist mostly of thick sequences (up to about 50,000 feet) of schists, e.g. the Vishnu and Yavapai, plus metasedimentary and metavolcanic rocks (Wilson, 1962), dated at about 1.65-1.80 b.y. They are widely exposed in the TZ of central Arizona (fig. 7); other less extensive outcrops are found in the Grand Canyon of the CP and in the BR of extreme northwestern Arizona (Lance, 1958; Shafiqullah and others, 1980; Condie, 1981).

Tectonism during this time involved northwest-southeast compression and thrusting resulting in accretion of crustal terranes via plate convergence and subduction in island arc (geosynclinal) settings near the southwestern margin of the craton. The Mazatzal revolution severely deformed these older Precambrian rocks through uplift and mountain-building, and also by intrusion of granite batholiths, gabbros, and pegmatites (Wilson, 1939). Major plutonism occurred about 1.4 b.y. ago culminating diastrophic events. Northeast-trending mountains were thus formed in central Arizona followed by nearly a half billion years of erosion. A pronounced unconformity separates Early Proterozoic rocks formed in the Mazatzal Mountains core from superjacent metasedimentary and sedimentary Precambrian strata.

Early Proterozoic rocks predominate in outcrop with some Middle Proterozoic epicontinental marine deposits exposed in the central TZ (Sierra Ancha Mountains of Gila County) and in the Kaibab uplift (KU) area of north-central Coconino County. The Grand Canyon Series (Unkar and Chuar Groups) is as much as 12,000 feet thick and is the northern equivalent of the Apache Group in central Arizona and the Belt Supergroup to the north. In the study area there are two main belts of these supracrustal Precambrian rocks, dated at about 1.0-1.2 b.y. These belts extend from the Sierra Ancha Mountains of central Arizona north-northeastward to FC, and

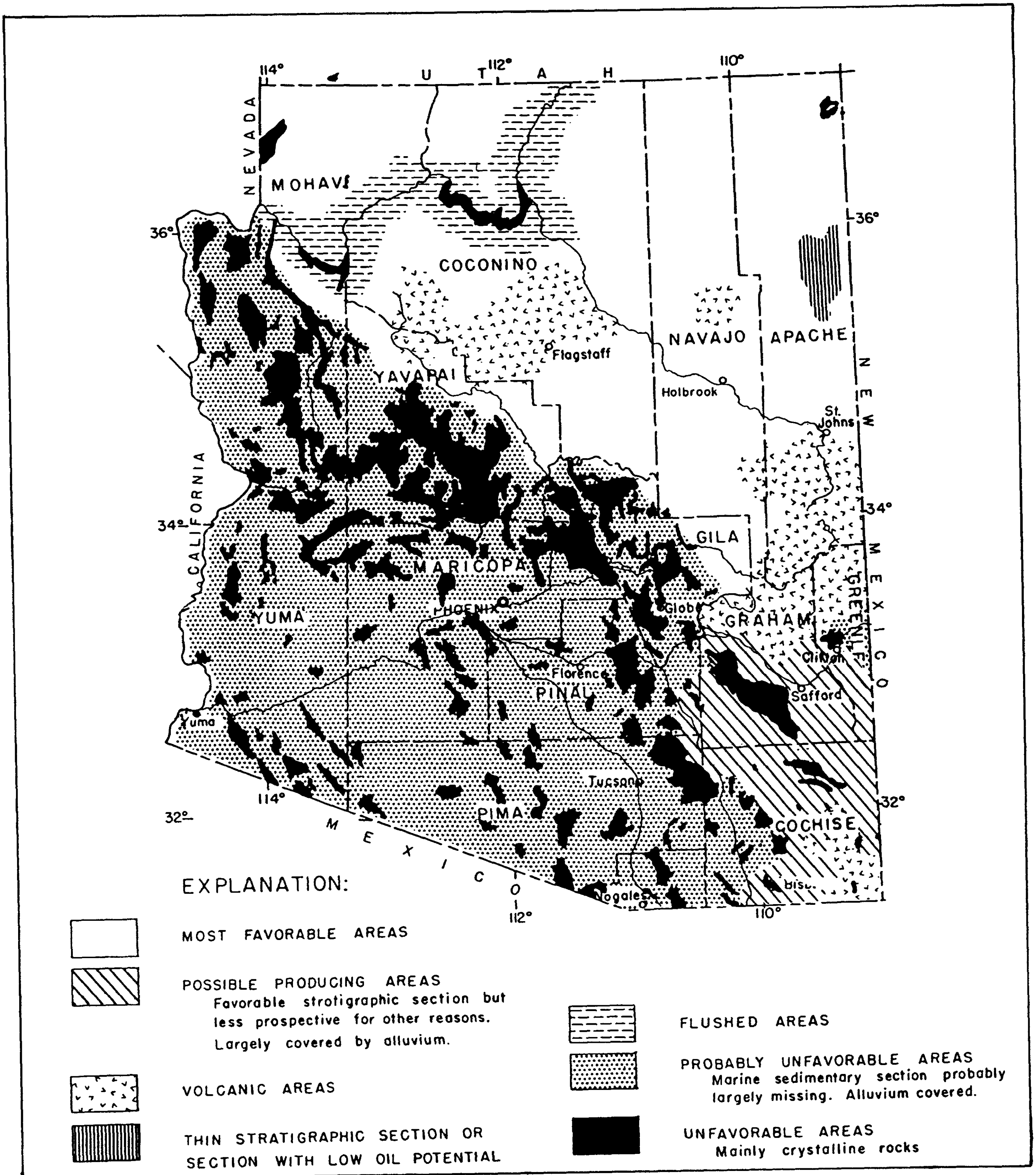


Fig. 7 —Map showing the oil potential of various parts of Arizona based upon the stratigraphic section present in each locality. The most favorable region is the white area of the map in northeastern Arizona; stratigraphically favorable but otherwise carrying a higher risk factor is the diagonally lined southeastern part of Arizona; the rest of Arizona ranges from poor to no oil or gas potential. (From Pye, 1961).

from the KU area of northern Coconino County northwestward (Bayley and Muehlberger, 1968; Stewart and Poole, 1974; Condie, 1981). Reynolds and others (1988) measured up to 5 percent total organic carbon (TOC) in mudstones of the Chuar Group of the Grand Canyon. Based on Rock-Eval results they believed these Precambrian rocks have source rock potential.

One of the last tectonic events (Late Proterozoic) to affect Precambrian rocks was the intrusion of extensive diabase sills in the central TZ. This period of metamorphism, tectonic relaxation, and regional block-faulting is called the Grand Canyon Disturbance. A third belt of 0.6-0.8 b.y.-old supracrustal rocks trends northeastward paralleling the Cordilleran hingeline (CH) in northwestern Mohave County. Except for extreme northwestern Arizona, a second pronounced unconformity separates the Precambrian supracrustal rocks from Phanerozoic strata. Figure 8 depicts the surface topography of the Precambrian crystalline basement.

Geophysical Expression and Possible Relationship to Petroleum

The history of Precambrian rocks, including identification of the fundamental zones of weakness, is important because the large-scale structural grain and depositional/erosional trends of Phanerozoic strata have been inherited from pre-existing features controlled by the generally northwest and northeast fracture pattern (see fig. 9 showing stress-strain ellipsoid) of the basement blocks. Each successive rejuvenation/deformation through time was significantly influenced by previous ones. Megashearing and normal and reverse faulting have occurred along the zones. Selected literature pertaining to basement trends includes: Baker, 1936; Kelley and Clinton, 1960; Turner, 1961; Wilson, 1962; Tweto and Sims (1963); Baars and See (1968); Case and Joesting, 1972; Hoppin (1974); Shoemaker and others, 1974; Davis, 1975 and 1978; Peirce, 1976; Stevenson and Baars, 1977; Warner, 1978 and 1980; Nations and others, 1983a; Stevenson, 1983b; Woodward-Clyde Consultants, 1983; Picha, 1986.

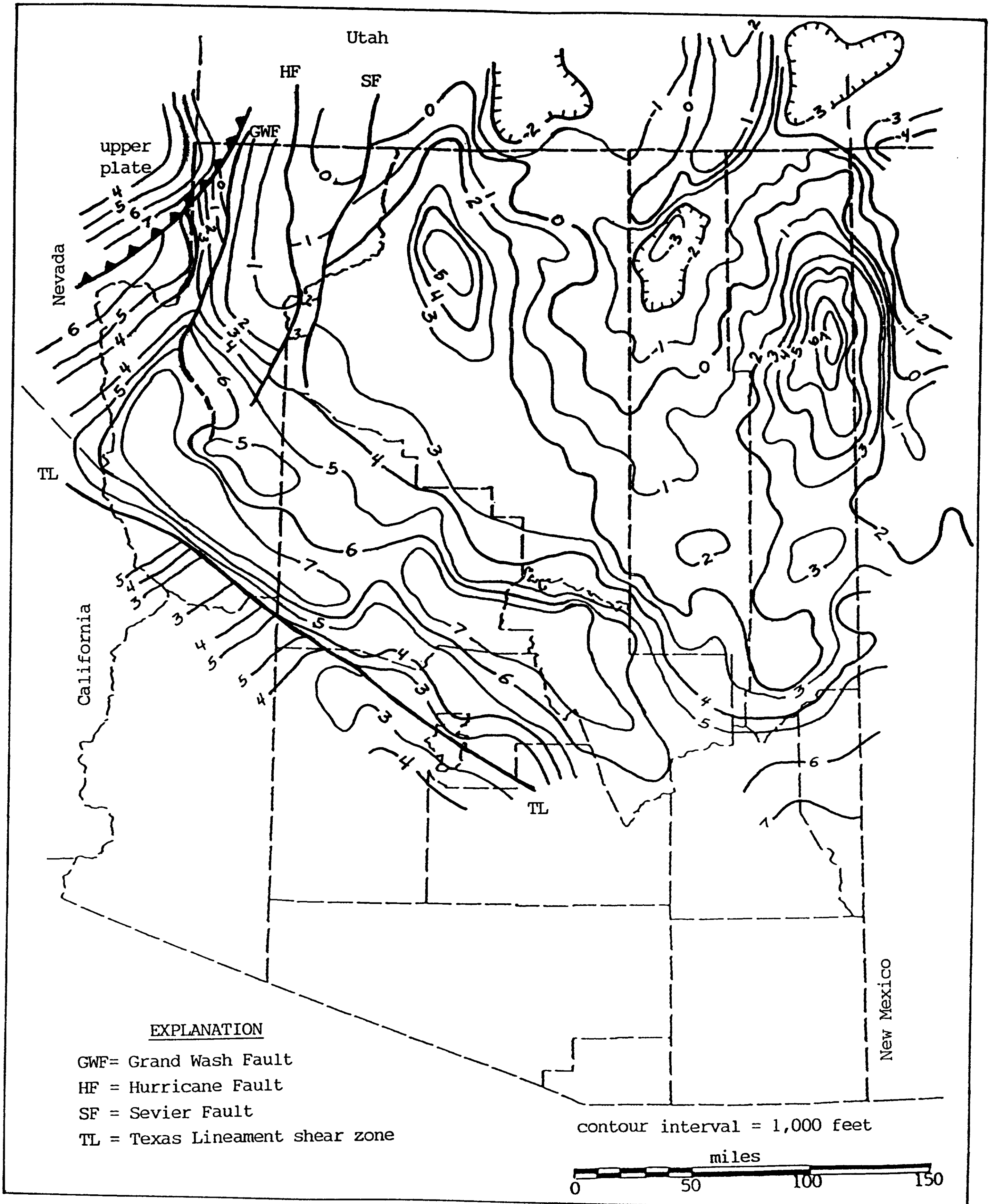


Fig. 8--Structural contour map on top Precambrian crystalline basement. Modified from Bayley and Muehlberger (1968), Kleinkopf (1972), and Conley and Giardina (1979).

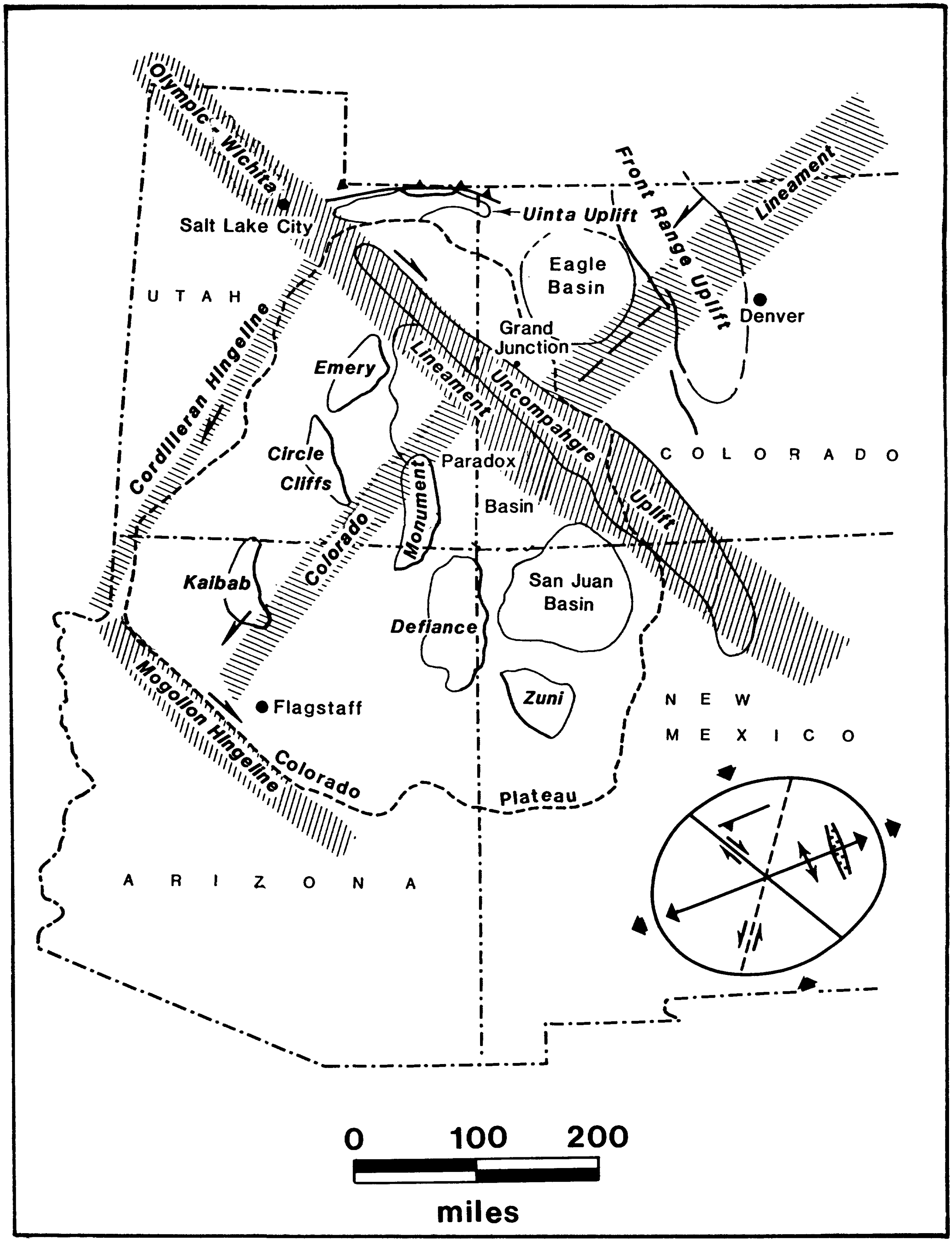


Fig.9-- **Map showing location of Colorado Plateau and relationship to major orthogonal set of lineaments. Northwest-trending lineaments are right lateral, northeast-trending lineaments are left lateral. Stress-strain ellipsoid oriented such that maximum compressive stress is directed from the north.** (From Baars and Stevenson, 1981).

Trends of geophysical anomalies (e.g. see maps in Gutman and Heckmann, 1977; Conley and Giardina, 1979; Titley, 1981) likewise reflect the basement configuration as determined through outcrop study and boreholes. Orthogonal to polygonal trends are evident at small to large scales on gravity maps by West and Sumner (1973), Sumner (1975), Lysonski and others (1980), Hildenbrand and others (1982), Jachens and others (1985), and Simpson and others (1986), and also on aeromagnetic maps by Sauk and Sumner (1971), Zietz (1982), and Cordell (1983). As noted below, some workers have also suggested that regional-scale fractures may have strongly influenced the accumulation of Paleozoic oil and gas in the FC area. In reference to the CP, Davis (1975) stated, "As loci of major fracturing, folding, and probably facies changes, the [basement] fracture zones have exerted control(s) on the entrapment of oil and gas." Stevenson (1983b) has also stated that all petroleum in northwestern New Mexico occurs at the intersection of these basement lineaments. Three plays in northeastern Arizona are adjacent to or include the area investigated by Stevenson. However, there are two major difficulties with this migration hypothesis: 1) reservoirs are generally very discontinuous in the Devonian, Mississippian, and Pennsylvanian fields, and 2) oil and gas would have to migrate long distances - in some cases down-dip against buoyancy - to fill traps. Picard and others (1960) and Kornfeld (1963) considered that primary migration has not play a major role in entrapment.

Paleozoic Era

Paleozoic deformation was mild and is best described as tilting, sagging, warping, and arching in response to primarily vertical basement readjustments with no evidence of magmatism. Three major tectonic features dominated northern Arizona during the Paleozic Era (fig. 10). Initially, the area was a stable shelf at the edge of the interior craton, i.e. a

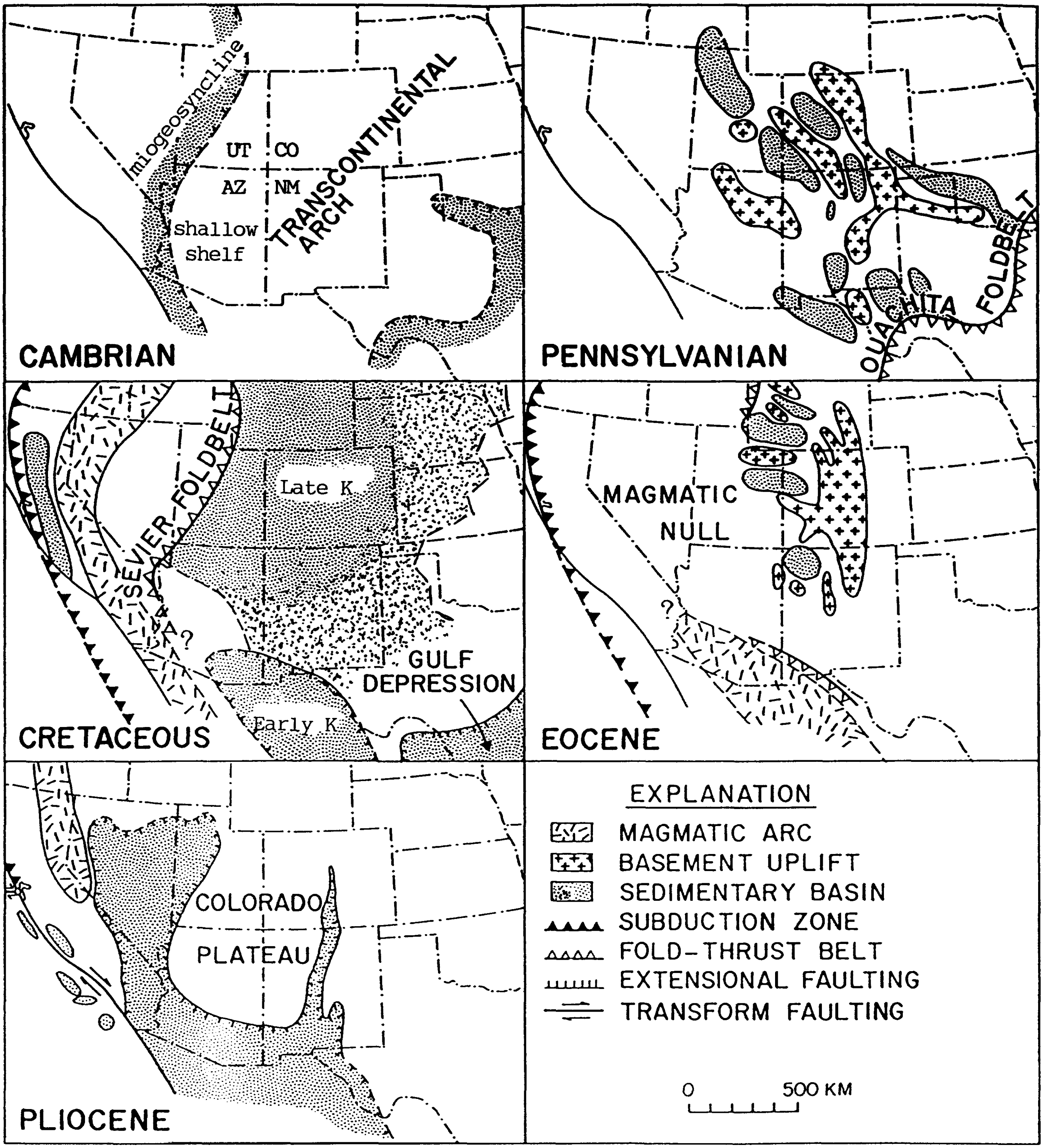


Fig. 10--Schematic paleotectonic setting of southwestern United States. The maps are not palinspastically restored. (Modified from Woodward and Ingersoll, 1979).

relatively passive plate margin with intervening shallow-marine basins and positive areas intermittently inundated by epicontinental seas. Secondly, the northeast-trending CH in extreme northwestern Arizona separated shelf from miogeosynclinal sedimentation farther west. It also separates the western allochthonous thrust sheets from the autochthonous rocks to the east. Other names for the CH are Wasatch, Sevier, and Las Vegas lines. Thirdly, the transcontinental arch (TCA), a prominent, long-lived, large-scale tectonic feature, influenced sedimentation and erosion from central Arizona northeastward to Minnesota (Eardley, 1951; Stokes, 1958 and 1961; Lessentine, 1965; Dott and Batten, 1971; Mallory, 1972; Nydegger, 1982; Kluth, 1986). The TCA was repeatedly flooded by shallow epeiric seas and periodically beveled by erosion, thus creating a constantly changing outline and many unconformities, wedge-outs, and potential hydrocarbon traps in the stratigraphic section, such as in the DU area. Both clastics and carbonates were deposited on the Paleozoic shelf. Thickness of the total Paleozoic strata increases from about 1,500-2,000 feet over the DU to about 3,500-4,500 feet southwestward in the HB to 7,000 feet or more in northwestern Arizona. Isopach maps in figures 11 to 16 provide an overview of the major Paleozoic depocenters and zero edges.

From the Cambrian through the Mississippian periods, the relatively stable tectonic setting did not change significantly; both siliclastic and carbonate sediments were deposited as platform cover (fig. 17) and increase in thickness from the DU to the CH. Seas generally transgressed eastward and southeastward out of the Cordilleran geosyncline and northwestward out of southeastern Arizona across a surface of low relief. These seaways led into and away from central Arizona, the southwestern end of the TCA. Here the arch is termed Mazatzal Land (ML) by Stoyanow (1942), Huddle and Dobrovolny (1952), and Wilson (1962) among others. The first Paleozoic onlap-offlap sequence deposited beach sand and offshore carbonate and shale

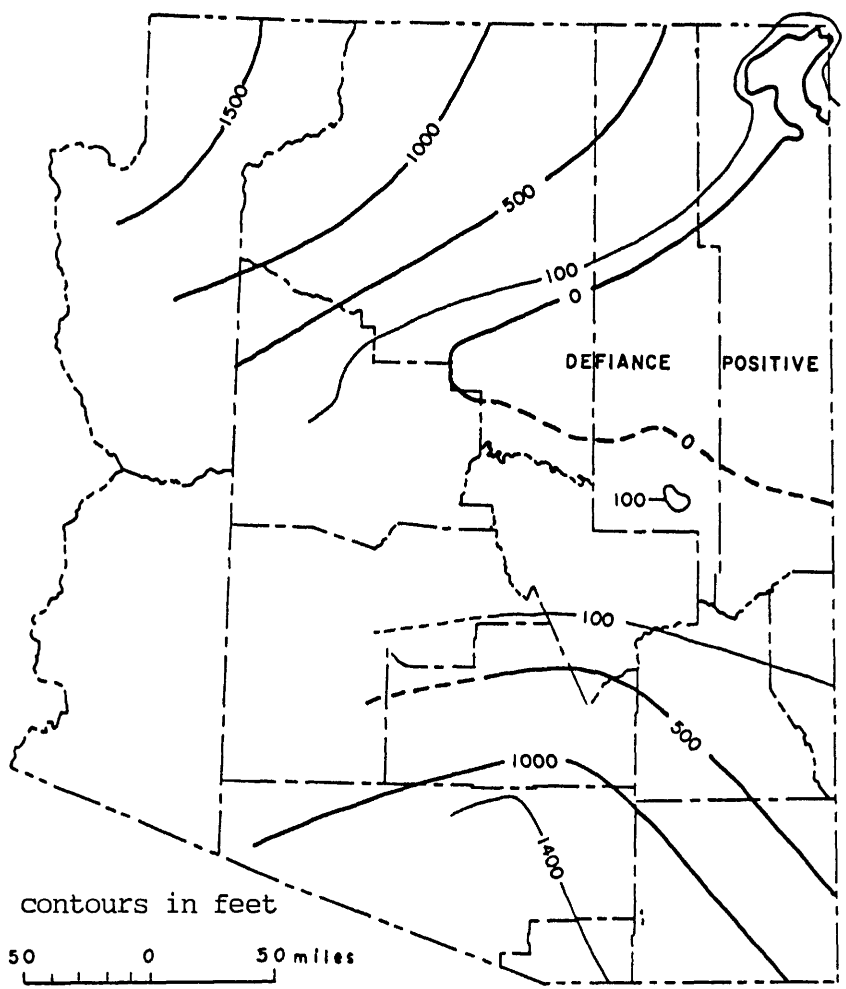


Fig. 11--Generalized isopach map of the Cambrian System. (From Peirce, 1976).

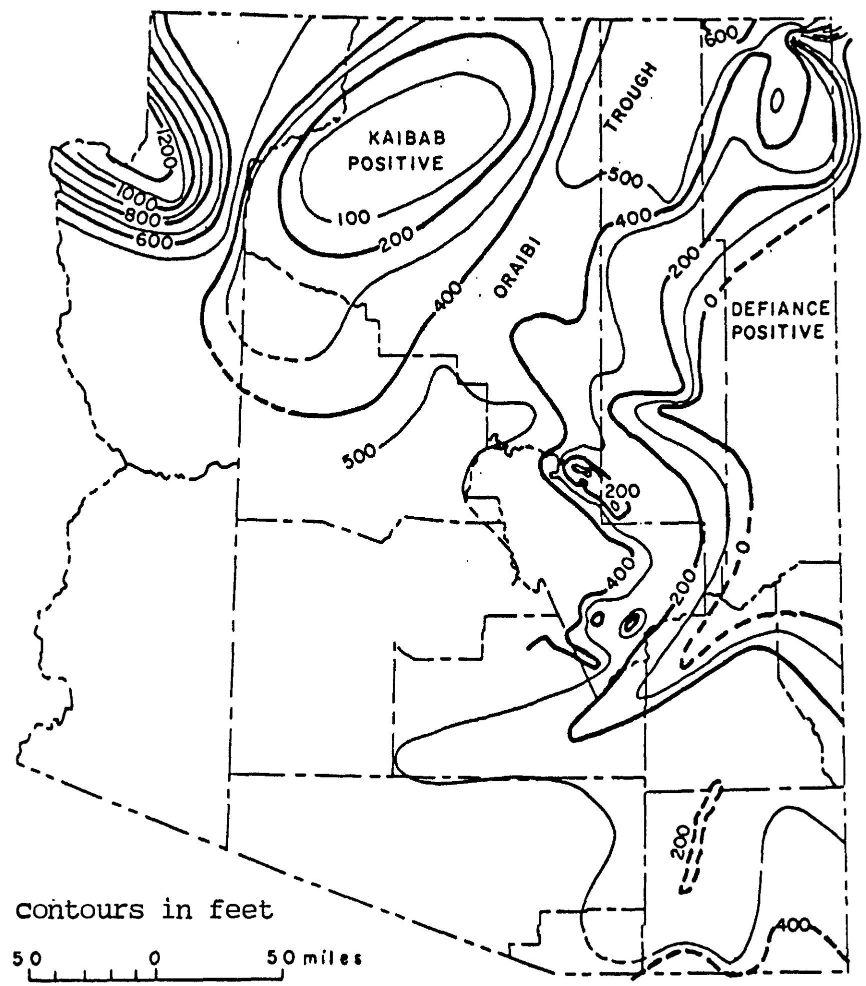


Fig. 12--Generalized isopach map of the Devonian System. (From Peirce, 1976).

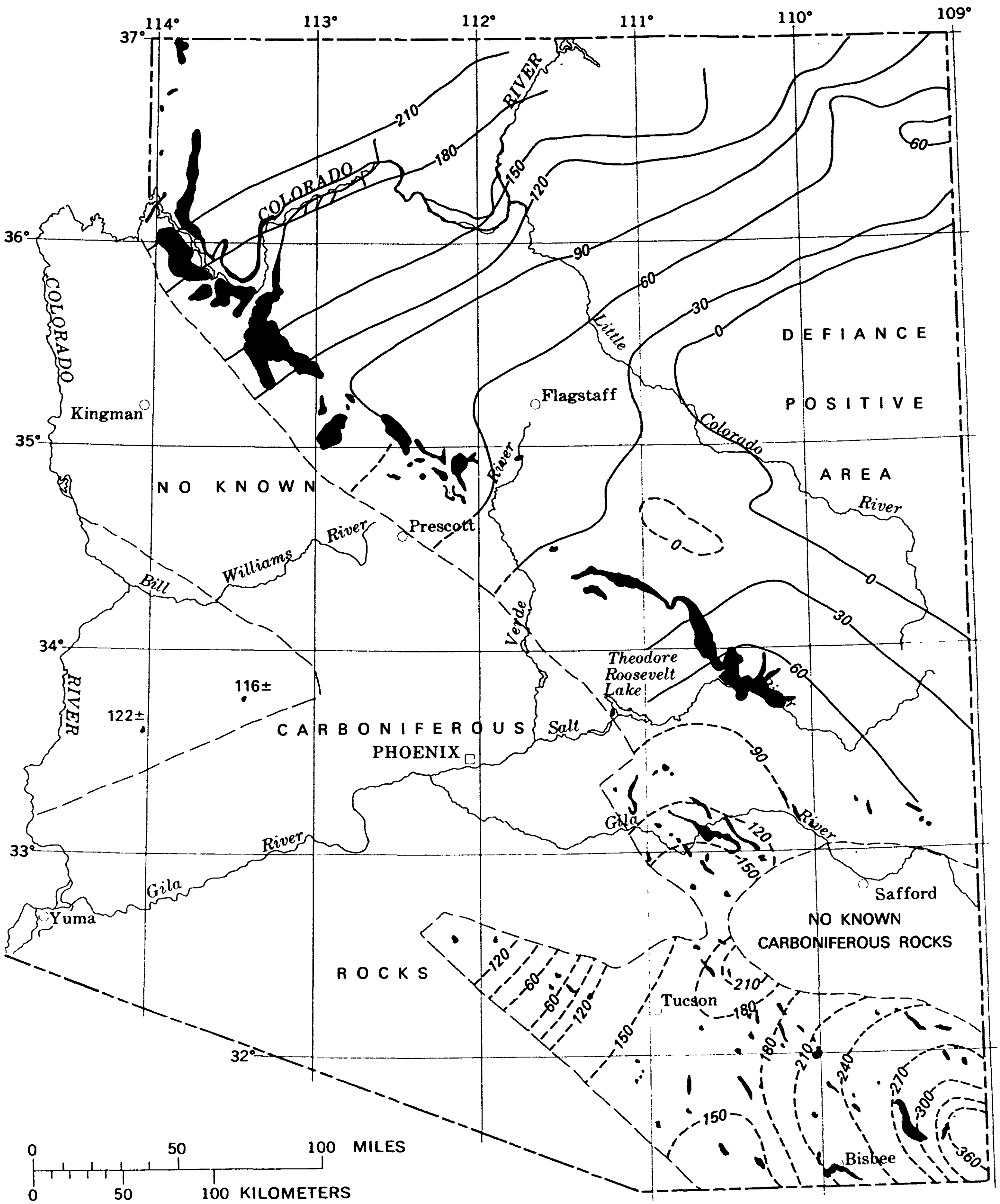


Fig. 13--Generalized isopach map of the Mississippian System as inferred from present distribution. Contour interval 30 meters. (From Peirce, 1979).

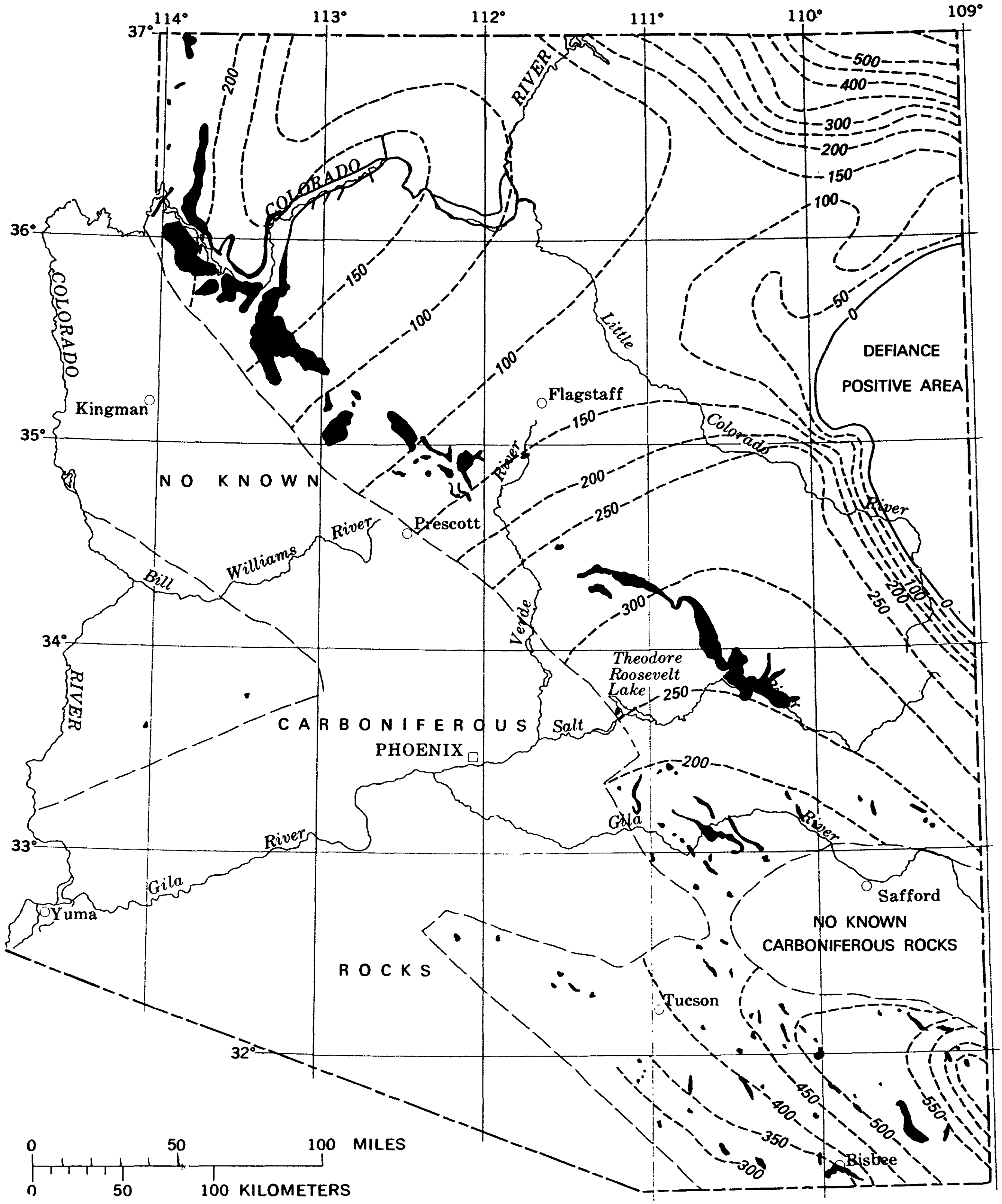


Fig. 14--Generalized isopach map of the Pennsylvanian System as inferred from present distribution. Countour interval is 30 meters. (From Peirce, 1979).

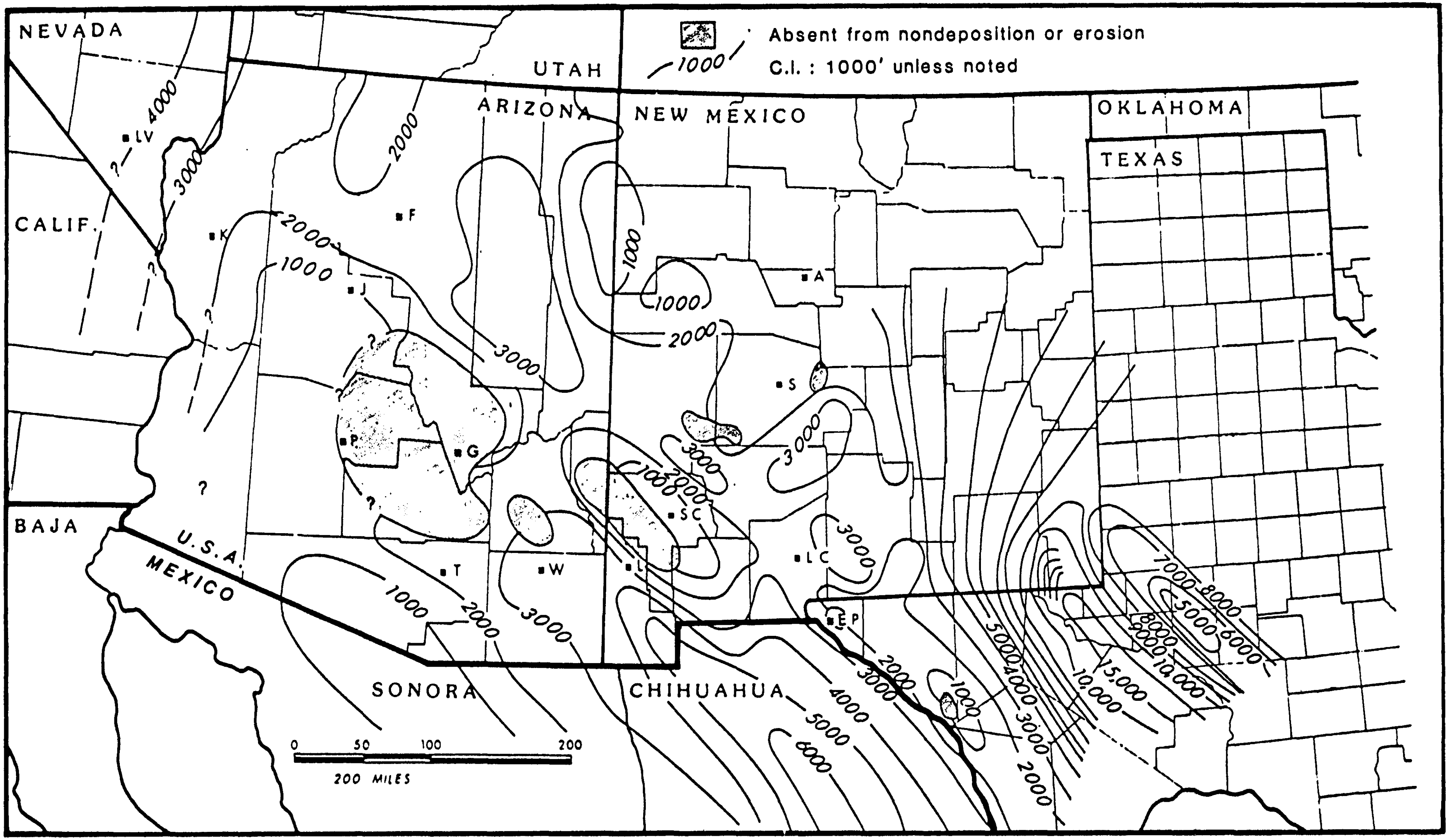


Fig. 15--Generalized isopach map of the Permian System. (From Nydegger, 1982).

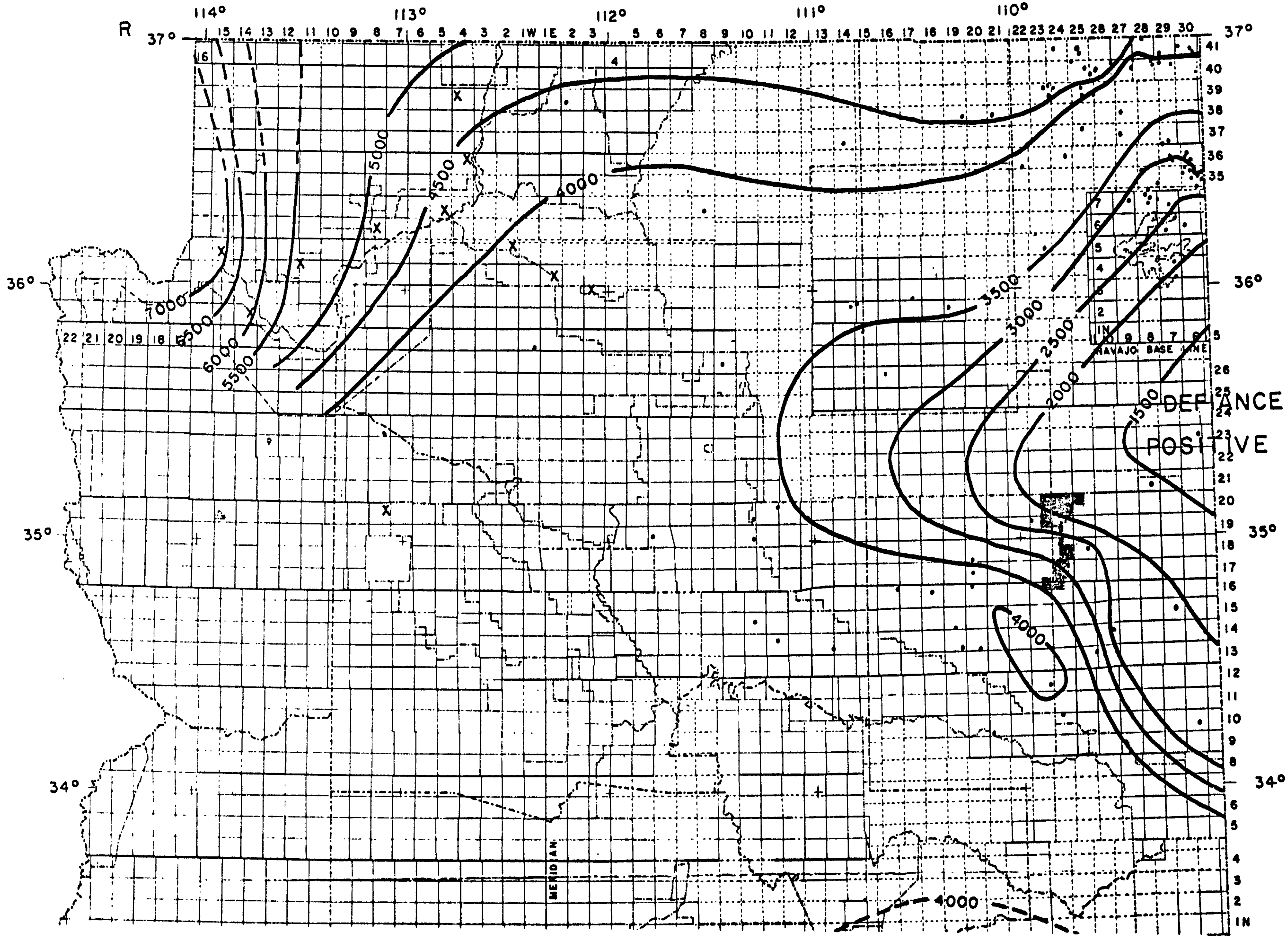


Fig. 16--Total Paleozoic isopach map of northern Arizona. Dots and crosses are wells and measured sections respectively. Contour interval is 500 feet. (From Peirce and others, 1970).

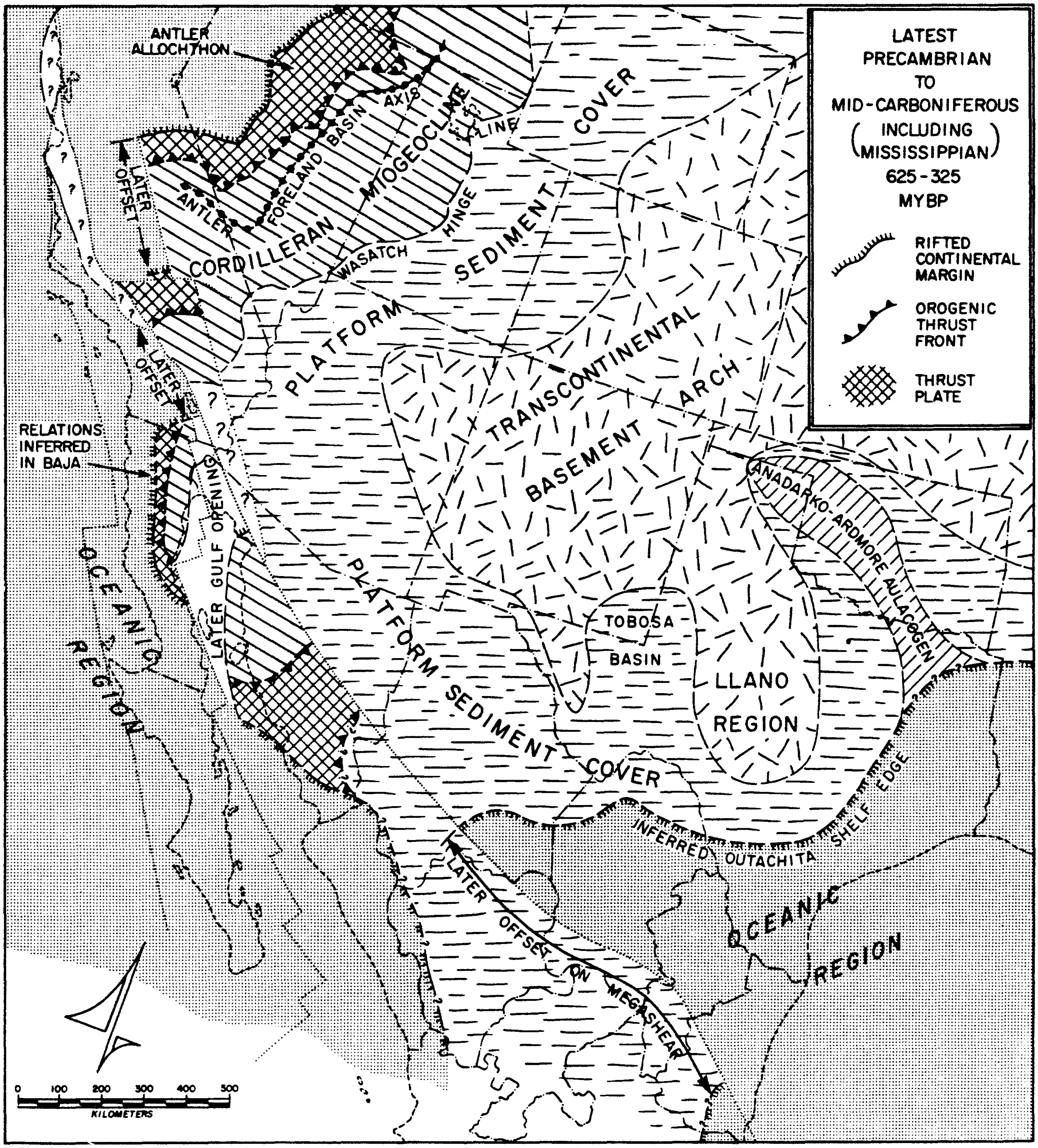


Fig. 17--Paleotectonic map of southern Cordillera, latest Precambrian to mid-Carboniferous (Mississippian-Pennsylvanian boundary) time, 625-325 myBP. Rifted continental margins to northwest and southeast of transcontinental arch of Precambrian basement formed 600-650 myBP in Cordilleran region and 500-525 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).

of middle and late Cambrian age (Lochman-Balk, 1971 and 1972). Thicknesses increase from zero to about 1,500 feet from the DU to the CH, respectively. Nearly all of Arizona was slightly positive during the Ordovician and Silurian Periods, and if strata of these ages were ever deposited, they were eroded in the late Silurian and/or early Devonian.

During the late Devonian, a shallow, northeast-trending, 50- to 100-mile-wide depression developed from approximately Flagstaff to the FC and is known as the Oraibi trough (Turner, 1958; Conley and Giardina, 1979). It should not be confused with the BMB which is a structural foreland basin of Laramide origin. This trough received as much as 600 feet of carbonaceous deltaic clastics, variegated shale, sandy dolomite, plus dark chemical carbonate and anhydrite sediments deposited in shallow marine to supratidal environments. Deposition generally kept pace with gentle subsidence. The predominant clastic sediment provenance was the DU to the east (Kashfi, 1983; Peterson and Smith, 1986). Devonian seas also deposited 100-200 feet of carbonates with interbedded siltstone and shale in the KU area, and similarly 700-1,200 feet were deposited in a depocenter in west-central Mohave County area (Poole and others, 1967). Renewed uplift in central Arizona during the late Mississippian caused erosion and widespread karst with terra rosa development. Elsewhere, in northern Arizona, clean to muddy/sandy/cherty, open-marine to supratidal, fossiliferous carbonates were deposited over a broad shelf (see McKee and Gutschick, 1969; McKee, 1979; Kent and Rawson, 1980). Regional erosion continued into the early Pennsylvanian.

In the middle Pennsylvanian and Permian, pronounced intraplate deformation took place in the FC states (fig. 18) due to partial rejuvenation along polygonal basement fractures. Fault-bounded, basement-cored uplifts and corresponding basins, i.e. horsts and rifts, resulted at this time when North and South America experienced a

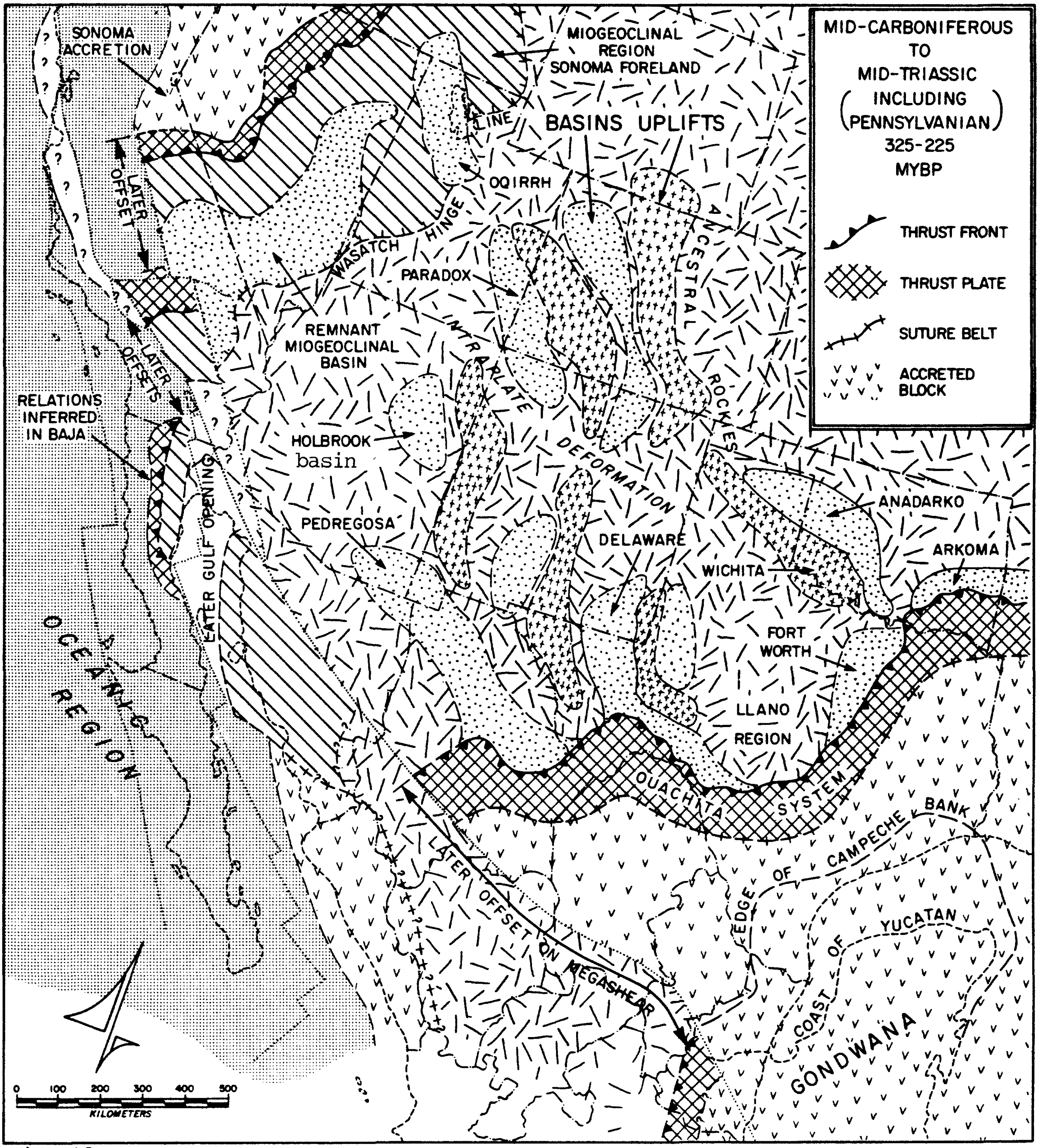


Fig. 18--Paleotectonic map of southern Cordillera, mid-Carboniferous (Mississippian-Pennsylvanian boundary) to mid-Triassic (end of Middle Triassic) time, 325-225 myBP. On southeast, Ouachita system is subduction complex of Paleozoic oceanic strata thrust over previously passive continental margin during Ouachita orogeny in Pennsylvanian and earliest Permian time, 325-275 myBP (note Arkoma and Fort Worth foreland basins). Coast of modern Yucatan and edge of present Campeche Bank shown in approximate positions occupied within Pangaea, from mid-Permian to mid-Triassic time (275-225 myBP), after suturing of Gondwanan crustal blocks to the craton along the Ouachita collision belt. Pennsylvanian and Early Permian uplifts and basins of Ancestral Rockies and related systems across southern Cordillera as far as Oquirrh and Pedregosa basins formed by intraplate deformation under stresses induced by Ouachita collision orogeny. Younger thrust plate on Cordilleran margin is Golconda allochthon, a subduction complex of upper Paleozoic oceanic strata emplaced during Permo-Triassic Sonoma orogeny (275-225 myBP), when composite arc terranes were also accreted to the continental margin. Relations in Mojave region and Mexico interpretive or speculative, or both. (From Dickinson, 1981).

progressive plate collision (Kluth, 1986). The PB aulacogen (Gorham, 1975; Baars, 1976; Stevenson and Baars, 1986) and DU are local examples of rapid vertical adjustments in the study area, and the Uncompahgre uplift (ancestral Rockies) of southwestern Colorado is a regional example affecting sedimentation in the FC. Although such foreland deformation in the greater FC area can be related to the same late Paleozoic stresses leading to thrusting and the evolution of the Ouachita- Marathon foldbelt in present-day Texas and further east into Oklahoma and Arkansas (Horak, 1974; Burchfiel, 1979; Ross, 1979; Kluth and Coney, 1981; Dickinson, 1986; Ross and Ross, 1986), its origin is linked to Proterozoic structures. Because the occurrence of petroleum in aulacogens of southwestern United States is significant, the reader is also referred to Burke and Dewey (1973), Hoffman and others (1974), Dickinson (1977), Walper (1977), Wickham (1978), and Burke (1980) relative to the stratigraphic and structural evolution of aulacogens.

Pennsylvanian and Permian sedimentation is characterized by carbonate-clastic-red bed cyclicity with rapid facies changes, local basining and shoaling, including deposition of thick evaporites in the PB and then later in the HB. Structure and stratigraphic intertonguing are more complex than in older systems. Subsidence in east-central Arizona delineates the HB. Blakey (1980) referred to the ML area during the late Paleozoic as the Sedona arch. Provenance of clastic sediments continued to be the DU and ML, but late Paleozoic sources also included southwestern Utah plus the Uncompahgre uplift which shed coarse arkosic sands southwestward into the PB. Finer-grained clastics reached Arizona where they become intercalated with carbonates. Significant thicknesses of Pennsylvanian strata occur in three areas: 1) the Grand Canyon embayment (1,000-1,500 feet), 2) the PB (1,500-1,800 feet), and 3) the HB (500-1,000 feet) (fig. 14). Permian thicknesses in the same three areas are about

1,800 feet, 2,000 feet, and 2,600 feet, respectively. Regional shoaling began during the middle Permian and later emergence removed all upper Permian strata. Peirce (1976) noted that 50-100 percent of the stratigraphic section of Arizona is represented by Pennsylvanian-Permian rocks. Given the importance of this depositional package, additional selected references worthy of note are: Baker and Reeside (1929), Baars (1962), Eardley (1963), Baars (1969), Bissell (1969), McKee (1969, 1975, 1982), Welsh (1976), Blakey (1979b), and Rawson and Turner-Peterson (1980).

Mesozoic Era

Figures 19 to 22 sequentially model the relationship between Mesozoic tectonism and the convergence of the North American cratonic plate and Farallon oceanic plate involving subduction of the latter beneath southwestern United States and development of a northwest-trending magmatic arc in southwestern Arizona (Coney, 1978; Dickinson, 1981). A major shift from mostly marine clastic and carbonate rocks to predominately nonmarine red-bed sedimentation began in Early Triassic time. At this time western Arizona, except the CH area, was an emergent alluvial-fluvial plain; streams flowed west from low hills in eastern Arizona. Triassic rocks thicken from zero in the DU area to about 2,000 feet in northwestern Arizona. Environments of deposition into the Jurassic included tidal flats, fluvial-dominated systems, and floodplains. Eolian dunes in Utah migrated into northern Arizona and by the Late Jurassic, the rising Cordilleran Mountains in the TZ area shed clastic continental sediments northeastward into a major backarc basin; these strata thicken in the same direction. Northeastern Arizona was tilted slightly northward during the Jurassic. Beginning in the late Jurassic, the Sevier orogeny and resulting highlands in western Utah and eastern Nevada contributed clastic sediments to extreme northwestern Arizona. Lower Cretaceous strata, 500-1,000 feet

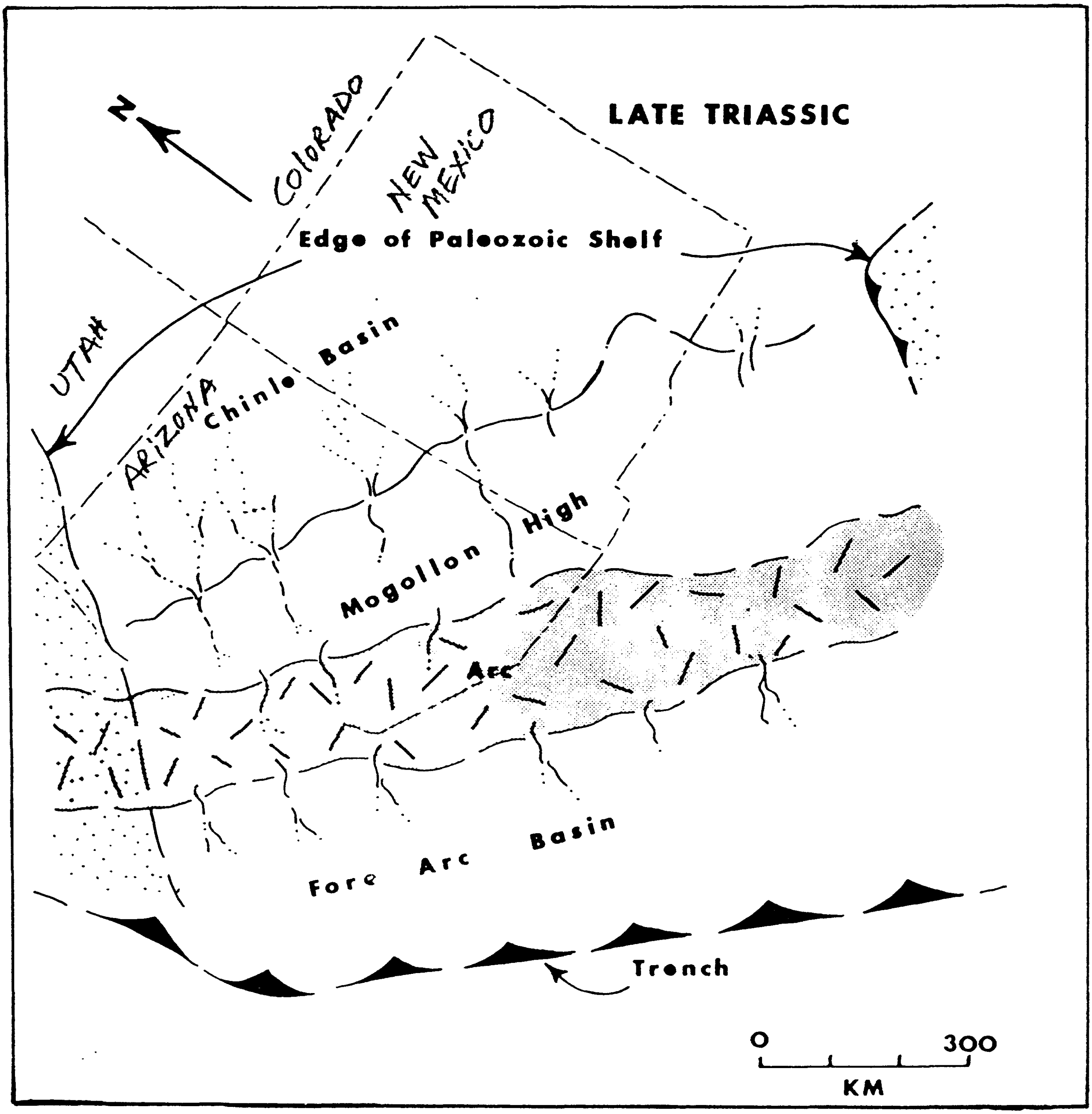


Fig. 19. Late Triassic. Summary map showing major tectonic features of late Paleozoic and early Mesozoic time. Stippled pattern shows Cordilleran Paleozoic geosyncline in northwest and Marathon region in southeast. On this and all other figures, outline of states is modified to account for middle to late Tertiary extension. North arrow on all figures is with respect to present day. (From Nydegger, 1982).

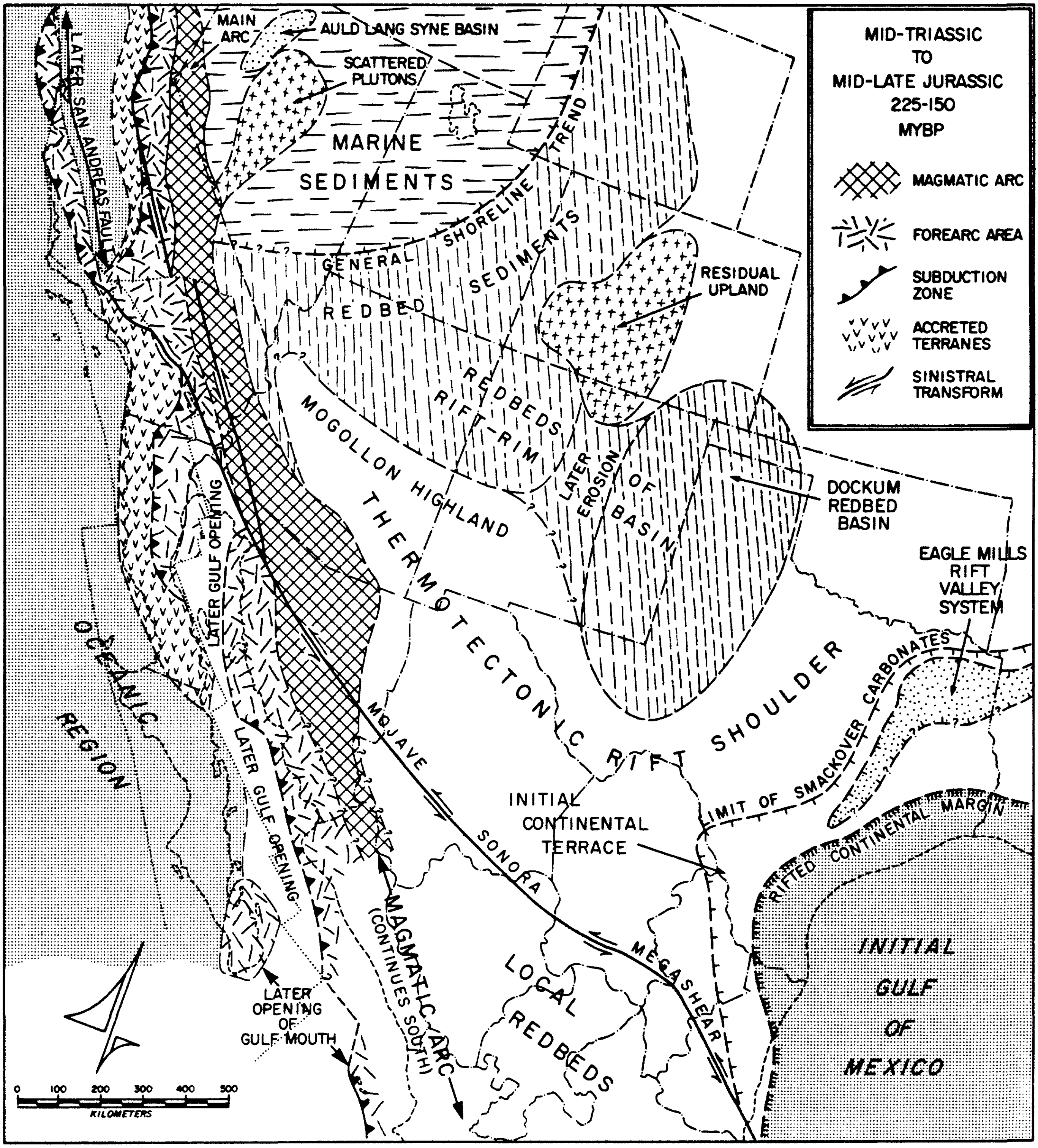


Fig. 20—Paleotectonic map of southern Cordillera, mid-Triassic (end of Middle Triassic) to mid-Late Jurassic time, 225-150 myBP. In Texas, rift-valley clastics overlain by Upper Jurassic carbonates form basal horizons of Gulf Coast sediment prism whose deposition along rifted continental margin was initiated 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).

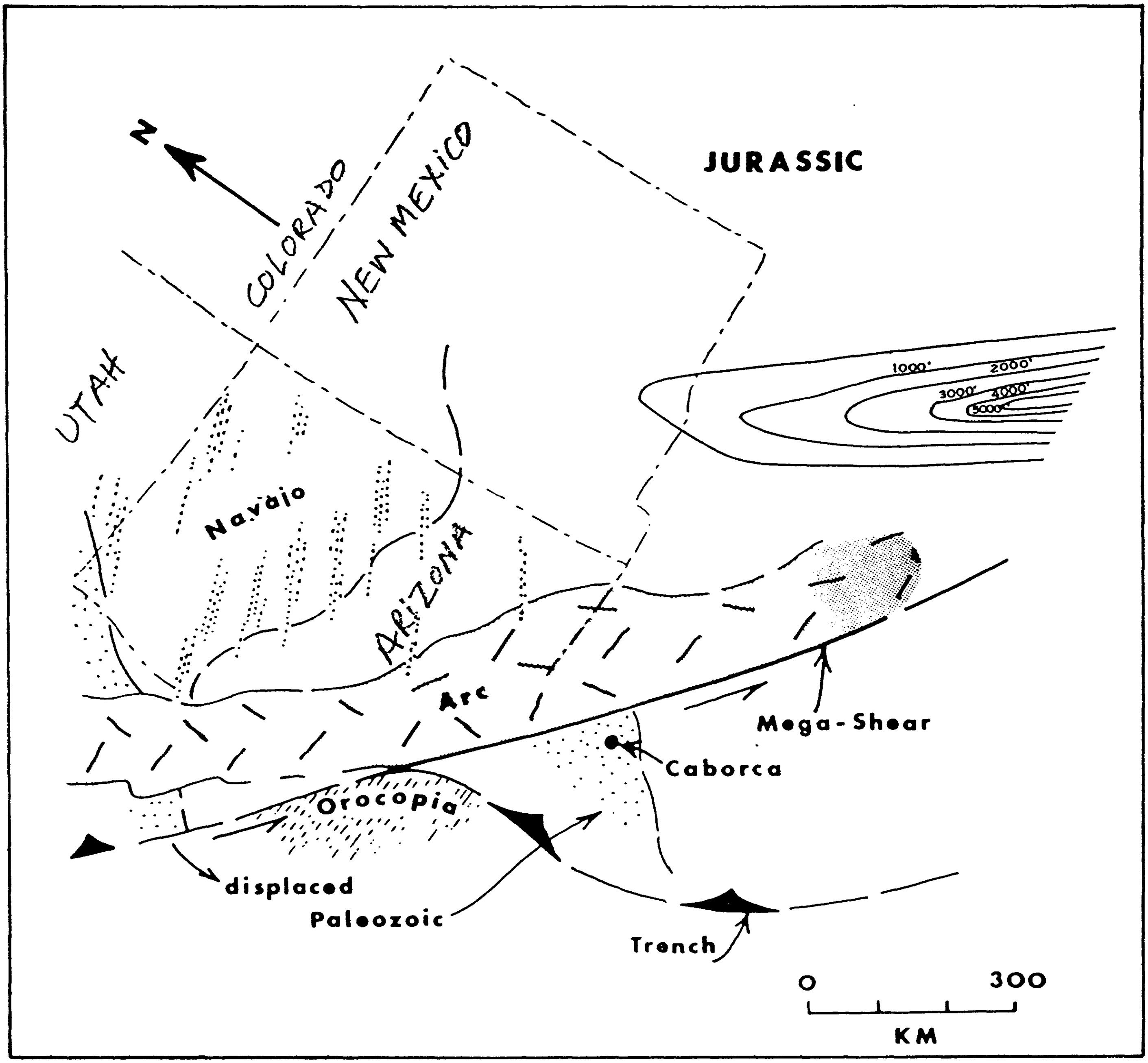


Fig. 21-- Jurassic. Major features of Jurassic arc (heavy dash-stipple pattern), including the Silver-Anderson mega-shear, and displaced Paleozoic (heavy stipple) and Orocopia (light dash) terraces. (From Nydegger, 1982).

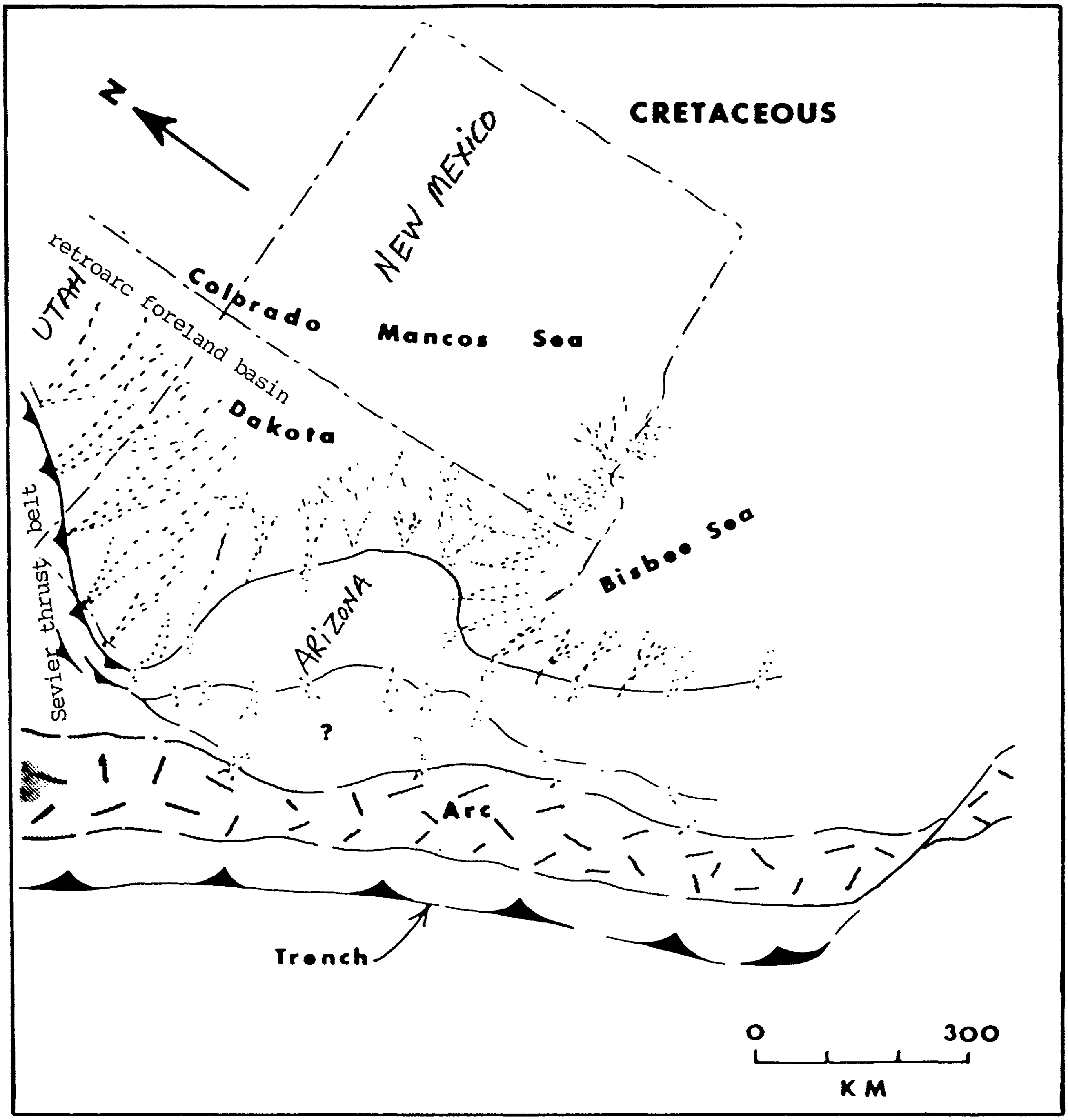


Fig.22–Cretaceous. Major features of mid-Cretaceous Peninsular batholith arc and Cretaceous interior seas. Sevier thrust belt shown by smaller barbed lines along far northwestern margin. (After Nydegger, 1982).

thick, are known only in northwestern Mohave County. Late Cretaceous seas of the Western Interior seaway (fig. 23a) transgressed southwestward across a Jurassic erosional surface into northeastern Arizona. Paludal and deltaic sediments, beach and bar sands, minor carbonates, and eventually thick deeper-water shales were deposited; northeastward regression followed (fig. 23b). From the MR to the Utah state line, the partially restored thickness of Mesozoic strata increases up to 7,000 feet (fig. 24), and reflects the mountainous terrane and source area to the south.

The Laramide orogeny (Late Cretaceous through Eocene age) is represented by mountain-building in the southwestern half of Arizona, eastward thrusting of older miogeosynclinal strata into extreme northwestern Mohave County, and less severe deformation elsewhere in northern Arizona, i.e. renewed vertical movement on basement blocks controlling the Kaibab, Echo Cliffs, Defiance, and Monument uplifts. Basement-cored uplifts typify Laramide structures surrounding the CP; surface monoclinal flextures are common in the CP (Woodward, 1976; Reches, 1978; Reches and Johnson, 1978). These monoclines may become normal or reverse faults at depth. Phases of the Laramide orogeny are coincident with plate convergence, such as the proximity to and eventual meeting of the East Pacific Rise and the southwestern margin of the craton (fig. 25), and flattening of the subducted Farallon plate (Keith and Wilt, 1986). Woodward and Callender (1977) and Hamilton (1981) have shown the area of the present-day CP yielded to the northeast and rotated counterclockwise during the Laramide compression with thrust faults nearly surrounding it (fig. 26).

Cenozoic Era

Differential uplift and erosion, plus normal faulting due to crustal extension, have been the primary tectonic activities of northern Arizona since the Laramide orogeny. Maximum uplift was during the Miocene

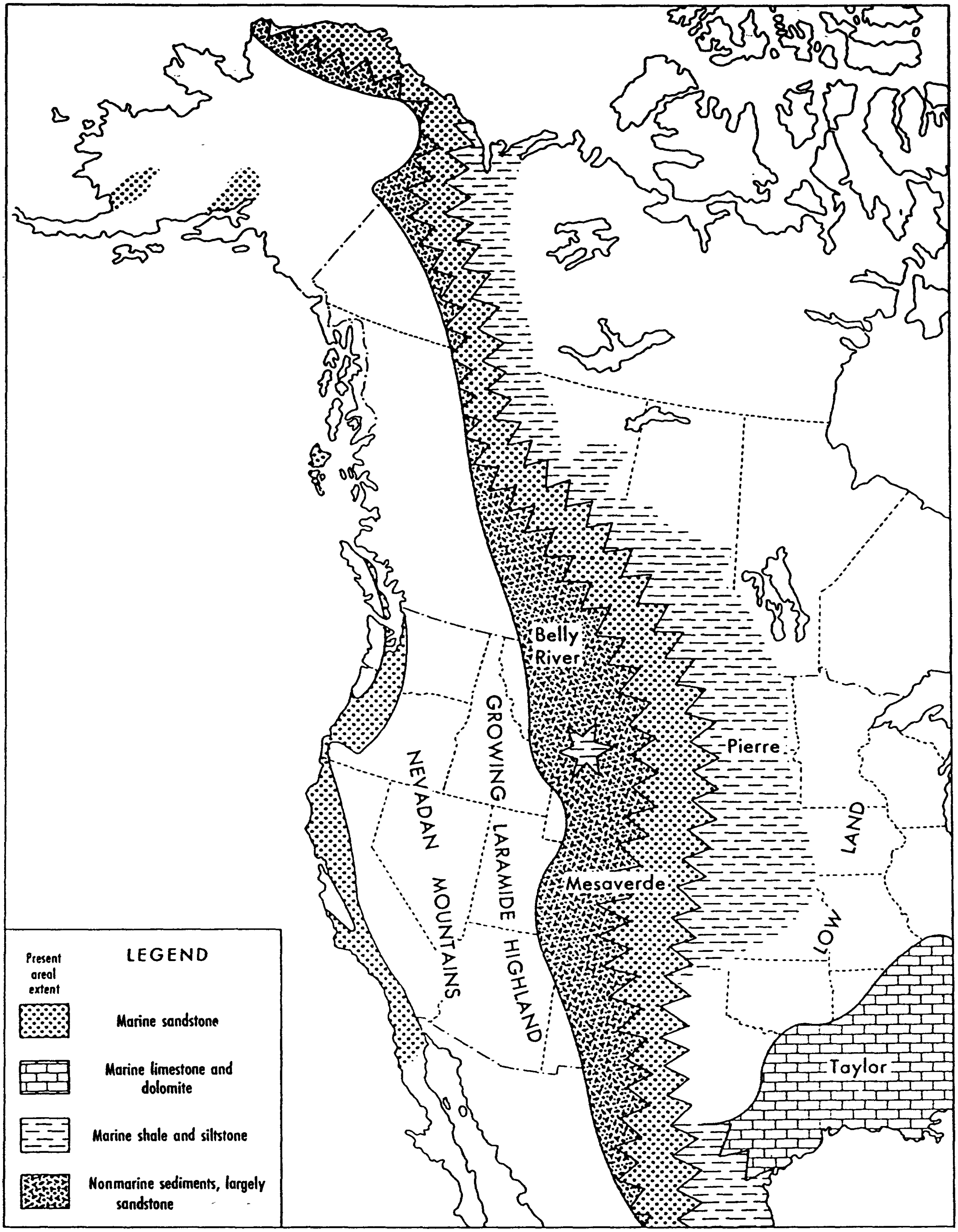


Fig. 23A--Simplified map of the facies of Upper Cretaceous sedimentary rocks in western United States. Marine deposition occurred in western interior seaway. (From Clark and Stearn, 1960).

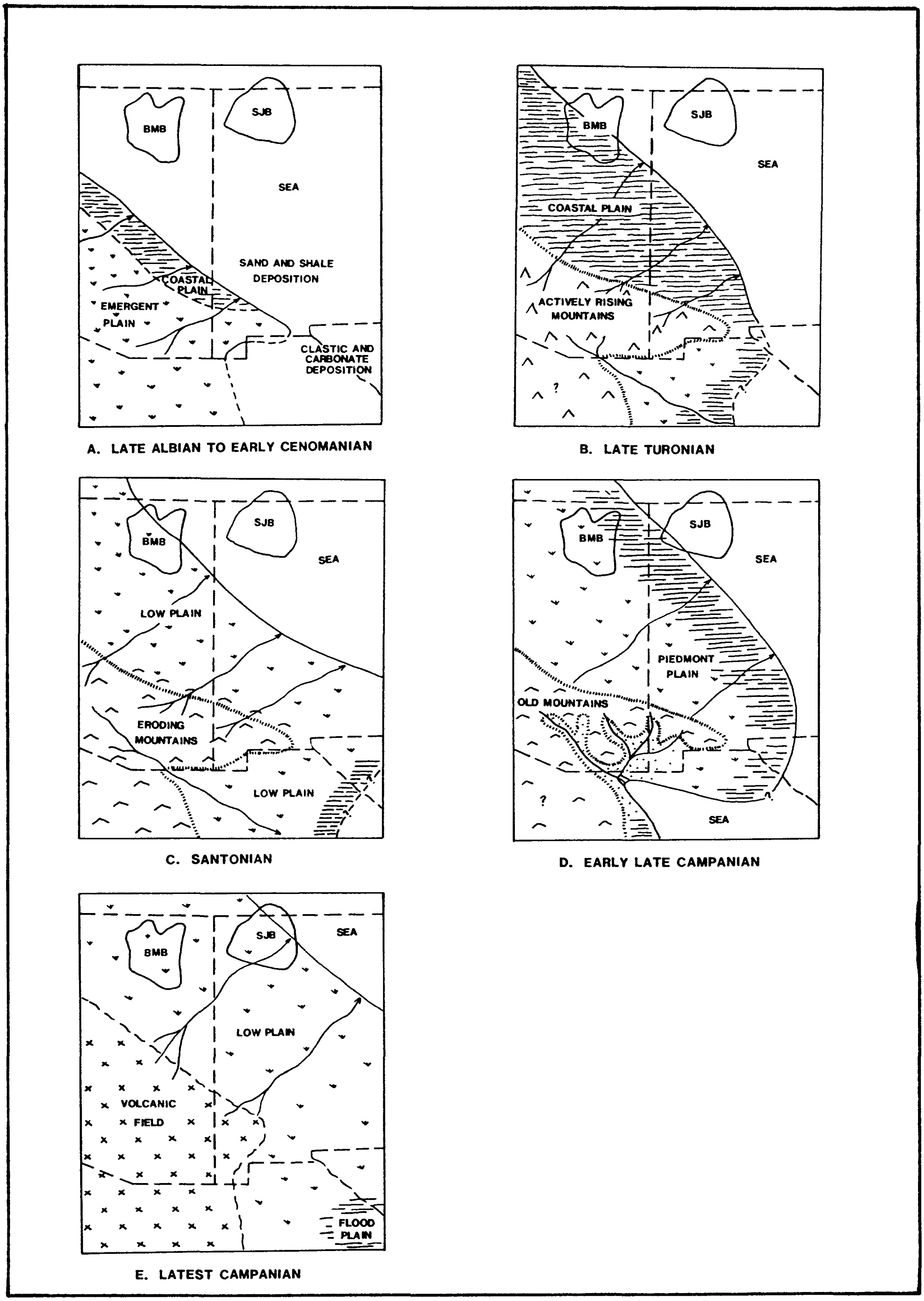


Fig. 23B--Paleogeographic maps of eastern Arizona and western New Mexico during Cretaceous time. (From Cumella, 1983).

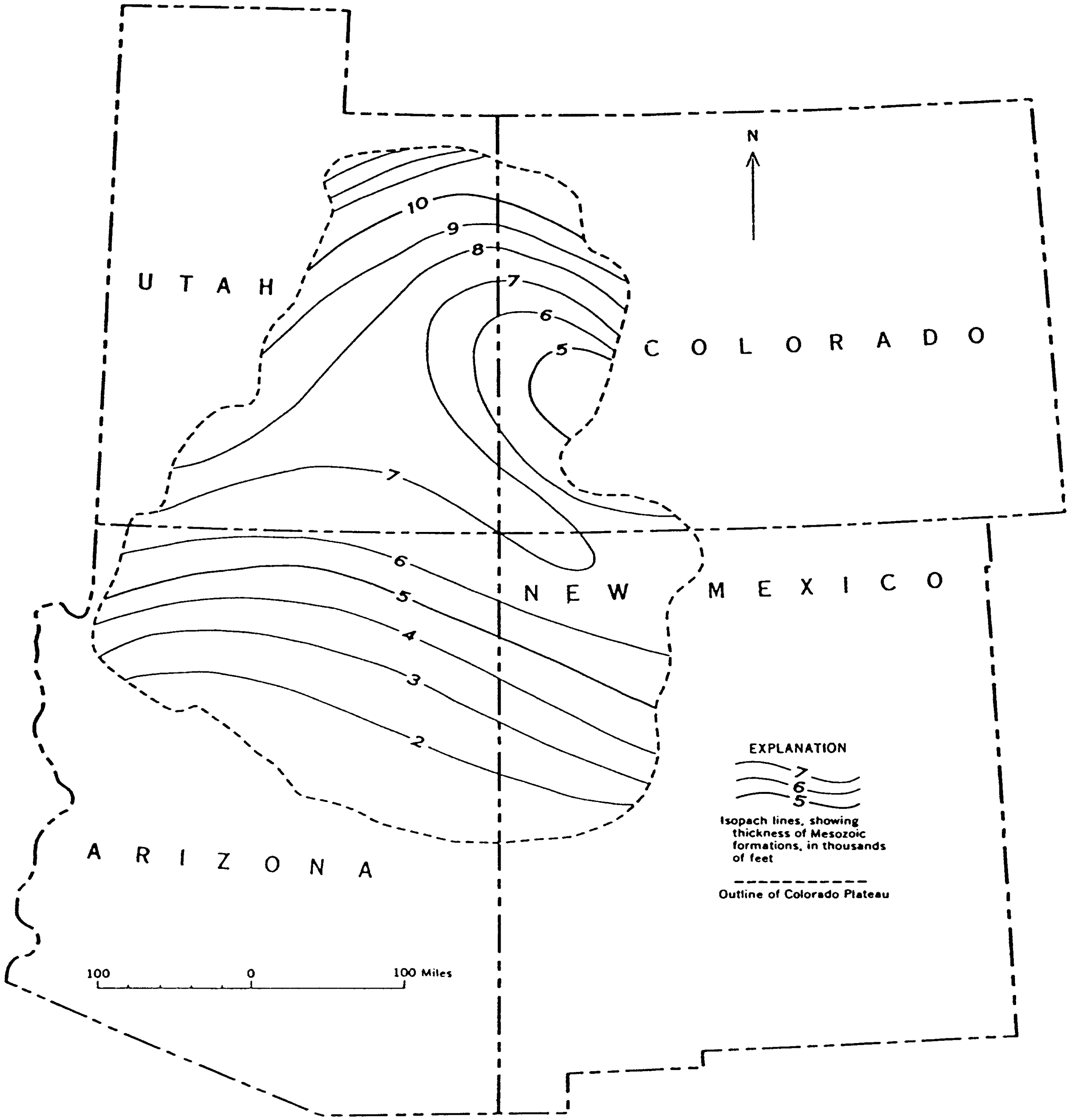


Fig. 24--Partially restored isopach map showing thickness of Mesozoic formations on the Colorado Plateau. (From Hunt, 1956).

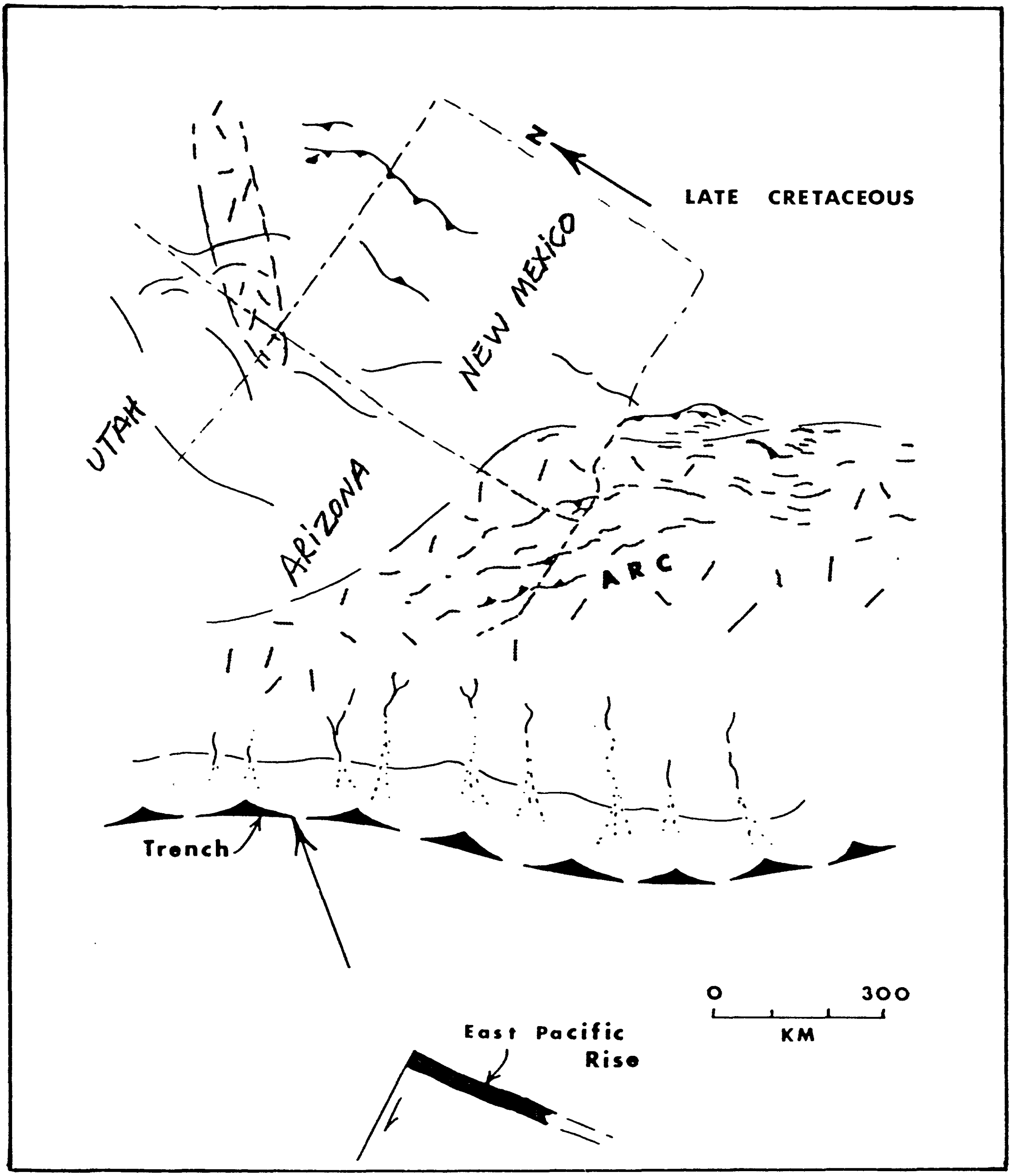


Fig. 25-- Late Cretaceous. Major features of Laramide deformation and magmatic activity. Position of East Pacific Rise approximate for end of Laramide time about 40 m.y. ago. Arrow on trench is direction of Farallon-North America convergence. (From Nydegger, 1982).

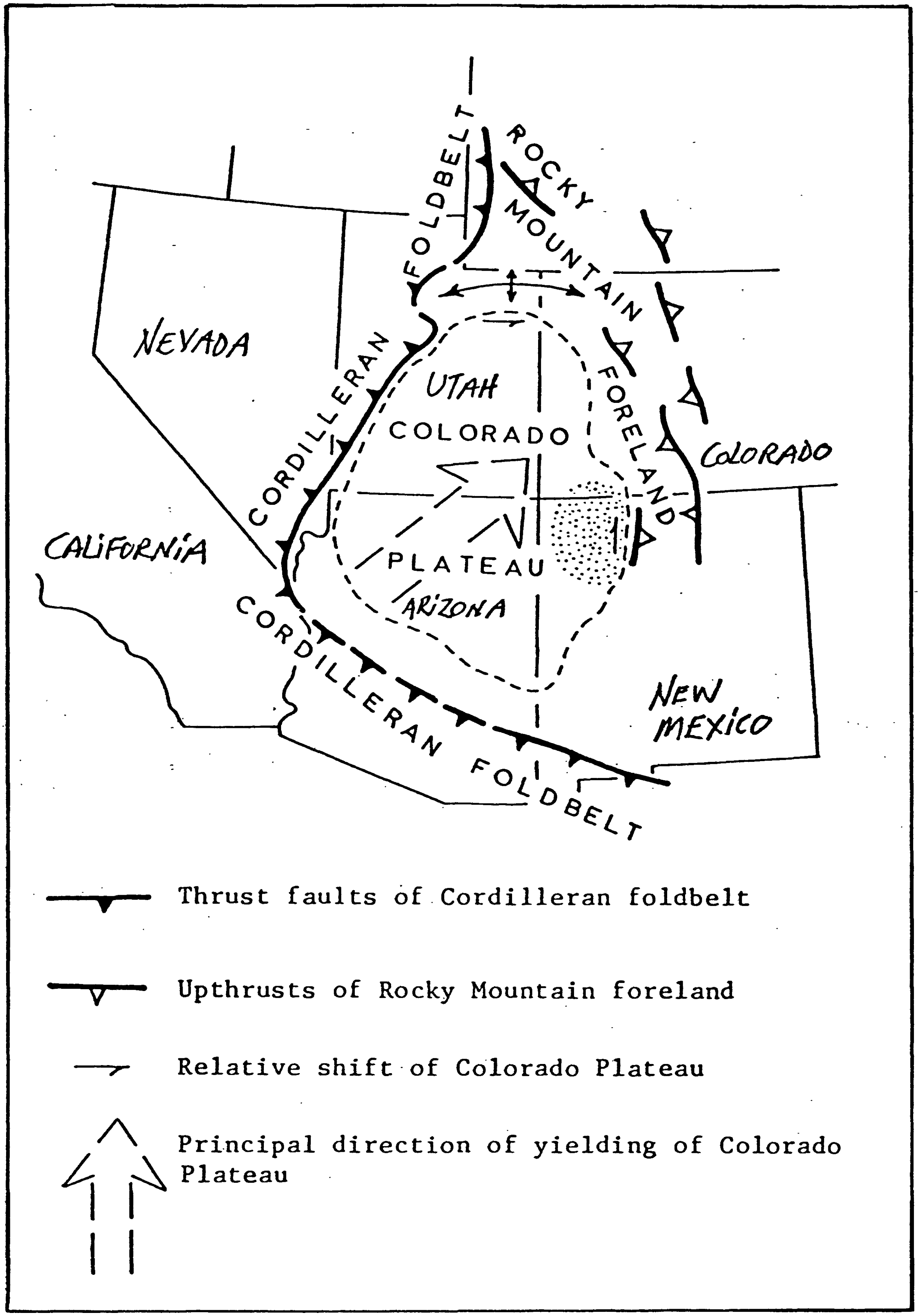


Fig. 26--Generalized tectonic map showing Cordilleran fold-belt, Colorado Plateau and Rocky Mountain foreland. San Juan basin stippled. (From Woodward and Callender, 1977).

(McGetchin and others, 1979) or during the Pliocene (McKee and McKee, 1972). Estimates of stratal thicknesses removed by erosion range up to 10,000 feet (Hunt, 1956; Thornbury, 1965), but probably amount to 6,000-7,500 feet in the western part of northern Arizona and up to 5,000 feet in the northeastern part. The amount of unloading is significant in predicting vertical maturity profiles; low reservoir pressures also result from unloading. Post-Laramide events include Oligocene to Quaternary volcanism and Miocene to Holocene normal faulting (Elston, 1976). By the middle Tertiary, the East Pacific Rise and associated heat plume were being subducted beneath the southwestern margin of the craton (fig. 27 and 28), thus possibly accounting for the mid-Miocene and younger eruptions of major volcanic centers, such as the San Francisco and White Mountains fields, and formation of metamorphic core complexes in the BR. Plate motion was taken up along the ancestral San Andreas transform fault during the Oligocene to early Miocene interval giving rise to BR extensional faulting and low-angle gravity sliding.

Eastern Basin and Range Physiographic Province

Stokes and Heylmun (1963) noted the eastern BR is an area of chaotic structure, subsidence, gravity slide blocks, normal and thrust faults, and widespread igneous activity. Particularly notable is the overprinting of earlier-formed structures in the BR by horsts and grabens formed by back-arc spreading. For example, the GWF has dropped its western BR block as much as 16,000 feet according to Longwell (1936) and Wilson (1962). One hypothesis suggests this characteristic, near-vertical normal faulting at the surface becomes listric to nearly horizontal at depth (Stewart, 1978; Zoback and others, 1981). Major structural, and consequently geophysical, differences separate the BR and CP. From west to east this sharp boundary in northwestern Arizona is characterized by increasing crustal thickness. For comparison, the crust is about 17.5 mi (28 km) thick in extreme

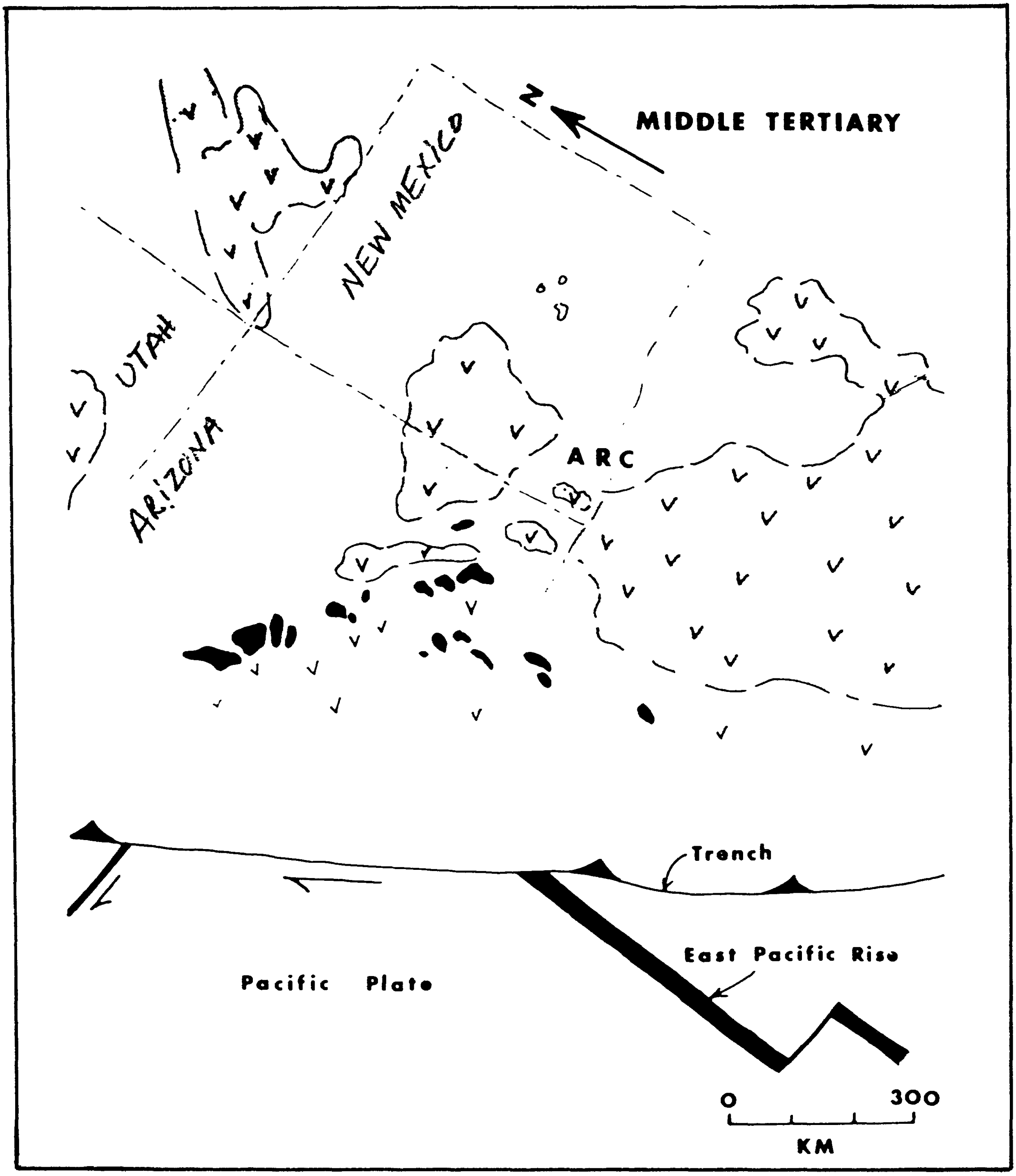


Fig. 27– **Middle Tertiary–Major features of middle Tertiary magmatism and development of metamorphic core complexes. Larger caldera complexes outlined by V-stipple pattern. Location of presently identified domal uplifts of Tertiary cataclastic gneiss in core complexes shown by solid black. Position of East Pacific Rise approximately 20 m.y. ago.** (From Nydegger, 1982).

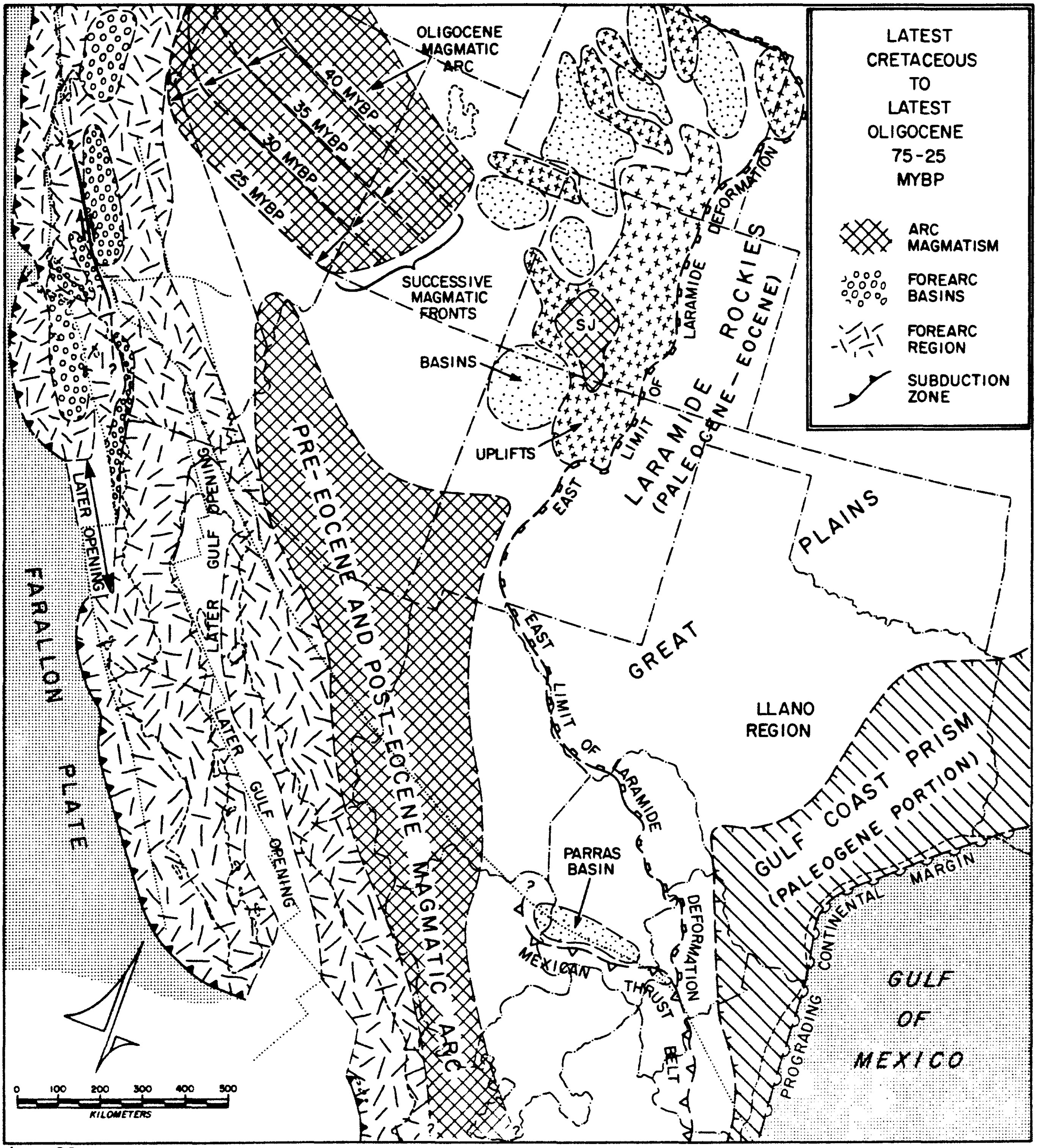


Fig. 28-- Paleotectonic map of southern Cordillera, latest Cretaceous (Campanian-Maestrichtian boundary) to latest Oligocene time, 75-25 my BP. Broad forearc region developed along Cordilleran margin as shallow descent of subducted Farallon plate beneath the southern Cordillera caused arc magmatism to shift eastward and wane from latest Cretaceous to mid-Eocene time (75-50 my BP). Simultaneously, contractional deformation expanded eastward to form broad Laramide orogen. Peak of intracontinental deformation to form uplifts and basins of Laramide Rockies by breakage of over-riding plate was roughly coincident with regional null in arc magmatism about mid-Eocene time (50 myBP). Arc magmatism swept back westward in Oligocene time as angle of descent of subducted Farallon plate steepened beneath the southern Cordillera, but Oligocene arc still lay inland from Cretaceous arc. Re-establishment of arc magmatism locally was accompanied by extensional deformation associated with Cordilleran metamorphic core complexes. On the Gulf Coast, progradational sedimentation advanced the shelf edge throughout Paleogene time, but latest Cretaceous to earliest Paleogene backarc thrusting in Mexico disrupted inland flank of Gulf Coast sediment prism, and formed Parras retroarc foreland. (From Dickinson, 1981).

northwestern Arizona, 27.5 mi (44 km) near the center of the CP in the FC area, and 19-22 mi (30-35 km) in the TZ (Thompson and Burke, 1974). West-to-east differences are also marked by an overall decrease in present-day heat flow, fracturing, and seismicity (Smith, 1978; Eaton, 1980). Keller and others (1975) suggested the actual transition between the two provinces may represent a mantle upwarp. The BR-CP transition indicates left lateral movement along the CH (see Frost and Martin, 1982) possibly due to clockwise rotation of the CP relative to the BR. Deformation during the Laramide orogeny was more intense in the BR than in the CP province and hence there is a greater potential for ore deposits associated with intrusions and higher heat flow than in the CP which has the higher petroleum potential.

Colorado Plateau Physiographic Province

The CP "microplate" consists of essentially horizontal to mildly deformed strata. It has behaved as a quasi-rigid, coherent block in Phanerozoic time, and has achieved its present structural and geomorphic identity since Late Oligocene time. Three general groups of previously-formed crustal structures documented in the CP of Arizona are typified by: 1) shallow sedimentary basins, platforms, and troughs; 2) gentle upwarps, arches, and structural basins; and, 3) monoclines and normal faults having unusually long axes. Faults are either vertical or dip steeply into the BR with their footwalls on the CP side; most also have displacements of several thousands of feet and serve to define the BR-CP boundary. Given the historical movement on some of these normal faults, the BR province is apparently growing at the expense of the CP. An apron of large, scattered volcanic fields (ash/lava flows and cinder cones) crops out around the periphery of the CP (Christiansen and Lipman, 1972). Laccoliths (Witkind, 1975), dikes, maars, and diatremes of Late Cretaceous through Tertiary age are other volcanic features within the CP. See Darton (1925), Fetzner

(1960), Thompson and Zoback (1979), Nations and Stump (1981), Reynolds (1982), and Baars (1983) for more detailed accounts of the CP in Arizona.

Central Arizona Transition Zone

Incipient TZ highlands grew during the Middle Mesozoic and are reasonably coincident with present-day TZ boundaries. Relative to the CP and BR, the TZ is an uplifted and severely eroded segment of crust; maximum differences in elevation of crystalline basement is on the order of 10,000-11,000 feet. The TZ is transitional in the sense of degree of deformation - more than the CP and less than the BR. Some of the oldest (Early Proterozoic basement) and youngest (Miocene and younger) igneous rocks in Arizona are abundantly exposed in the mountainous terrane of the TZ. Tertiary and Quaternary alluvium fills local graben valleys. The petroleum potential is very low in the TZ province due to the almost complete absence of Paleozoic and Mesozoic sedimentary rocks. However, organic matter has been documented in black mudstones, probably of lacustrine origin, of the Apache Group (Middle Proterozoic) of the TZ in Gila County (Desborough and others, 1984). Despite their age, these mudstones are unmetamorphosed and some samples contain slightly over 6 percent TOC. Maximum depth of burial was less than 7,000 feet and their maximum geothermal temperature, ascertained from the mudstone, was 176-248^{o}F (80-120^{o}C), according to Desborough and others (1984).

HYDROCARBON OCCURRENCES

Pennsylvanian reservoirs in northeastern Arizona on the southern margin of the PB aulacogen(?) have produced nearly all of Arizona's oil and gas to date. Ten to 20 miles north in southeastern Utah, these same-aged reservoirs have produced over 350 million barrels (BBLS) of oil and condensate plus 325 billion cubic feet of gas (BCFG) from the greater (giant-sized) Aneth Field (fig. 29). These data are estimated from the

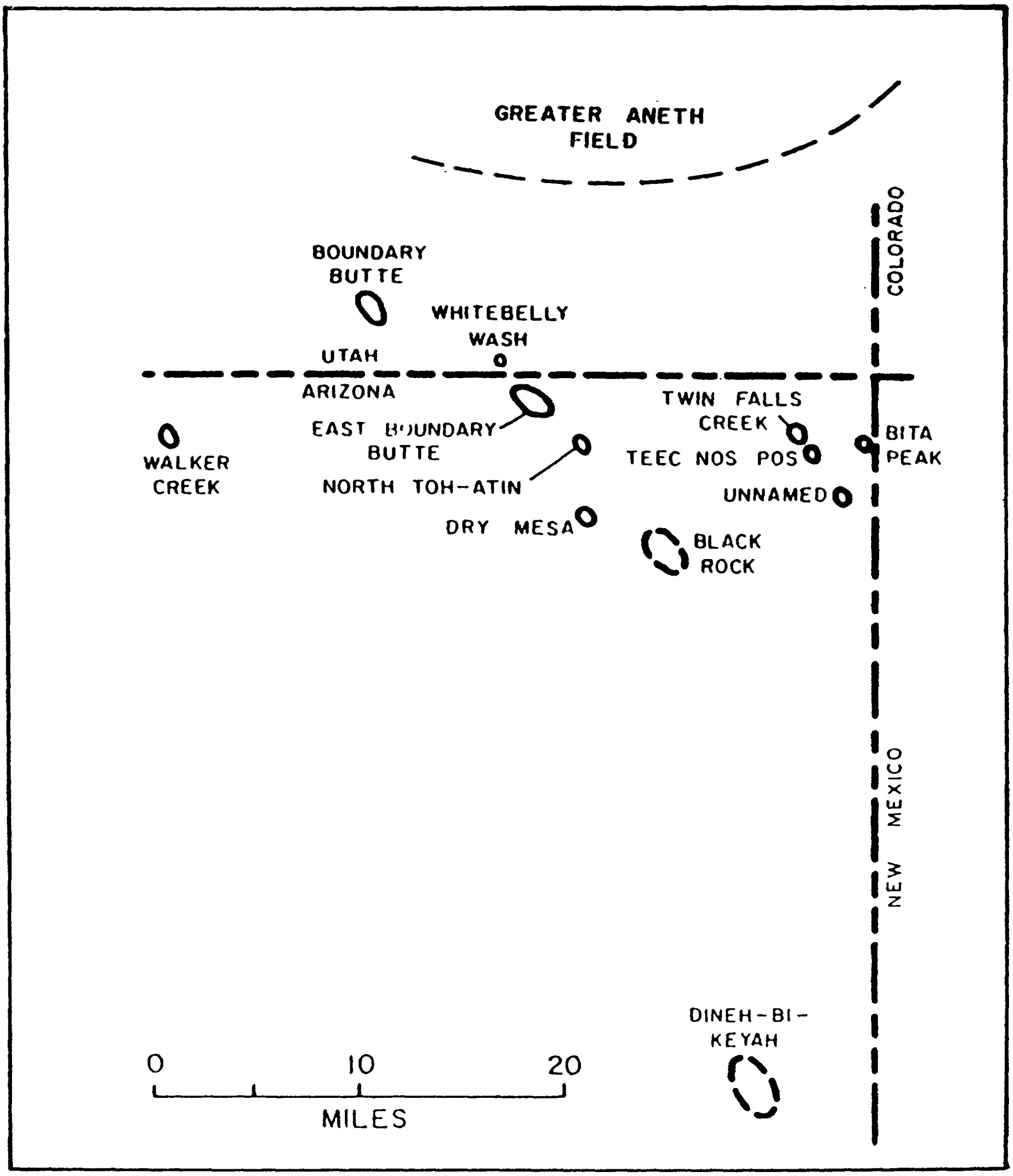


Figure 29- Map of northeast region of Arizona and adjacent portion of Utah, showing location of oil and gas pools. A one-well unnamed pool adjacent to Bita Peak is not shown. (From Conley, 1974).

Nehring pool-size data base owned by the U.S. Geological Survey.

Aspects of petroleum occurrences (including shows, seeps, and oil-impregnated rocks), potential, and production statistics of northern Arizona and adjacent areas have been reviewed in the following publications and used in the play identification section of this report: Brown and Lauth (1957 and 1961), Heylmun (1958a), Turner (1958 and 1961), Pye (1961), Swapp (1961), Cook (1963), Witkind and Thaden (1963), Ball Associates (1965), Lessentine (1965), Turner (1968), Barwin (1969), O'Sullivan (1969), Landes (1970), Peirce and others (1970), Barwin and others (1971), Lyth (1971) Curtis (1972), Peirce and Scurlock (1972), Bissell (1973), Conley (1974), several papers in Fassett (1978), Blakey (1979a), Conley and Giardina (1979), Nations and others (1983a,b), Ryder (1983), Stevenson (1983a,b), Brady (1984), Ariz. Oil and Gas Conserv. Comm. (1986?), and Beikman and others (1986). Conley (1974) and Nations and others (1983a) have charted the oil, gas, and helium fields according to depth, reservoirs, and production status (fig. 30).

According to the papers in Fassett (1978), the ten oil and gas fields in the Arizona portion of the BB together with their years of discovery, producing formation(s), and product/field status are: Bita Peak, 1956, Ismay zone of the Paradox (abandoned gas); Black Rock, 1971, Paradox and Pinkerton Trail (abandoned oil and gas); Boundary Butte East, 1954, Upper Hermosa Group plus Ismay, Desert Creek, and Akah zones of the Paradox (oil and gas); Dry Mesa, 1959, Leadville (oil and gas); Teec Nos Pos, 1963, Ismay zone of Paradox (oil and gas); Tohache Wash, 1960, Aneth/McCracken (abandoned oil and Leadville-reservoired helium); Toh-Atin, 1962, Akah zone of Paradox (abandoned oil) but considered by some to be a Leadville reservoir; Toh-Atin North, 1956, Barker Creek zone of Paradox (abandoned gas); Twin Falls Creek, 1957, Ismay and Desert Creek zones of Paradox (abandoned gas); and, Walker Creek, 1963, McCracken Sandstone Member of

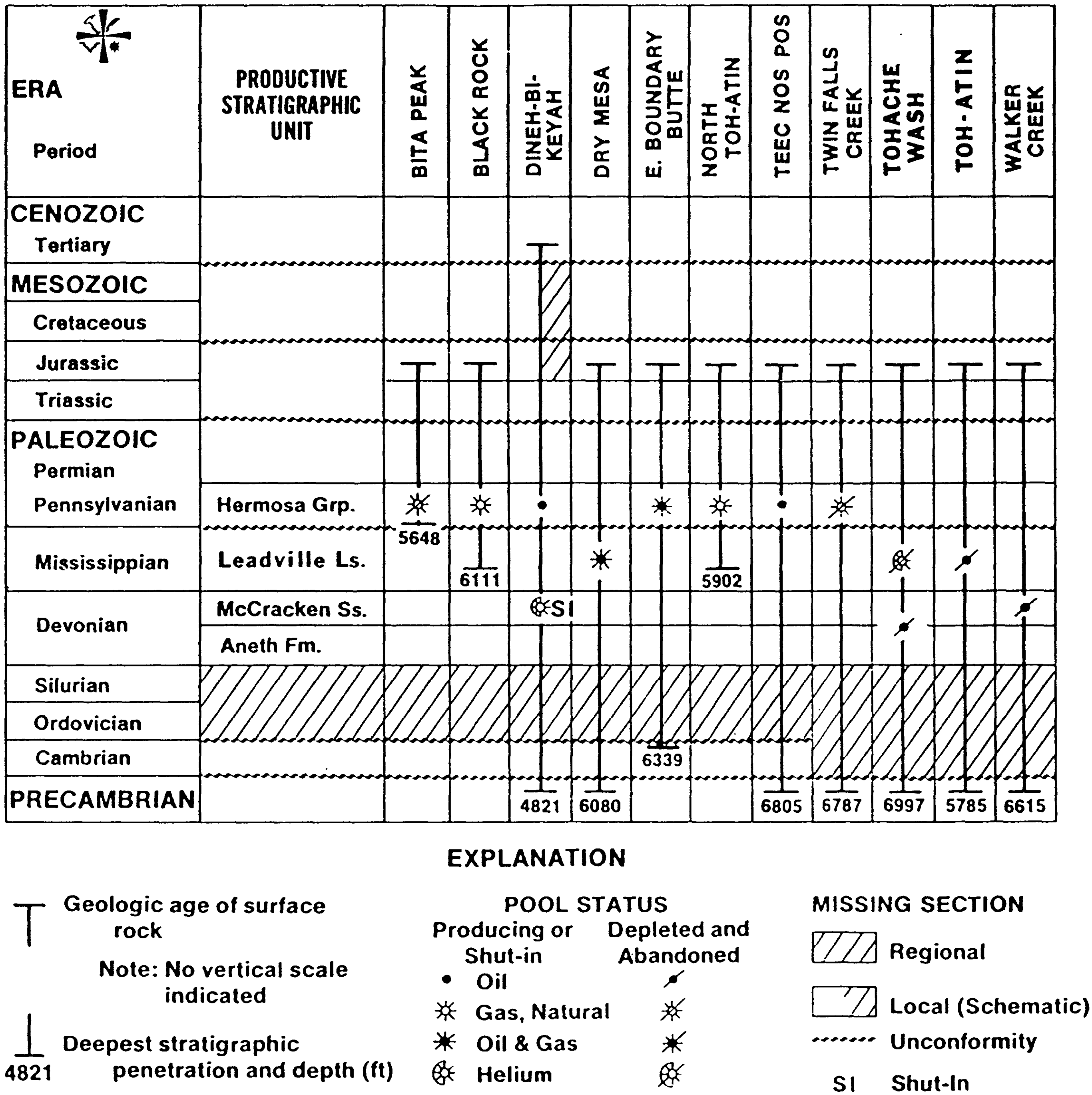


Fig. 30--Stratigraphic sections and producing intervals in oil and gas fields and areas of Arizona. (From Nations and others, 1983a).

the Elbert (abandoned oil).

Of the Pennsylvanian fields (Bita Peak, Black Rock, Boundary Butte East, DBK, Teec Nos Pos, Toh-Atin(?), Toh-Atin North, and Twin Falls), all except DBK produce from fossiliferous carbonates in northern Apache County. Cumulative production from DBK is about 17 million BBLS and 4 BCF of gas, and from all other seven fields it is approximately 1.4 million BBLS of oil and 15.25 BCF of associated gas. The latter seven fields are small, isolated, and not associated with deep-basin conditions typically expected for significant hydrocarbon resources.

In their evaluation of northeastern Arizona's petroleum potential, Conley and Giardina (1979) concluded that the area north of about 36°25′ N. lat. and east of about 109°35′ W. long. in Arizona has very favorable opportunities for accumulations in Pennsylvanian and older strata.

PETROLEUM PLAY IDENTIFICATION

Petroleum plays are primarily identified on 1) the presence of potential source rocks, i.e. their organic richness, thickness, and thermal maturity, 2) on proximity to petroleum fields and quality of shows in boreholes, 3) on presence of potential reservoir rocks, and 4) on timing of generation and migration.

Data for interpretation of present-day thermal gradients and heat flow have been taken from the following sources: Gough and Porath (1970), White and Williams (1975), Crough and Thompson (1976), DeFord and Kehle (1976), Sass and others (1976), Conley and Stacey (1977), Grim (1977), Lachenbruch and Sass (1977), Swanberg and others (1977), Blackwell (1978), Grant (1978), Hahman and others (1978), Conley and Giardina (1979), Grim and Berry (1979), Keller and others (1979), Reiter and others (1979), Reiter and Shearer (1979 and 1981), Witcher (1979), Ariz. Bur. Geol. and Min. Tech. (1980), Guffanti and Nathenson (1980), Aiken and Ander (1981), Sass and others (1981), Kron and Stix (1982), Witcher and others (1982), Conley and Stacey (1983), Nathenson and others (1983), Reiter and Mansure (1983), Stone (1983), and Eggleston and Reiter (1984). Interpretation of the mean surface heat flow for the Colorado Plateau ranges from 1.62 HFU according to Crough and Thompson (1976) to 1.3 HFU according to Keller and others (1979) and about 1.56 HFU for the non-volcanic areas of the province (Reiter and Mansure, 1983). Figure 31 illustrates the present-day low heat flow of the CP core.

Analysis of the geothermal maturity of outcrops is based on the author's unpublished vitrinite reflectance (R_o) and Conodont alteration indices (CAI) data (fig. 32), plus CAI data of Harris and others (1980), Wardlaw and others (1983), Wardlaw and Harris (1984), and Reynolds and others (1986). CAI values were converted to corresponding R_o values and plotted as such.

Cordilleran Overthrust Belt Play

Location and Size

The Cordilleran Overthrust belt (COB) in the Basin and Range (BR) province in northwestern Mohave County is a small 275-300 square-mile segment within the southernmost part of this hydrocarbon-productive thrust belt in the western United States. The Grand Wash fault (GWF), which merges with the Cedar Pocket Canyon fault (Lovejoy, 1976), more or less defines the northeastern play boundary. The entire COB is being evaluated in a similar report covering the eastern Great Basin assessment province.

General Statement

Composite thicknesses of Cambrian through Pliocene strata range between 11,300 and 16,000 feet in the Virgin Mountains area of Arizona and Nevada (Seager, 1970). The Virgin Mountains in the east-central play area is the predominant exposed fold-structure of the play (fig. 33) and is

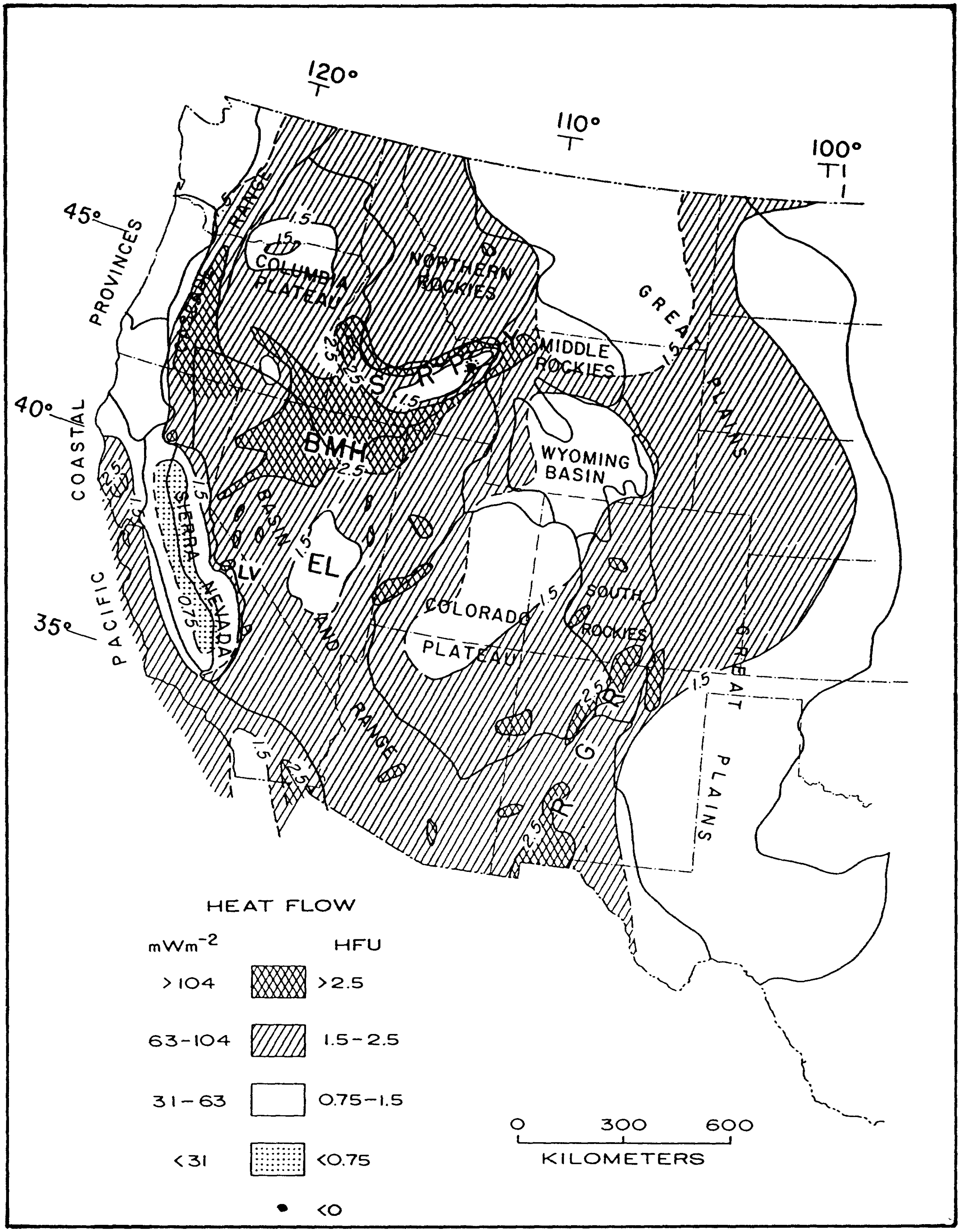


Fig. 31-- Map of the western United States showing heat-flow contours (in heat-flow units, HFU, 1 HFU = 41.8 mWm^{-2}), heat-flow provinces, and major physiographic divisions (SRP: Snake River Plain; BMH: Battle Mountain High; EL; Eureka Low; RGR: Rio Grande Rift Zone; Y: Yellowstone; LV: Long Valley). (From Sass and others, 1981).

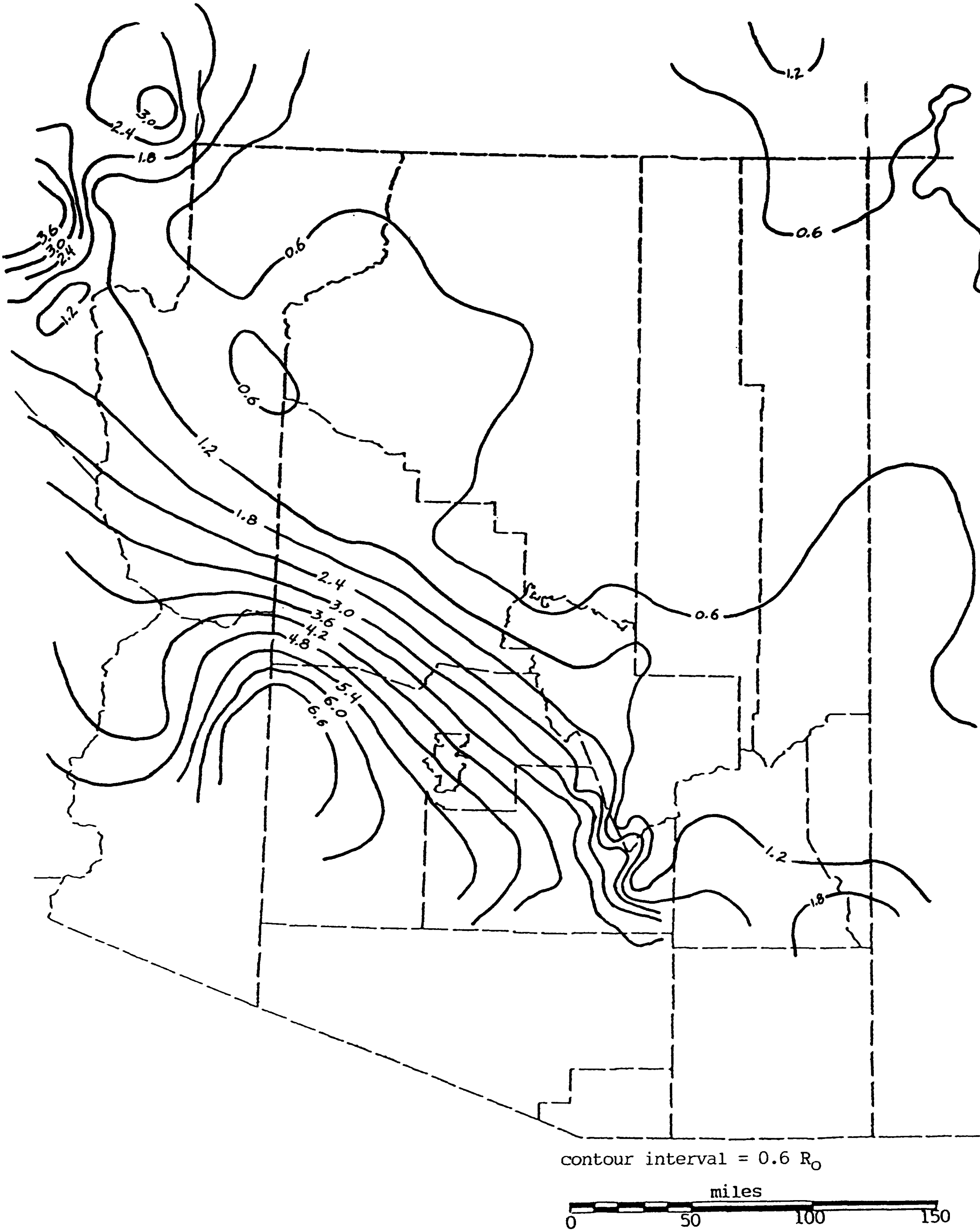


Fig. 32--Highly generalized map showing surface geothermal maturity isotherms (Ro) for Paleozoic and Mesozoic strata in central and northern Arizona. Data are in vitrinite reflectance equivalents.

ROCK SYMBOLS

Qtb=Quaternary-Tertiary basalt
Trm=Triassic Moenkopi Fm
Pkt=Permian Kaibab-Toroweap Fms.
PZ =Paleozoic strata
P€ =Precambrian rocks

Principal Mesozoic and Cenozoic Structural Events.

GROUP	STRUCTURES	DIAGNOSTIC FEATURES	AGE	PRINCIPAL STRAIN
I	Beaverdam thrust and associated folds and imbricate faults.	Faults and fold axes strike north-south; have been affected by later folding.	Post-Jurassic to mid-Cretaceous(?).	East-west shortening
II	Virgin Mountain anticline, Cedar Wash fault, Cottonwood fault, and associated faults and folds. Left lateral(?) component on Hungry Valley and Lime Kiln faults.	Faults and fold axes strike northeast, faults display reverse movement and produced overturned beds. Movement involved Cottonwood Wash Formation but not Muddy Creek Formation.	Late Cretaceous to pre-Middle Miocene; possibly pre-Late Eocene.	Northwest-southeast shortening
III	Grand Wash, Piedmont, West Branch, and Sullivans Canyon faults. Normal displacement on Hungry Valley and Lime Kiln faults.	Large amounts of normal displacement, involve late Cenozoic rocks, produced graben and horst blocks.	Late Pliocene(?) to Recent	Northwest-southeast and east-west extension

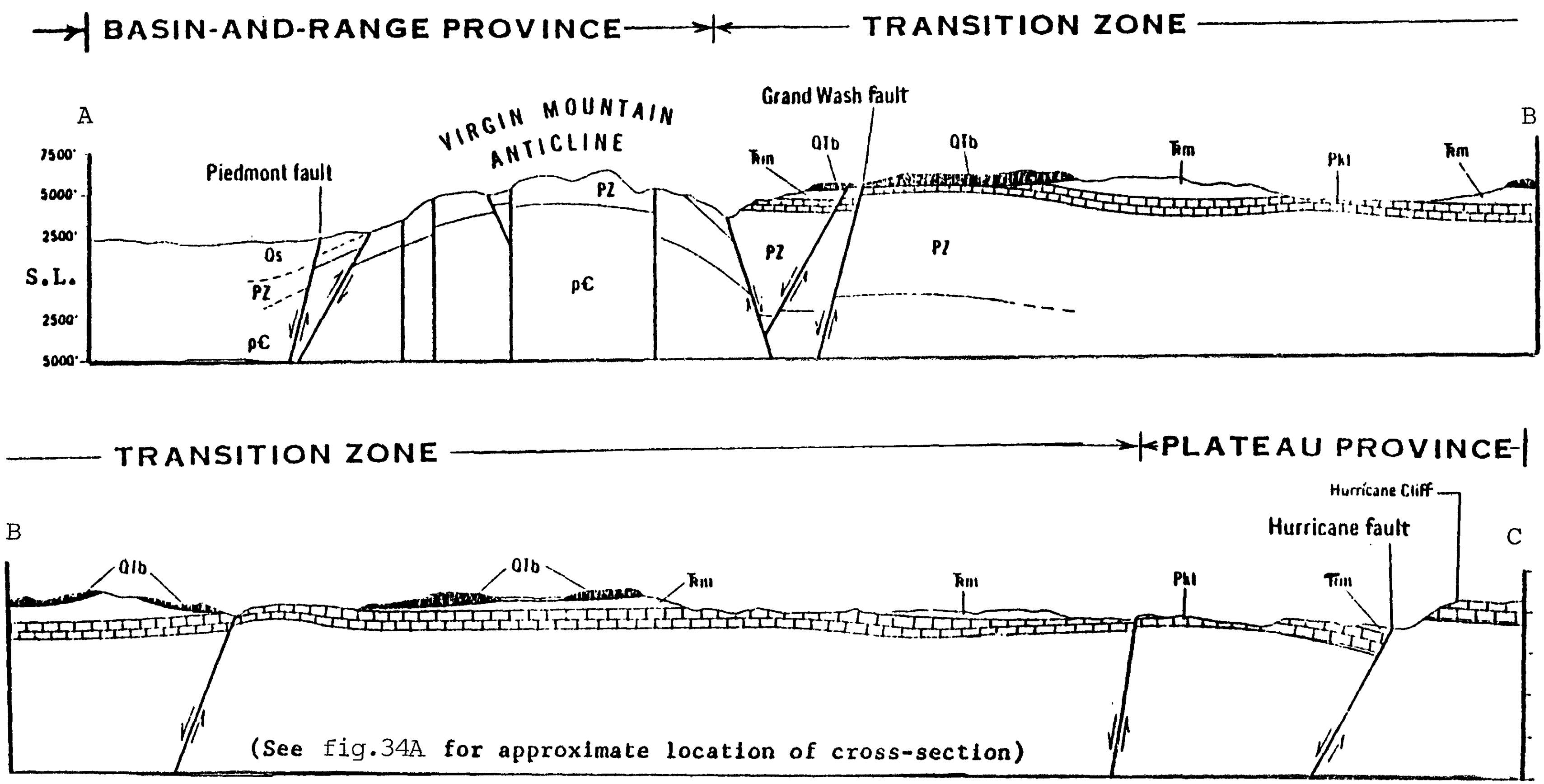


Fig. 33-- Generalized cross section, Basin and Range Province (From Giardina, 1979).

cored by wedges of Precambrian granite and granite gneiss (Wilson and Moore, 1959). Both of these wedges may be rootless. The Virgin Mountains "batholith" is a northeast-plunging anticline which is concordant with the overall structural grain. Strata of the CP near the GWF dip 2-4^{o} northeast (Luccitta, 1974), except for local flexures. Major reverse-drag folds occur in the down-dropped block west of the GWF (Hamblin, 1965).

Both compression and extension, operating at different geologic times, are working hypotheses invoked by geologists to explain basement-cored "uplifts" in extreme northwestern Arizona. The best current hypothesis which models the complex structure of this play invokes an allochthonous terrane floored by a zone of generally west-dipping thrust sheets (e.g., see Armstrong, 1968; Hansen, 1976; Steed, 1980). Crustal blocks originally several miles to the west were emplaced during the Laramide orogeny. The major zone of imbricate overthrusts (Bull Valley and Keystone) of the Sevier thrust system is exposed from five to several tens of miles west of this play (fig. 34a and b), such as in the brittle and intensely faulted Muddy Mountains east-northeast of Las Vegas, NV. (Temple, 1979; Burchfiel and others, 1982; Bohannon, 1983). However, the belt probably does not extend southeast through central Arizona (Matthews, 1982; Beikman and others, 1986) where some geologists have directly connected overthrusting to the Chihuahua tectonic belt of northern Mexico near El Paso, TX.

Jones (1963) argued that faults in the western Beaver Dam Mountains of southwestern Utah, previously interpreted as thrusts, may in fact be directed westward due to Tertiary gravity sliding. Seager's work (1970) expands on this second structural model. He believed normal faults surround the uplifted Precambrian core of the northern Virgin Mountains in Arizona and Nevada and are the result of low-angle gravity sliding. Laramide to late Tertiary uplifts created the central anticline of this

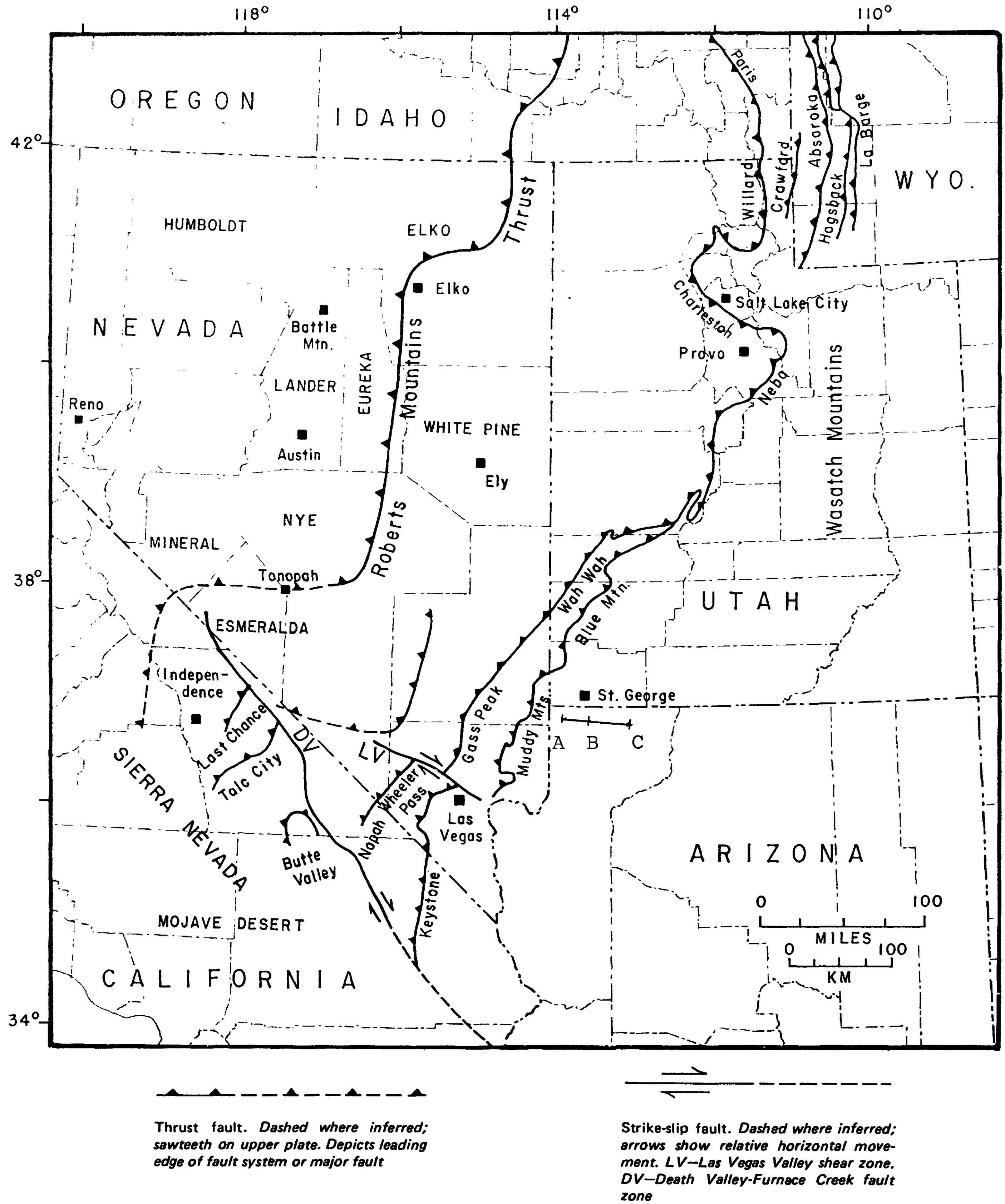


Fig. 34A--Index map of the Great Basin region showing major thrust and strike-slip faults. (From Stewart, 1980).

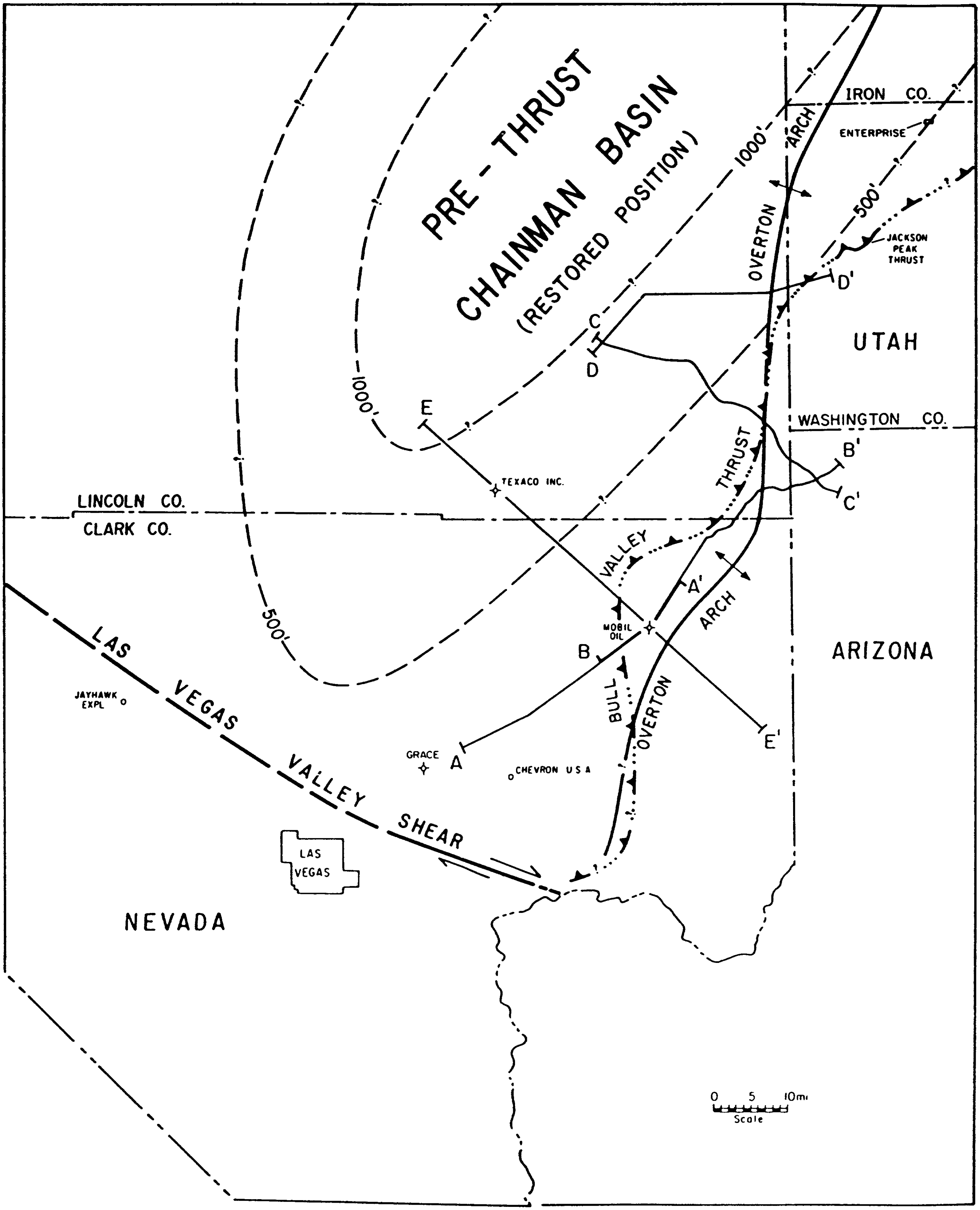


Fig. 34B--Map of southeastern Nevada showing location of the Bull Valley thrust fault and isopachs of the Chainman Shale. (From Moulton, 1982).

horst-and-graben structure. Major glide plates, controlled by the structural grain of the basement, slid from the crest of the anticline to the east and west. In this model, plastic flowage and drag folding are required to place older Precambrian metamorphic rocks above younger (mostly Paleozoic) rocks.. Also, south-southwest of the play in the Black Mountains of northwestern Arizona, mid-Miocene detachment faulting has exposed Precambrian basement.

A third, rather tenuous, structural hypothesis, offered by Moulton (1982) is based on seismic data and involves underthrusting of at least 20,000 feet of Paleozoic and Mesozoic strata beneath the Virgin Mountains. His cross-section depicts over 50,000 feet of Precambrian through Tertiary rocks comprising the thrust sheets near the Nevada-Arizona border.

Source Rocks and Geothermal Maturity

With respect to the petroleum-generation window, outcrops in the play area increase in geothermal maturity southeast to northwest (fig. 32), i.e. from immature for heavy oil (0.45 R_o) to peak maturity for condensate (1.50 R_o). Values of R_o increase to 3.0 and higher 20-30 miles northwest of a northeast-trending line through northwestern-most Arizona. These super-mature and metamorphosed outcrops support the widely-held idea that these strata were once deeply buried in the flysch trough of the Cordilleran geosyncline and subsequently uplifted via imbricate thrusting. The present-day geothermal gradient near St. George in southwestern Utah is less than 1.1^{o}F/100ft (20^{o}C/km). Within the play, gradients are higher at 1.4-1.6^{o}F/100ft (25-29^{o}C/km).

Through oil migration of several tens of miles, reservoirs could be sourced by phosphatic shales of the Chainman Shale of late Mississippian age in the Deseret basin of east-central Nevada and west-central Utah. The Chainman Shale, a proven source rock in eastern Nevada (fig. 35) with TOC of 4.5 percent (Moulton, 1982), feathers to zero thickness in northwestern

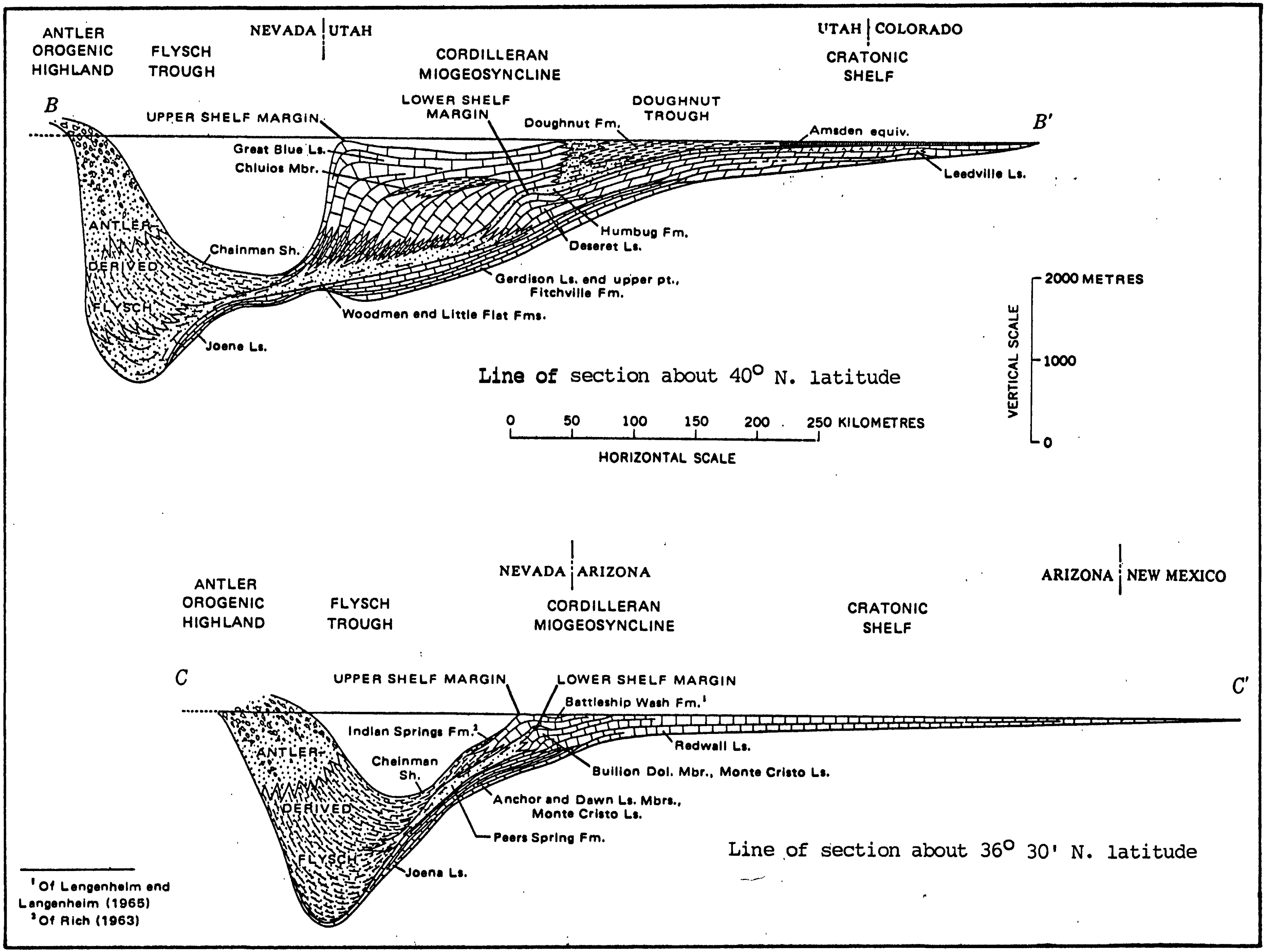


Fig. 35--Generalized west-east regional Mississippian stratigraphic cross sections showing local names of units and relative thicknesses. (From Rose, 1976). Vertical exaggeration X65.

Arizona (Meissner and others, 1984; Sandberg and Gutschick, 1984). Other Mississippian strata of claystones and calcareous siltstones a few tens of miles west and northeast of this play have TOC values between 1.0-1.7 percent. See Langenheim (1963) for descriptions of black Mississippian carbonates. Other potential source rocks include Devonian, Pennsylvanian, and Permian carbonate rocks of eastern Nevada (see fig. 36 for nomenclature). A geochemical and geothermal study by Britt and Howard (1982) showed that maximum oil generation in, and expulsion from, Mississippian rocks in central Utah's CH occurred during the Permian. Poole and others (1979) have found that the Chainman Shale of east-central Utah generated petroleum during the early Mesozoic and is currently within a renewed second cycle. Southward-sweeping Late Miocene arc volcanism (Best and others, 1980; Reynolds and others, 1986) may have facilitated additional hydrocarbon generation and eastward up-dip migration into Laramide-formed traps.

Reservoir Rocks

Reservoirs are plentiful and include carbonates of Devonian through Pennsylvanian age and sandstones of early to middle Permian plus late Triassic through Jurassic age (see appendix A and Langenheim and Larsen, 1973, for formation names and correlations). These carbonates are porous algal bioherms and biostromes (see Bissell, 1962; Rose, 1976; Welsh, 1979; Poole and Claypool, 1984) and are especially attractive targets. Updip wedge belts of permeability may have allowed eastward migration of petroleum from starved foreland basin to carbonate shelf facies. Mississippian strata thicken from about 2,300 feet along the CH westward to 4,600 feet in the Pioche basin east of the Antler orogenic highlands of central Nevada (Rose, 1976). Deep Paleozoic burial and/or Laramide thrust-sheet loading may have charged potential reservoirs with petroleum.

Traps and Seals

Although subsurface data are sparse, good potential exists for a

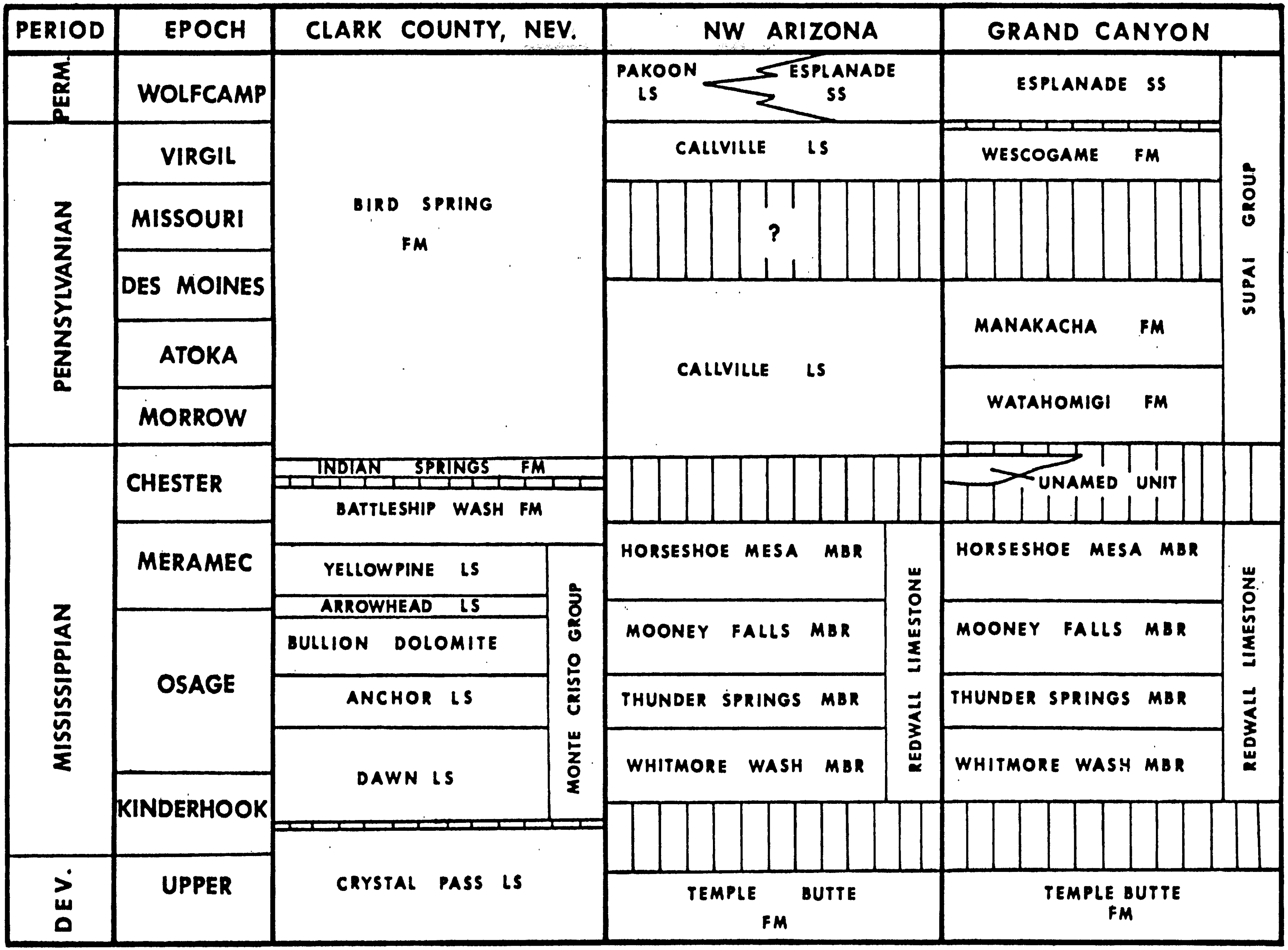


Fig. 36--Devonian through Permian stratigraphic nomenclature for northwestern Arizona and southeastern Nevada. (From Beus and Rawson, editors, 1979).

variety of both stratigraphic and structural traps based on analogs with the central COB. Both low- and high-angle reverse-faulting, active since the Precambrian Era (Moore, 1972), may have put wedges of older igneous, metamorphic, and sedimentary rocks over younger petroliferous rocks. West-to-east thinning of Paleozoic strata and merging of disconformities have undoubtedly created depositional pinchouts and high potential for stratigraphic traps. From southwest to northeast, approximate analogs of better-understood structural styles and potential stratigraphic traps include: the Muddy Mountains of Clark County, NV.; central Utah, such as in the Pavant Range (Baer and others, 1982; Villien and Kligfield, 1986); and, the COB of southwestern Wyoming about 300-350 miles to the northeast along structural trend (Royce and others, 1975). Traps in this Arizona play are postulated to exist directly beneath the concealed thrust faults and in intraplate anticlines and should be inviting exploration targets. Jurassic shales and evaporite rocks (fig. 37a,b), plus tight carbonate formations juxtaposed to thrusts, could provide effective seals. However, BR faulting and fresh-water flushing in the upper part of the stratigraphic section may have occurred.

Depth of Occurrence

Depths to reservoirs within the oil and oil/condensate windows of generation are estimated to be 2,500 to 7,500 feet in the east and 5,000 to 15,000 feet in the western part of the play.

Exploration Status

The nearest hydrocarbon production is the abandoned Virgin oil field of southeastern Washington County, UT. (See EXPLORATION STATUS of the HF play below). Shallow oil seeps and oil-impregnated rocks have also been found in Black Rock Canyon a few miles east of the GWF. Ubiquitous oil shows and staining occur in almost all Devonian through Jurassic strata penetrated by test wells in northwestern Arizona and southwestern Utah, and

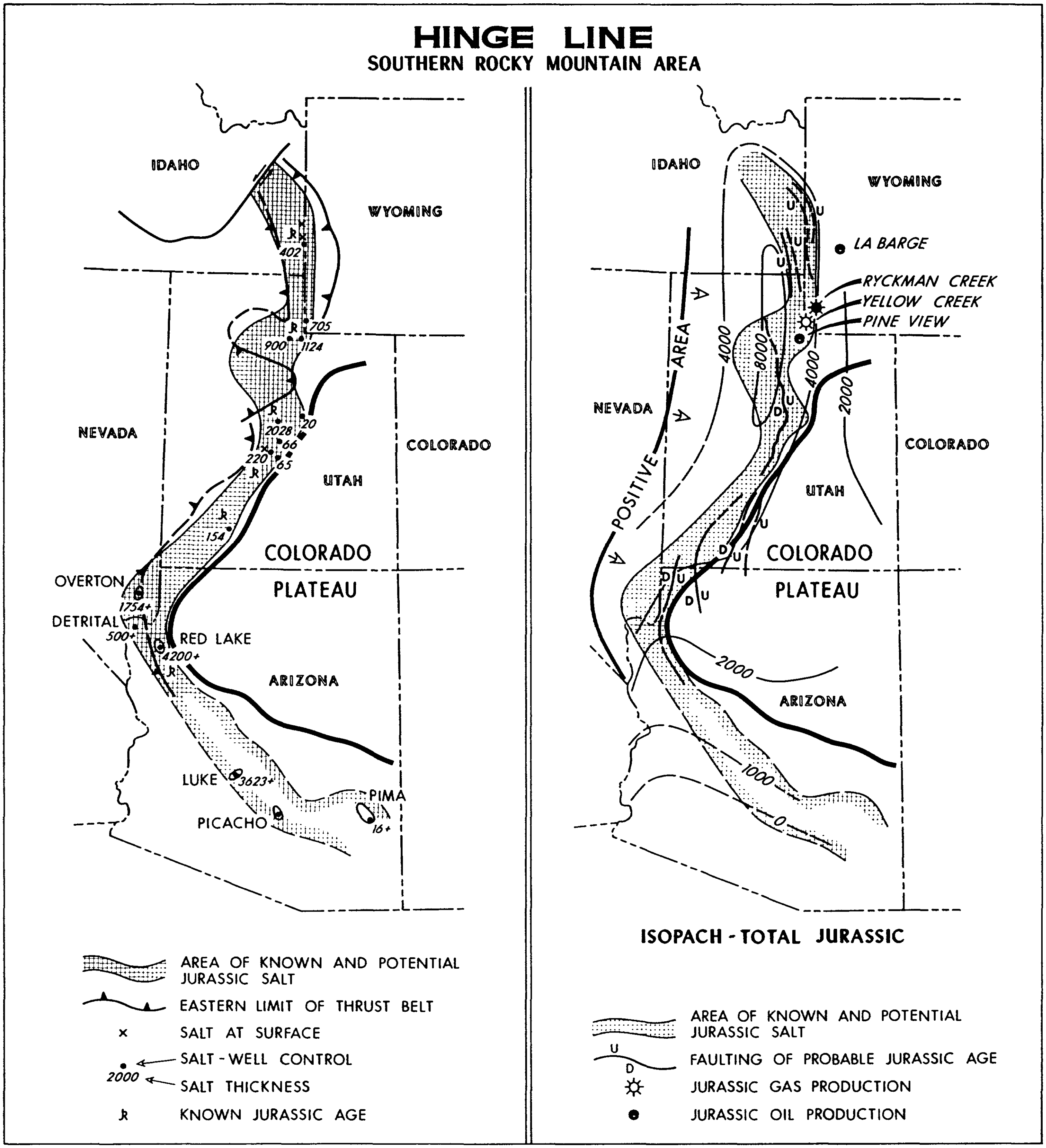


Fig. 37A- **Distribution of known and potential Jurassic age salt, southern Rocky Mountain Hingeline area.**

Fig. 37B- **Isopach map, total Jurassic, southern Rocky Mountain Hingeline area.** (Both figures from Hansen, 1976).

in Devonian and Mississippian strata penetrated in southeastern Nevada.

Only a few boreholes have been drilled in this play, all in the northwest section. They were spudded in alluvium and did not exceed 2,600(?) feet deep. No information is available on formation penetrated at total depth (Conley and Stacey, 1983; Ariz. Oil and Gas Conserv. Comm., 1984?). The nearest Arizona borehole not drilled into alluvium is about 6 miles east of the GWF. It was spudded in 1960 in the Moenkopi Formation due east of the central play area (sec.35, T39N R13W), and bottomed at 4,015 feet in either Mississippian (Peirce and Scurlock, 1972; Giardina, 1979) or in Devonian(?) or Cambrian(?) strata (Veal, 1976). Dead oil stains were encountered in the Toroweap, Queantoweap, Pakoon, Callville, and Redwall formations. There is some deep-exploration interest between Las Vegas, NV., and this play; e.g., in 1980 Mobil Oil Company finished drilling the No. 1-A Virgin River well, a 19,562-foot dry hole that bottomed in Precambrian basement, about 60 miles east-northeast of Las Vegas and 20 miles west of this play.

Hurricane Cliffs-Uinkaret Plateau Play

Location and Size

The Hurricane Cliffs (HC)-Uinkaret Plateau (UP) area is a 600 square-mile area in north-central Mohave County north of the Colorado River and almost entirely east of the Hurricane fault (HF); it is bounded on the east approximately by the $113^{o}7'30''$ W. long. line.

General Statement

Relatively thin Paleozoic strata are nearly flat-lying and contain numerous erosional disconformities. The total sedimentary section, consisting of Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, and Triassic rocks, is about 4,500-7,000 feet thick and consists of strata deposited in the CH area between geosyncline and shelf in tropical marine to desert (low coastal plain) environments. Sedimentary rock outcrops are primarly the Kaibab Limestone and Moenkopi Formation. The underlying Hermit Shale and Coconino Sandstone are exposed in the Hurricane Cliffs.

The north-trending HF, a recurrent fault of probable Miocene or younger age, is near the west-central edge of the CP (fig. 38). The HF extends at least 170 miles north-south through northwestern Arizona and southwestern Utah (Huntington and Goldthwait, 1903). It may be a normal-faulted monocline with Paleozoic and Triassic rocks on the west side down-dropped about 1,000 to 1,500 feet in northern Mohave County (Wilson, 1962; Huntoon, 1977). Displacement increases northward from about 200 feet at its southernmost trace south of the Colorado River to 2,800 feet near the Utah state line (Anderson and Mehnert, 1979), to about 6,000 feet at Hurricane, UT. (Hamblin, 1970), to as much as 10,000 to 16,000 feet near Cedar City, UT., according to Averitt (1964) and Lovejoy (1973). Some geologists consider this fault to be the CP-BR boundary. The Phanerozoic history of the HF, related to recurrent shifts in basement blocks, is a geologic enigma. Its history of manifesting recurrent offsets possibly begins as early as the Permian Period (Pierce, 1977), or the Laramide orogeny (Lovejoy, 1973), or the Miocene (Cook, 1960), or as late as the Pliocene or Quaternary (Koons, 1945; Anderson and Mehnert, 1979).

Source Rocks and Geothermal Maturity

Thermal maturity for surface rocks is 0.55 R_o near the Arizona-Utah border and 1.00 R_o near the Colorado River (fig. 32). This indicates slight immaturity in the northern play area and near peak maturity south of there with respect to the oil-generation window of occurrence for outcrops. Present-day thermal gradients of 1.3^oF/100ft and 2.1^oF/100ft (23.6 and 38.2^oC/km) have been measured in the east-central play area in two bore-holes. Present-day geothermal gradients of 1.2-1.8^oF/100ft (21.8-32.7 ^oC/km) are interpolated; these gradients and heat-flow data generally

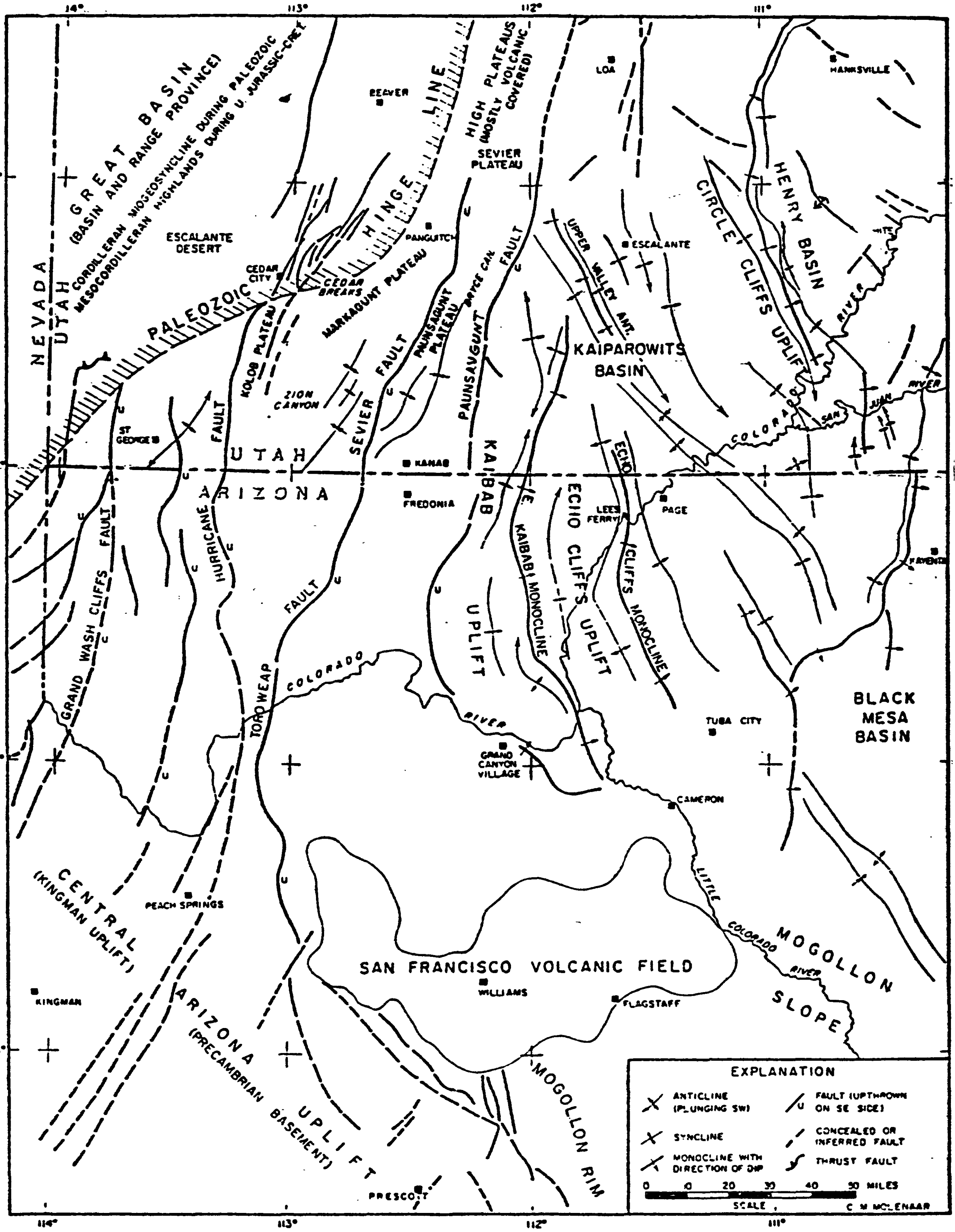


Fig. 38--Tectonic map of NW Arizona - SW Utah. (From Giardina, 1979).

increase northeast to southwest. Mineralization at relatively low temperatures occurs in breccia pipes near the southern play area (Wenrich, 1985).

Potential source rocks are undocumented but may include the Temple Butte, Redwall, Callville, Toroweap, and Kaibab formations. This conclusion is partially based on appropriate environments of deposition, e.g. open-marine (carbonate shelf) facies, and on the high number of oil shows in this area; it is not based on extensive geochemical data. The dark dolomites and subordinate mudstones of the Temple Butte are strongly fetid in northwestern Arizona (Beus, 1980). The Redwall is an open-marine shelf to shelf-edge, cherty, fossiliferous carbonate (packstone and grainstone) also showing less common intratidal to supratidal (stromatolitic/sabkha) facies. The Callville Limestone consists of 500 feet of limestone with lesser sandstone and dolomite. From west to east, open-marine to extensive sabkha environments are also documented in the Toroweap Formation consisting of mostly limestone (packstone and wackestone) and lime mudstone with lesser dolomite, gypsum, and eolian sandstone. The carbonates of the Kaibab Limestone were deposited in transgressive, open-marine seas.

Reservoir Rocks

Potential reservoirs could include all formations present in the stratigraphic column at this location, particularly middle and, to a lesser extent, upper Paleozoic strata. Oil shows are ubiquitous in the entire stratigraphic section in the drilled parts of the play area, and also within an area about 10 miles to the east and to the north in eastern Washington County, UT. (Cary, 1963). All geologic systems and nearly all formations have some indication of either live or dead oil shows, and tar or stains; the most significant shows being in the Redwall, Callville, Pakoon, Queantoweap, Hermit, Coconino, Toroweap, Kaibab, and Timpoweap Member of the Moenkopi (Giardina, 1979). One significant oil show in northeast Mohave County (Sec. 26, T40N, R6W) occurred in the Brooks No. 1 - 26 Federal Well which in 1983 reached a total depth of 7,170 feet (7,064 feet according to Petroleum Information Corp. records, 1984). The well had 20 feet of free oil and 70 feet of oil-cut mud from the Triassic Moenkopi at 570-foot and 642-foot depths, and oil shows in the Permian Toroweap Formation (Conley and Stacey, 1983; Nations and others, 1983a). Low permeability caused its abandonment. One of the few boreholes drilled on the Antelope Springs anticline in 1956 encountered eight zones of live to dead oil. The well bottomed at 3,753 feet in the Redwall Limestone and was abandoned due to lost circulation (Giardina, 1979).

Seeps, stains, fetid odors, and shallow asphalt deposits also occur in the Kaibab, Moenkopi, and Shinarump formations in Black Rock Canyon, Arizona, about 15-20 miles west of this play. Furthermore, oil-impregnated beds along the HF have been reported 5-7 miles south of Hurricane, UT. These petroliferous deposits, plus other minor ones, occur in the Timpoweap Member of the Moenkopi Formation in southern Utah and northern Arizona. Host rock lithology of the Timpweap includes chert pebble conglomerate and pisolitic calcarenite to fossiliferous carbonates deposited in tidal flat to lagoonal environments (Blakey, 1979a).

Traps and Seals

Strata are nearly horizontal, only dipping north-northeast (fig. 39) about half to one degree over the approximate 50-mile length of the play; there are local exceptions where strata are flexed 2-4^{o}, or where folded adjacent to the HF. Basement rocks and superjacent strata rise 2,000-3,000 feet southward in the play area. This could mean that the southern, less-explored part of the play might have enhanced resource potential if there has been considerable updip migration of oil.

Mid-Tertiary to present(?) continental extension created large horst-and-graben structures of the BR and large rotated "slump" blocks in

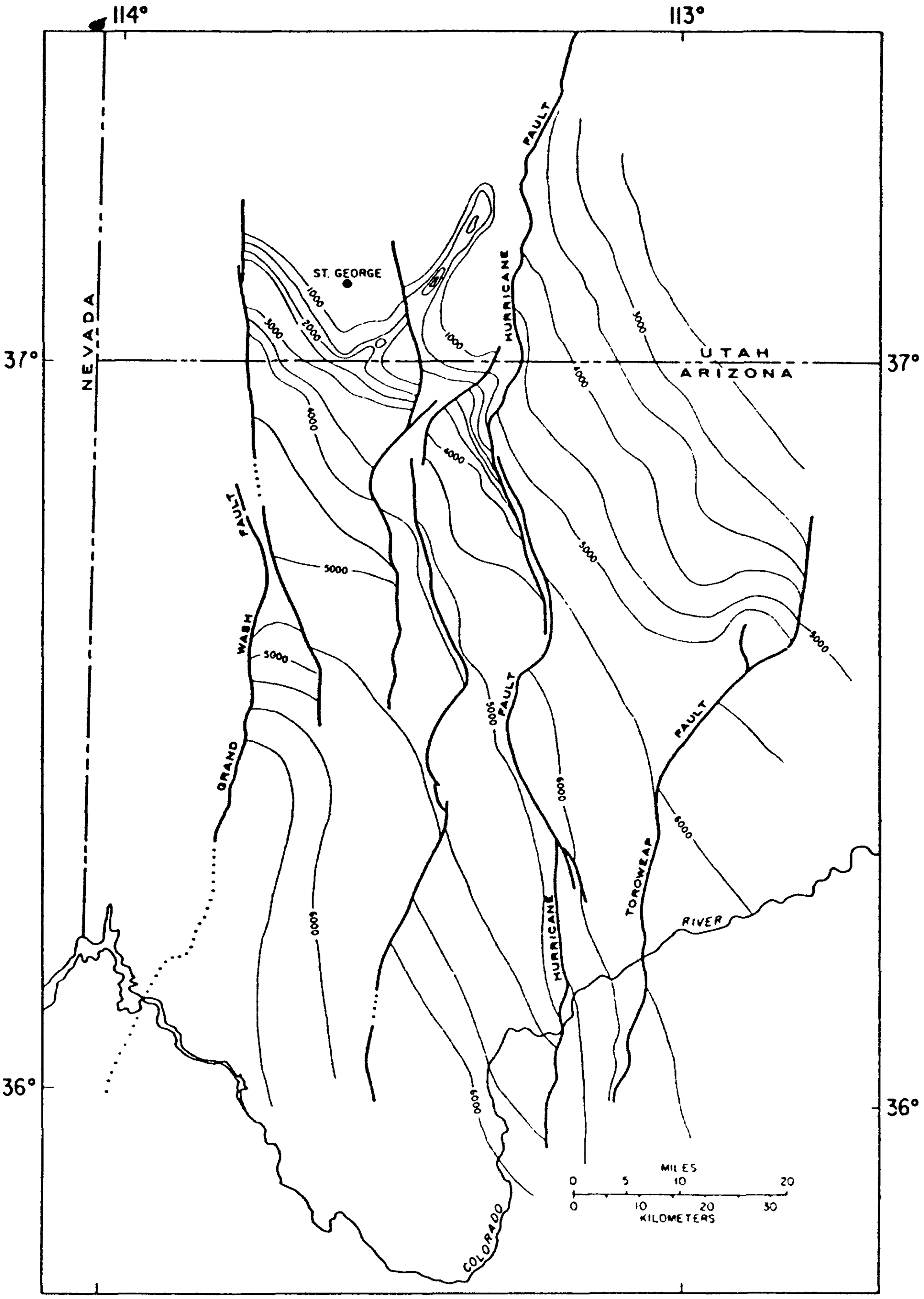
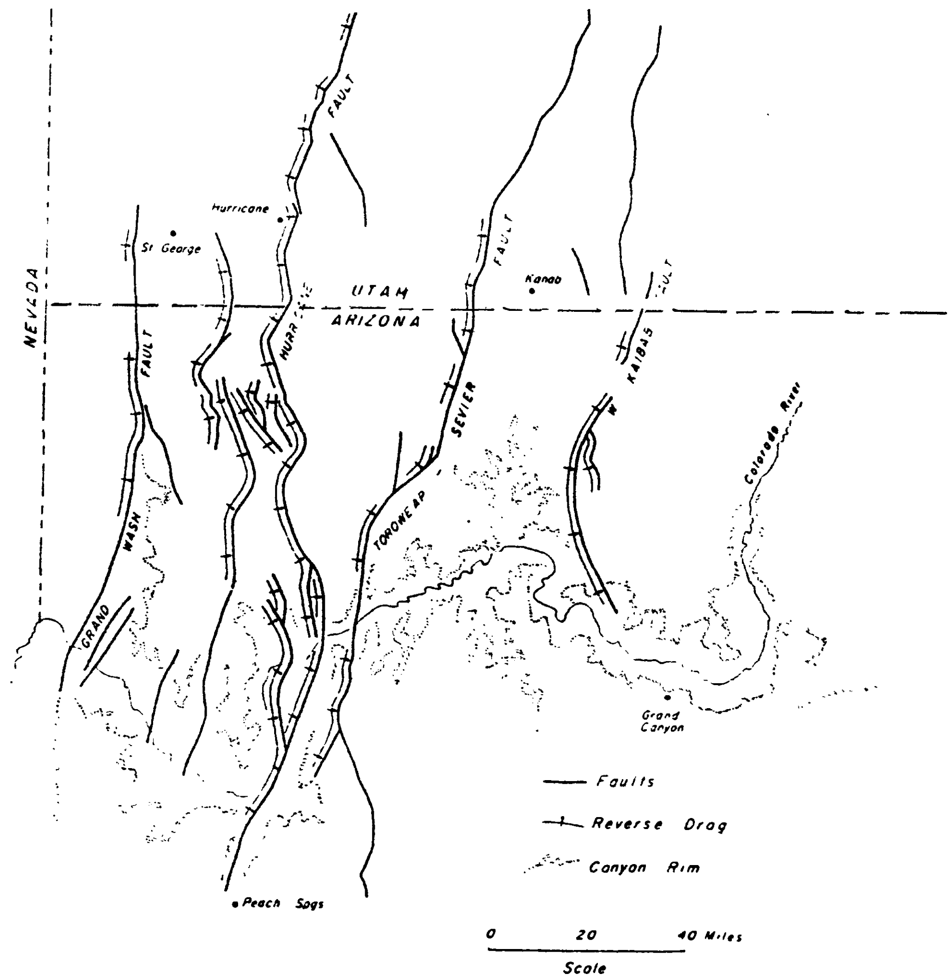


Fig. 39-- **Structure contour map on top of the Permian Kaibab Formation (unpub. work) showing regional northeast dip. Contours are in feet above sea level.** (From Best and Hamblin, 1978).

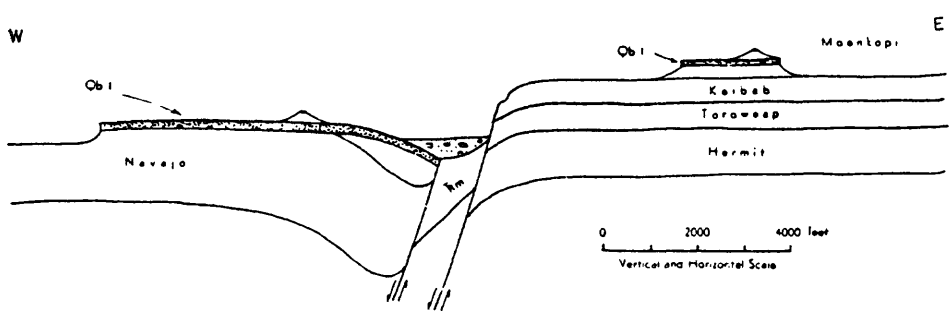
the UP region along Precambrian faults. A few smaller northwest- to northeast-trending, horst-and-graben structures were also formed in the play area (Koons, 1945; Huntoon and others, 1981). Drag and reverse-drag anticlinal folds (fig. 40), formed during mid-Tertiary faulting, are associated with and parallel to the monocline; these folds may trap hydrocarbons. Reverse-drag folds on the western hanging wall and the normal drag folds on the eastern footwall are described by Hamblin (1965). He stated that reverse drag.., "is characterized by a broad asymmetrical arc on the downthrown block, approximately one mile wide, with maximum dips of more than 30 degrees near the fault plane. It is concluded that reverse drag results from an alternate response to the same forces that produce antithetic faults and develops because of curvature of the fault plane at depth. Normal movement along a curved fault plane, in effect, tends to pull the blocks apart as well as to displace them vertically. Adjustments to fill the incipient gap by rupture produces antithetic faults, whereas failure by flexing develops reverse drag." Reverse drag, or antithetic down-folding on the hanging wall, may have also developed from a faulted monocline with recurrent (growth) movement, or through a combination of these two hypotheses. The axial trace of the drag, reverse-drag, and monoclinal folds is within several miles of the HF.

Other anticlines have evolved roughly parallel to the HF on the UP, and as potential oil traps, they plus the drag and reverse-drag folds, form much of the basis of this play. Heylmun (1960) and Giardina (1979) have located the northwest- to-northeast-trending Antelope Springs and Rock Creek anticlines in an area 6-10 miles east of the HF (fig. 41). Their combined axial length is about 40 miles and is prime exploration territory.

In addition to the north-south trending anticlines, there is some possibility that east-west pinchouts of Paleozoic rocks in the central to eastern play area may have stratigraphically trapped hydrocarbons. McNair

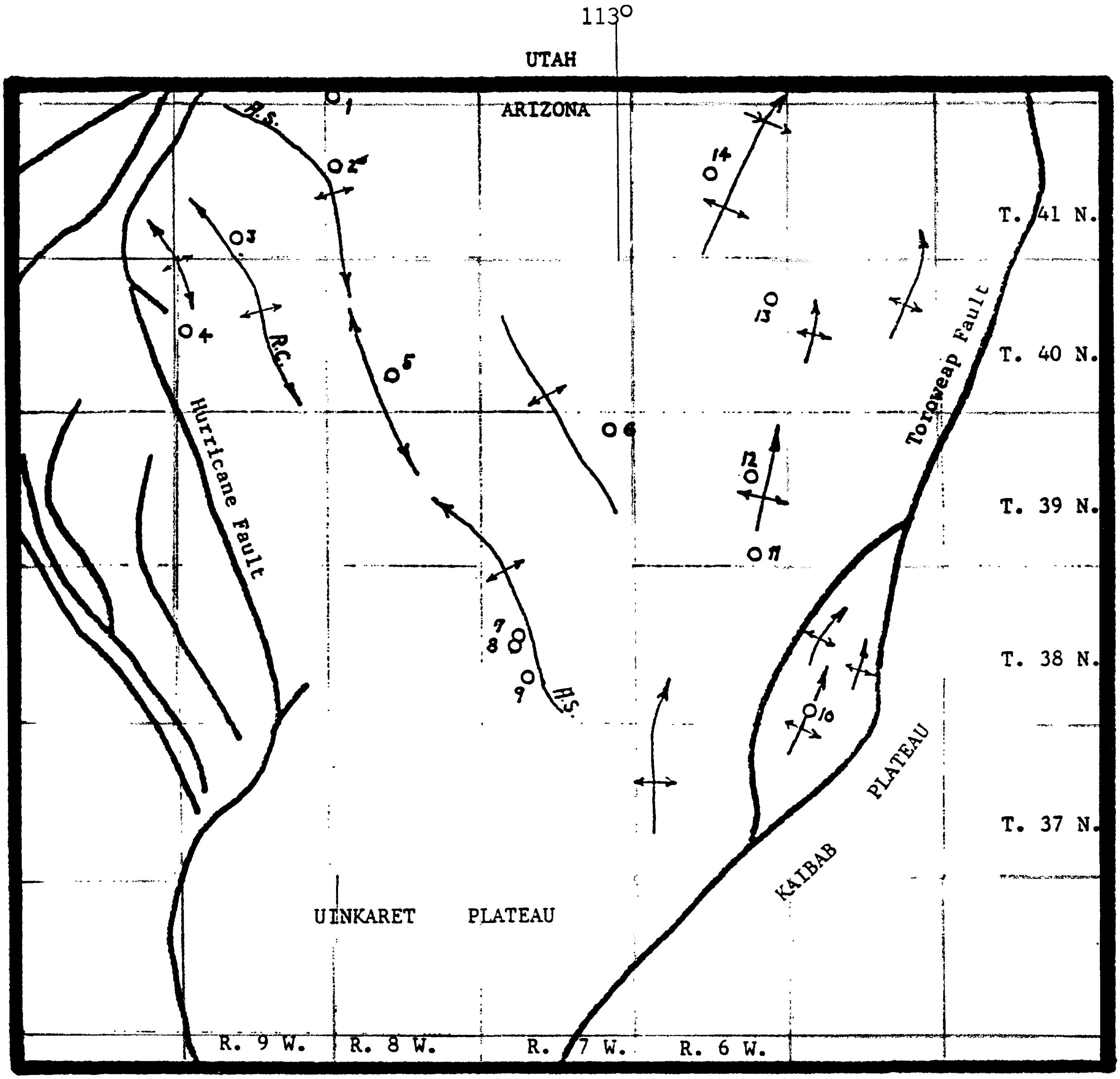


Map showing major faults and reverse-drag flexures in the western Grand Canyon region



Section across the Hurricane fault approximately 8 miles south of Hurricane, Utah, showing variations in reverse-drag flexures in the Navajo Sandstone and older Quaternary basalts (Qbl)

Fig. 40--Location of reverse-drag flexures in the western Grand Canyon area. (From Giardina, 1979).



A.S. Antelope Springs Anticlines
R.C. Rock Creek Anticline

Numbers	O&GCC ID	Numbers	O&GCC ID	Numbers	O&GCC ID	Numbers	O&GCC ID
1	8-22	5	33	9	502	13	40
2	8-20	6	347	10	43	14	8-19
3	676	7	41	11	56		
4	677	8	53	12	42		

Fig. 41--Generalized structure map of Uinkaret Plateau showing location of petroleum exploration wells. Numbers refer to the Arizona Oil and Gas Conservation Commission identification number. (From Giardina, 1979).

(1952) stated, "The Paleozoic rocks of the the corner area of Utah, Arizona, and Nevada contain numerous marine formations that show striking facies relationships, intertonguing, and truncation by overlap. It would appear that the most likely potential oil horizons occur in the Devonian dolomitic limestones, at the base of the Redwall (Rogers Spring) limestone, and in the Pennsylvanian-Permian marine rocks below the widespread Permian red beds. Regional unconformities occur at the base of the Devonian, Mississippian, and Pennsylvanian systems. These factors produce a combination of possibilities for potential petroleum production in the Colorado Plateau of southwestern Utah and northwestern Arizona." Pierce (1977) likewise found abrupt facies changes in Permian strata near the HF. Local warps in Permian strata have also been created by solution collapse within the gypsiferous Kaibab and Toroweap formations. Ryder (1983) suggested that petroleum may have migrated into this region from as far west as the CH. Potential oil generation and migration times are unknown, but if Paleozoic oil was trapped, Laramide tectonics may have caused secondary migration from lower traps into stratigraphically higher traps.

Possible adverse factors to the accumulation of hydrocarbons are: 1) inadequate TOC in the potential source beds to generate commercial quantities of oil and gas; 2) low subsurface pressures; 3) flushing of reservoirs by fresh water (Osmond and Elias, 1971; Eaton, 1979); 4) the long time(?) between generation of petroleum and formation of structural traps; 5) fracturing along the HF with loss of hydrocarbons; and, 6) the relatively shallow burial of the reservoirs.

Depth of Occurrence

Potentially economic prospects in strata of Devonian through Permian age range in depth from 4,000 to 4,500 feet.

Exploration Status

The nearest production to this play has been from the Virgin Oil field of southeastern Washington County in southwestern Utah about 15 miles to the north. The field, discovered in 1907, is now abandoned; it produced minor amounts of oil from the shallow Timpoweap Member (Rock Canyon of Bahr, 1963) of the Moenkopi Formation at 475- to 800-foot depths. Reservoir lithologies are thin, very fossiliferous, oolitic, algal to sandy limestones and calcareous sandstones and lesser fractured fetid black shale (Bahr, 1963; Driscoll, 1978). The trap type is probably a northeast-plunging fold with components of lenticular porosity and fracturing.

Methodical exploration of this area has been lacking and most wells were drilled on promotional ventures rather than on solid concepts of petroleum geology. Only 20,000-25,000 feet of strata have been drilled in all boreholes in this play; however, the show index (ratio of number of shows to dry holes) for Mohave County is greater than 1.0 for boreholes 1,000-5,000 feet deep (Stark and Gordon, 1982) and is encouraging for continued exploration. Giardina (1979) stated, "Northwestern Arizona has not been explored sufficiently to prove or disprove its merit for commercial oil production. Surface geologic and structure maps are generally limited to small-scale regional maps while published geophysical investigations are practically nonexistant. Subsurface stratigraphic control is sparce and irregularly distributed, averaging about one test well per 400 square miles. Some of the major folds have been tested but none adequately." Pye (1961) and Sandberg and Lyons (1962) have considered this general area as one of the most favorable in Arizona for the discovery of petroleum based on its encouraging oil shows, good reservoir qualities, and abundant structural and stratigraphic traps. It is evident, however, that not only should more wells be drilled on the UP but also, and more importantly, deeper reservoirs need to be tested.

Greater Black Mesa Basin (Oraibi Trough) Play

Location and Size

The greater Black Mesa basin (BMB) play, which includes the Devonian Oraibi trough (OT), encompasses an area of 8,750 square miles south to southeast of Monument Valley (MV) in east-central Coconino, central Navajo, and northern Apache Counties.

General Statement

About 96 percent of this play is on Indian lands which were not open to drilling until the mid-1960's. As such, many of the references cited for this play incorporate "pre-lease thinking". As shown in figures 2, 3, and 42, this play includes present-day highlands of the Black Mesa proper, lowlands of the structural Tyende saddle (Chinle Valley) to the northeast, plus the BB portion of the southernmost PB (Kelley, 1955a; Kelley and Clinton, 1960). The region is noted for its spectacular and colorful cliffs, buttes, canyons, alluvial flats, "badlands", and "painted desert-petrified forest" landscape. BMB proper, superimposed on the OT, is irregularly and almost continuously outlined by a narrow band of Dakota Sandstone outcrops. BMB proper is a Laramide structure of 3,200-4,000 square miles; its defining Cretaceous outcrops (fig. 43) are distributed roughly symmetrical with a north-south axis. The Black Mesa "basin" is a low-relief structural basin (fig. 44-46) having prominent erosional boundaries. Differential uplift of the greater BMB may have totalled 7,500 feet during the Cenozoic Era. Present-day topography and structure bear little relationship to the Paleozoic paleotectonic setting of the OT.

The total sedimentary section in the greater BMB is at least 4,000 feet thick with a maximum of 7,750-8,500 feet. A water well in T36N, R18E of northern Apache County encountered a stratigraphic section that if drilled to basement would presumably make the total maximum thickness of all strata over 9,000 feet (Conley and Giardina, 1979). About half of the sedimentary section is Paleozoic strata of foreland shelf origin and half

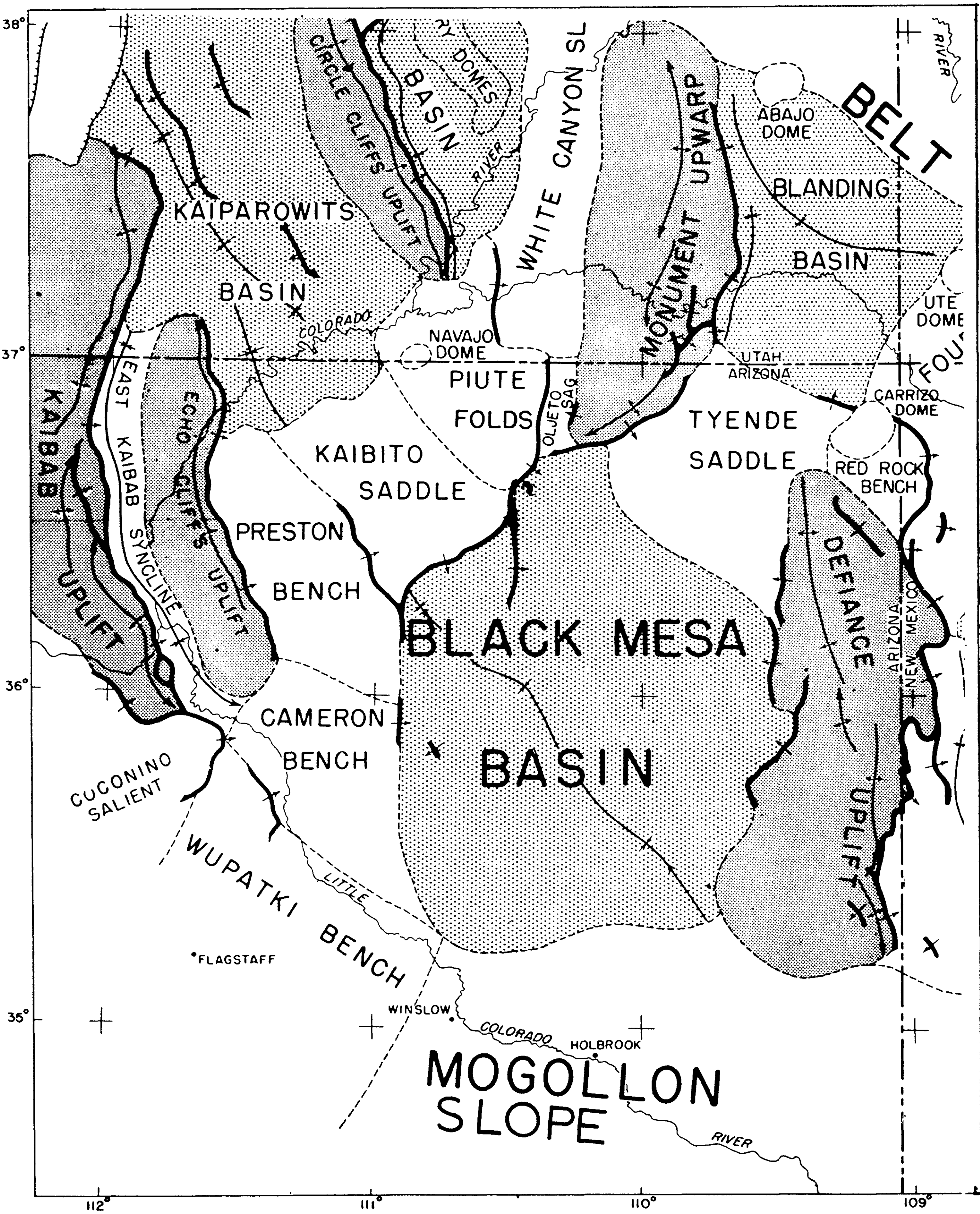


Fig. 42-- Index map of the tectonic divisions of the Black Mesa basin region. (From Kelley, 1958).

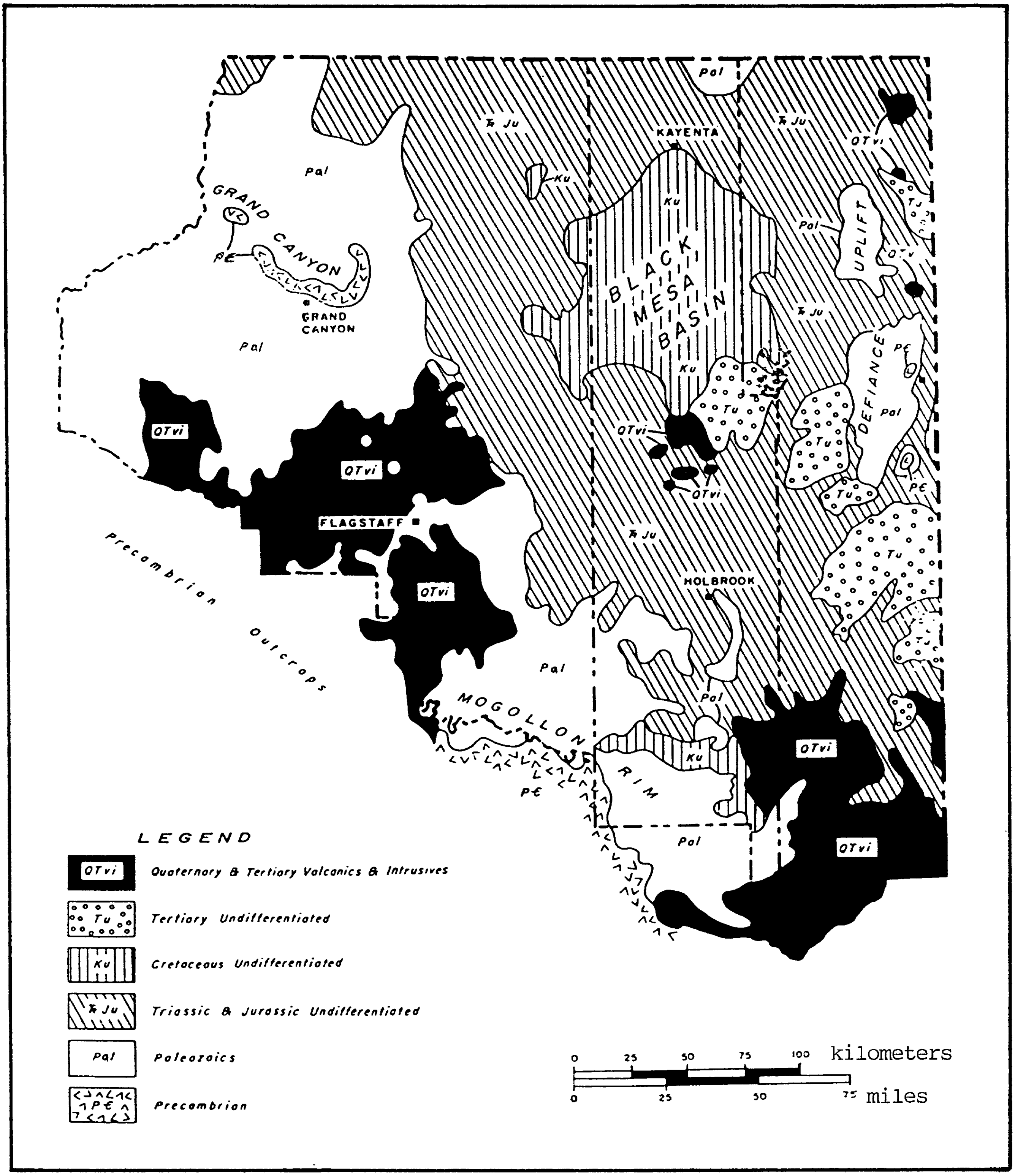


Fig. 43--Generalized geologic map of northeastern Arizona. (From Barwin and others, 1971).

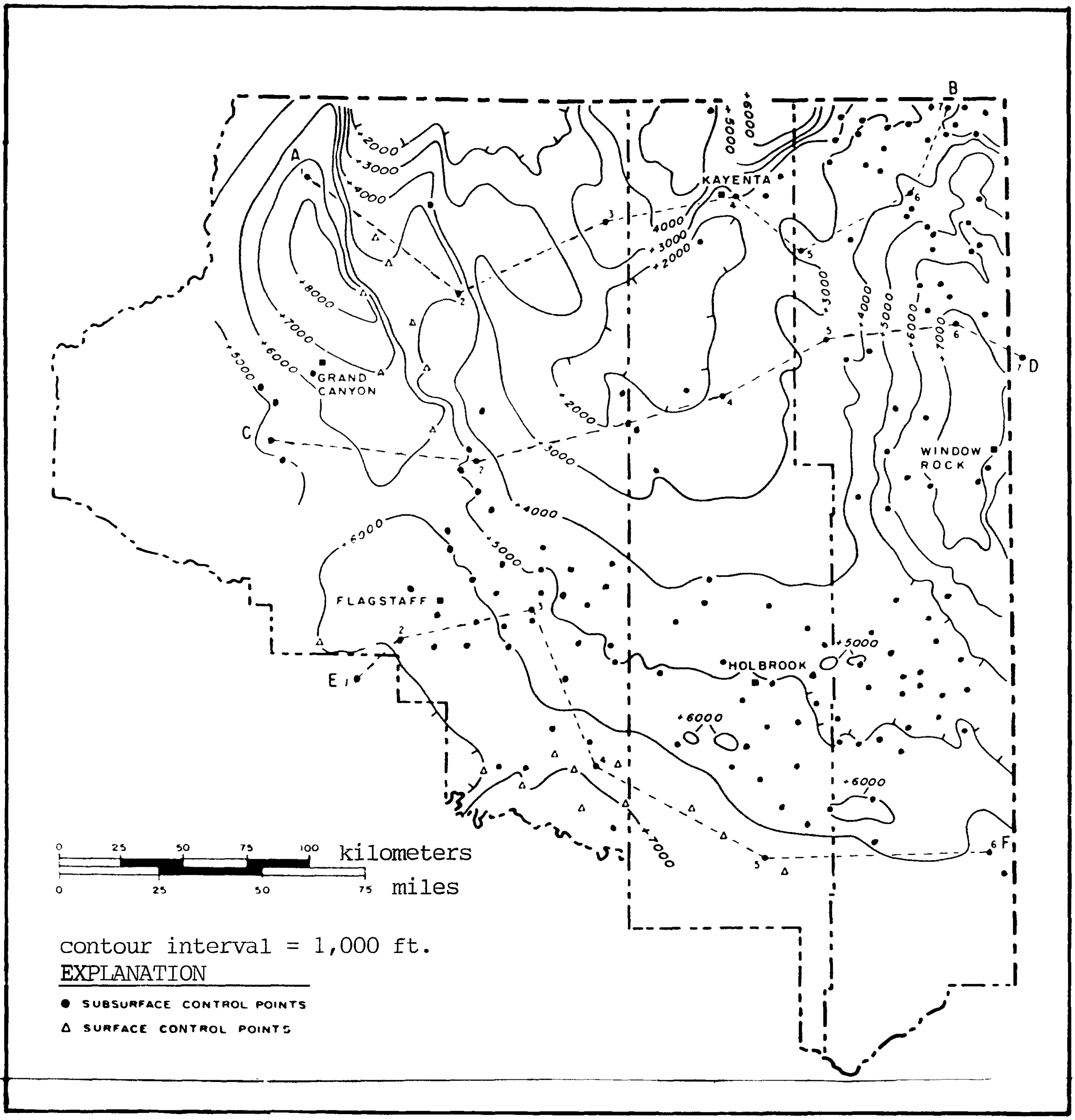


Fig. 44--Structural contour map of northeastern Arizona. Datum is top of Coconino or DeChelly Sandstone. Cross section lines of figures 45 and 46 are shown. (From Barwin and others, 1971).

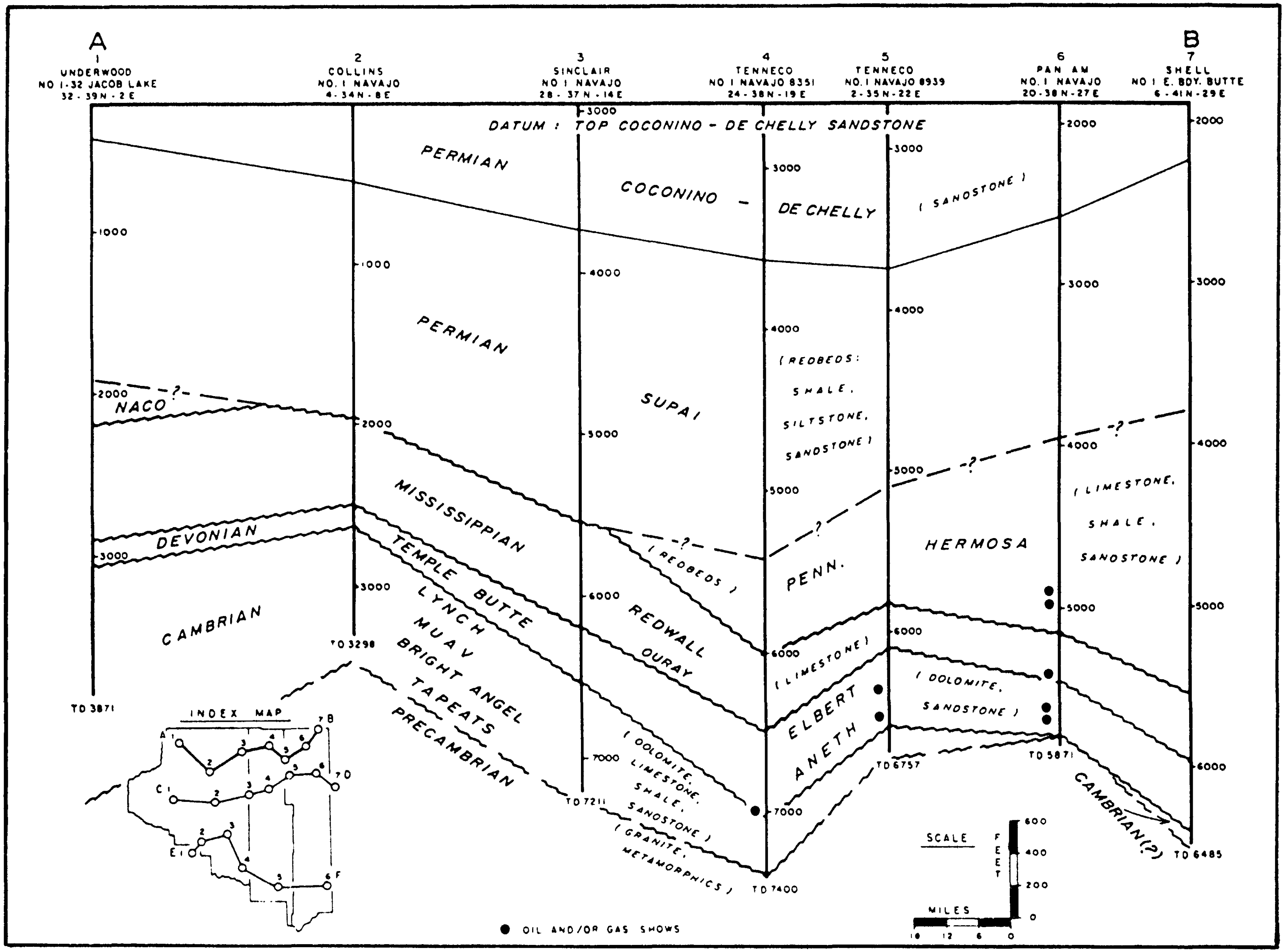


Fig. 45--West-east stratigraphic cross-section A-B, northeastern Arizona. (From Barwin and others, 1971).

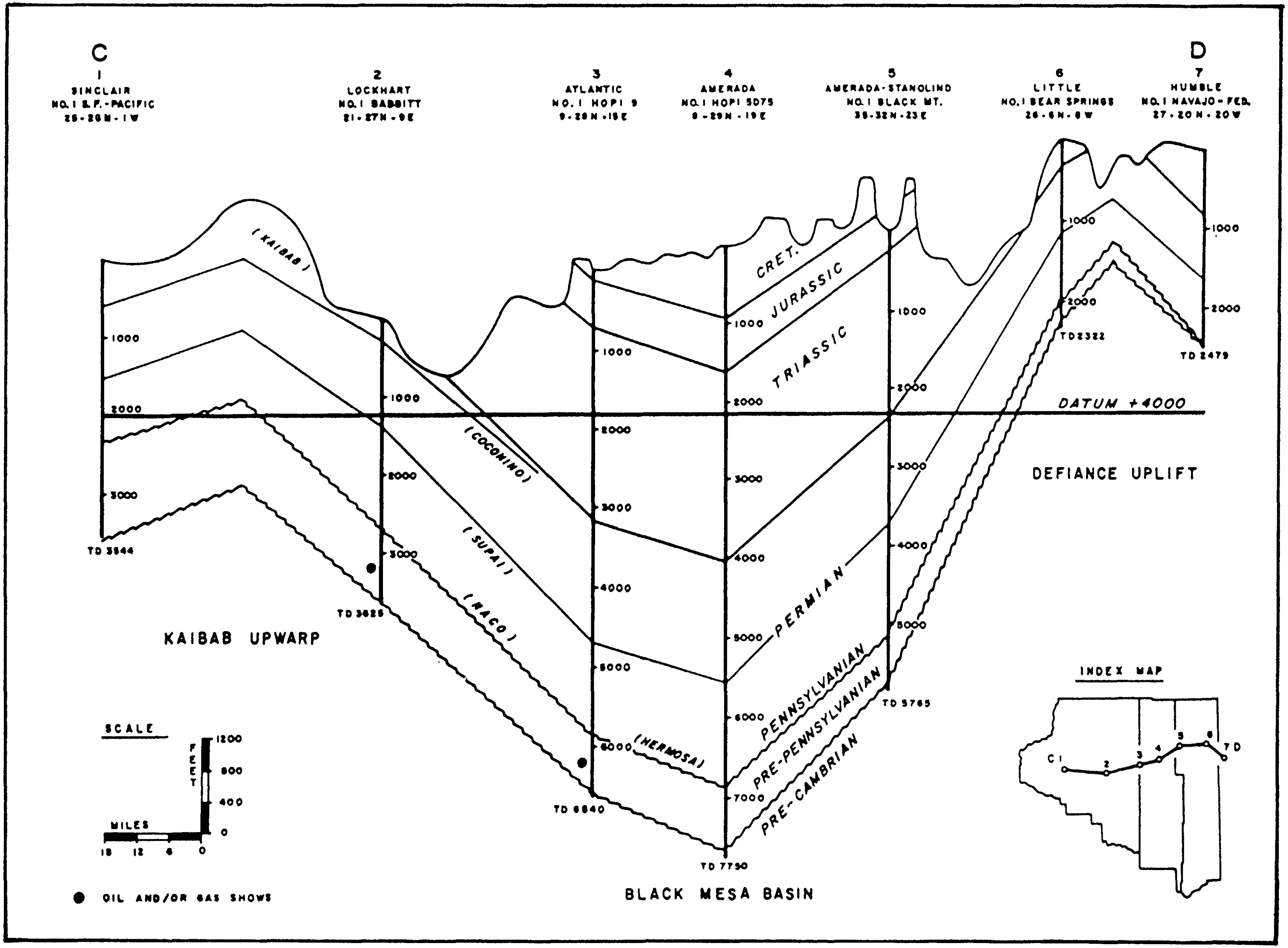


Fig. 46--West-east structural cross-section C-D, northeastern Arizona. (From Barwin and others, 1971).

Mesozoic strata of mixed continental-marine origin. Outcrops are almost entirely Mesozoic in age (for lithologic descriptions, see Repenning and Page, 1956; Harshbarger and others, 1957; Stewart and others, 1972) with some minor Cenozoic deposits in the southeastern section (fig. 43). Devonian rocks of the sedimentary OT are the most promising to test for petroleum, but other secondary targets are included within the Mississippian- Pennsylvanian-Permian interval, particularly on the east side where strata of these ages pinch out against the DU. Secondary targets are not described as separate plays because of their lesser potential and because they would be encountered in drilling to the stratigraphically lower Devonian target.

The Hopi Buttes volcanoes in the southern play area (Williams, 1936; Hack 1942: Shoemaker, 1953; Peirce and others, 1970; Sutton, 1974; Scott, 1975) are explosive diatremes originating from exceptionally gassy magmas and are composed of feldspathic basalt which intruded during the late Miocene or Pliocene. These diatremes have had little effect on the surrounding sedimentary rocks. Remarkably few surface faults of any consequence have been mapped in the play.

Source Rocks and Geothermal Maturity

Very little public information is available on the geochemistry of potential source rocks in the greater BMB. In the adjacent petroliferous San Juan basin (SJB), considerably more geochemical data and maturation studies on source rocks are available. Based on a study of oil characteristics in northern Apache County, Tucker (1983) concluded the oils in the small Arizona fields are probably genetically related. Her data from a core sample taken from a dry hole near Walker Creek, a one-well abandoned Devonian field, indicates that the shale from the Aneth Formation has a TOC content of 1.03 percent and is gas prone rather than oil prone. Turner (1961) also suggested that the BMB area has the potential to be a gas-rich province. However, from 1963 to 1969 Walker Creek produced about 100,000 BBLS of oil with no reported associated gas (Spencer, 1978a). Tucker's analyses showed hydrogen-deficient organic matter, probably derived from land plants, suggesting a predominant type III kerogen source. Although the maximum measured thickness of the Aneth Formation shale is about 150 feet, sufficient organic matter may not be available to form economic accumulations of oil.

Outcrops in this play are geothermally very close to the window of oil occurrence, based on sparse data. The few R_o values available average 0.61. The highest value available is near FC, but presumeably locally higher values occur near igneous intrusions. In a simplistic sense, given an assumed linear change of 0.10 R_o/1000ft and surface elevations from 7,000 to 7,500 feet in BMB, the bottom (floor) of the oil-occurrence zone would be at sea level to -500 feet below sea level. In a second scenario with a surface (well site) elevation of 6,500 feet and an assumed higher linear maturation gradient of 0.20R_o/1000ft, the oil floor would be at elevation 3,000 feet.

Present-day geothermal gradients (see references in PETROLEUM PLAY IDENTIFICATION section) range from about 1.1^{o}F/100ft (20^{o}C/km) in the basin's center to about 1.9^{o}F/100ft (35^{o}C/km) on the east-central side. Gradients in the northwest and southern sectors of the play have been measured to be 1.05^{o}F/100ft (19^{o}C/km) and 1.25^{o}F/100ft (23^{o}C/km), respectively; the highest value of about 1.4^{o}F/100ft (25.4^{o}C/km) is near FC. Heat loss in northeastern Arizona ranges from 1.13 to 1.80 HFU and averages 1.49 HFU.

Thermal events in parts of the play may be required, in addition to maturation via depth of burial, to generate oil and gas. Thus, higher potential may be warranted for areas around laccoliths and other intrusions and extrusions such as occur in the Carrizo Mountains and Hopi Buttes in the northeastern and southern parts of this play, respectively.

Reservoir Rocks

The following have all recognized the favorable Devonian stratigraphy of the northeastern Arizona-FC area, and hence its potential for major discoveries: Huddle and Dobrovolny (1952), Brown (1956), Brown and Lauth (1957), Turner (1958 and 1961), Pye (1961 and 1967), Turnbow (1961), Lessentine (1965), Conley (1974), Conley and Giardina (1979), Oil and Gas Journal (1979), and Tucker (1983, p. 28-29). Every system, Cambrian through Cretaceous, has hydrocarbon shows in northeastern Arizona. BMB proper has several Devonian and Triassic shows; however, Mesozoic units have less potential due to their shallower depths of burial resulting in lower maturation levels and lower hydrostatic pressures. The Coconino Sandstone and Navajo Sandstone are the main aquifers of northeastern Arizona (Cooley and others, 1969) and hence oil would most likely be flushed from them. Seeps, shows, and petroleum impregnated rocks at shallow depth are found surrounding the play. For a listing of oil and gas shows see references in the HYDROCARBON OCCURRENCES section of this report.

Outcrops of the Martin Formation of the MR area are known for their petroliferous or fetid odor in the lower dolomite units (Teichert, 1965) and has led some geologists to consider the Devonian favorable for oil and gas accumulation. Turner (1958) has written, "The Devonian System present thoughout the entire Black Mesa basin region is one of the major potential oil and gas resevoir horizons in the area. Evidence of oil accumulation appears on the north, the west, and the south side of the Black Mesa basin extending from southern Utah, through the western rim of the basin near the Grand Canyon and south to the Mogollon Rim on the south side of the basin." Most exploration in the OT, and consequently most shows, has occurred in southern San Juan County, UT. Drilling to date has concentrated almost entirely on large structures, but in the future drilling should test promising stratigraphic traps as well.

Barwin (1969) stated, "The Pennsylvanian section of the Black Mesa basin is not particularly favorable and the primary objectives in the future may be the Devonian rocks and to a lesser extent, the Mississippian and Cambrian. The Devonian stratigraphy, however, is known primarily from a few boreholes and a few subsurface lithologic studies. Undrilled anticlinal trends are present in the northern part of the basin..." The transgressive Aneth Shale, the McCracken Sandstone Member, and upper member of the Elbert Formation (dolomite and anhydrite) make an excellent combination of source, reservoir, and seal rocks, respectively (Turner, 1958; Kashfi, 1983) and form the basis of this play. Spencer (1978a) and Gustafson (1981) attributed the McCracken sands to deposition in transgressive seas, whereas Kashfi (1983) believed it to be of regressive-sea origin. The Aneth formation is dark, fetid, glauconitic, argillaceous, aphanitic dolomite with interbedded dark shale, carbonaceous shale, coal, limestone, evaporites, and dark siltstone. The McCracken, a poorly- to well-sorted, medium- to coarse-grained, glauconitic sandstone with minor sandy dolomite, is thickest in north-central Apache County. It becomes coarser upwards and may locally represent a westward prograding deltaic complex and channel sands in a neritic environment (Kashfi, 1983). Some small carbonate buildups may be present in the McCracken. The eastward transgressive upper member of the Elbert Formation is a thin-bedded, pelletal, sandy dolomite with interbedded variegated waxy shale. From the DU area, the McCracken Sandstone Member grades westward into the Upper Elbert dolomite (Gustafson, 1981). Zones with good porosity in Upper Devonian rocks are erratic and thin according to Barwin and others (1971). For a facies analysis and correlation of the BMB Devonian, see Baars (1972) and Harrison (1976).

Traps and Seals

The McCracken Sandstone offers the best objective for structurally- and stratigraphically-controlled traps. The OT has Devonian structural relief of about 3,500 feet (well information from Petroleum Information Corp., 1984) and Laramide folds have structural closure on the order of 500-1,000 feet. Regionally, strata on the southwest side of BMB dip about half a degree, but increase to about one degree on the northeast side. Higher dips are found around the periphery of the play, such as near Comb Ridge and the DU, and also locally as folds.

The long monoclines, anticlines, and synclines of Laramide origin have northwest, north-south, east-west, and northeast orientations and are classic large-scale geologic features in northern Arizona (fig. 47). Limbs of most folds dip only several degrees. Axes plunge only slightly and may extend 70 miles or more in length. According to Davis (1975), there is evidence that some folds may be refolded. To date, all petroleum in Arizona has been found in anticlines. At least 350 miles of monocline and anticline axes are present as depicted on regional maps (e.g., Kelley (1955a,b); nonetheless, exploration should not be restricted to these large superimposed structures. Long-trending, subtle stratigraphic zones also have good petroleum potential (Barwin and others, 1971). Elston (1960) stated , "Possibilities for oil and gas discoveries in stratigraphic traps seem best in the northern and western parts of the Black Mesa basin, where a moderately thick Paleozoic marine section is present and where complex facies changes occur in rocks of several Paleozoic systems." Nations and others (1983a) concluded that the Devonian System in the BMB should be considered as a favorable target, "due to numerous shows in wells and the complex stratigraphy due to facies changes, onlap relations, and erosional unconformities." These authors also emphasized that Devonian strata wedge out in the eastern part against the DU, and to the south against the MR, thus creating stratigraphic traps.

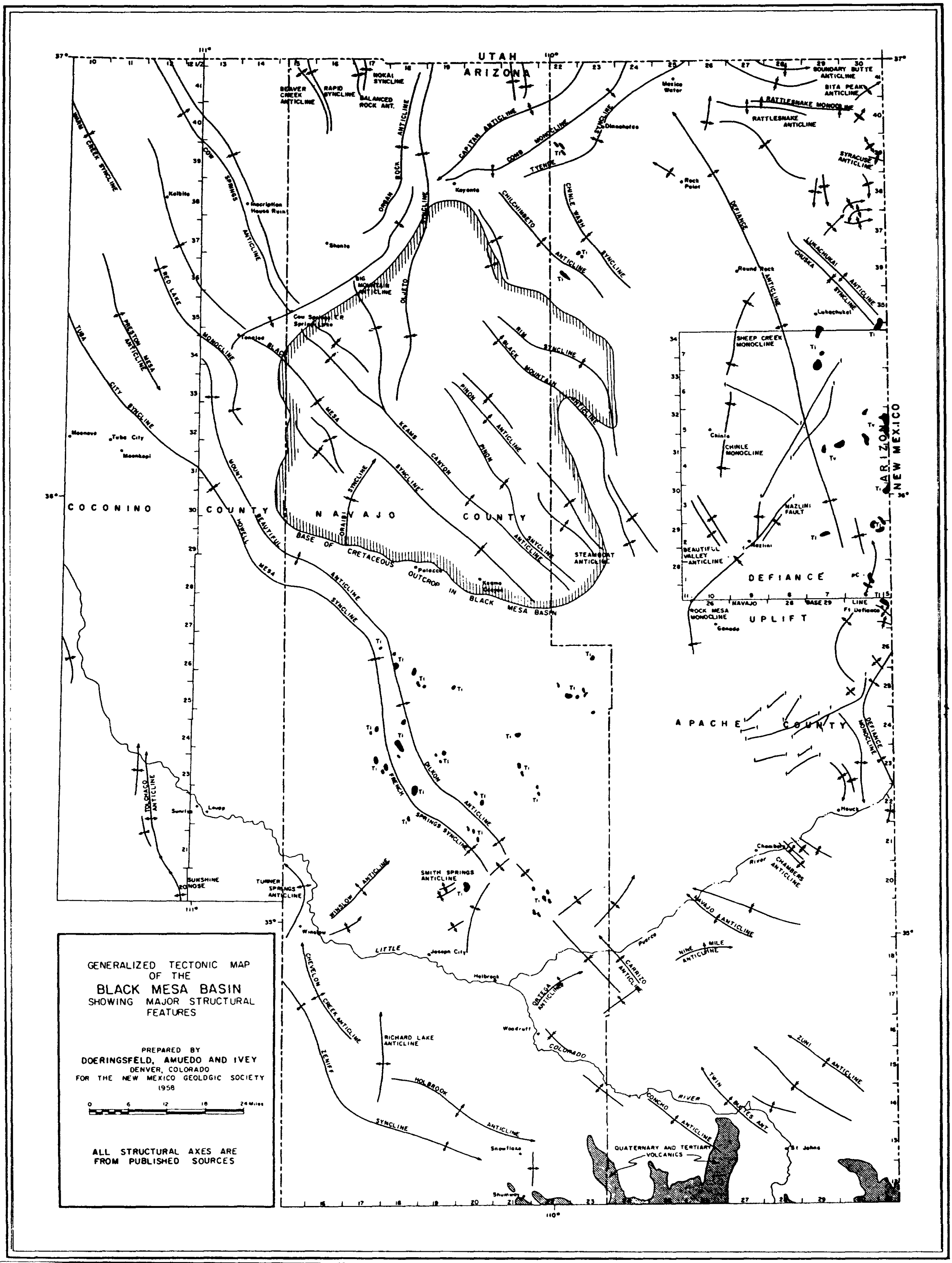


Fig. 47--Generalized tectonic map of the Black Mesa basin showing major structural features. (from Doeringsfeld and others, 1958).

Conceivably, some deep-seated intrusions are yet to be uncovered by erosion in the play area. The likelihood of structural traps and enhanced fracture porosity also increase towards these igneous rocks. In evaluating the gas potential of northeastern Arizona, Turner (1961) has emphasized that the presence of intrusions, "is looked upon as enhancing the potential for oil and gas, <u>not</u> as a detrimental factor as so often concerns management in exploration. Intrusive contacts observed at the surface are commonly indicative of 'dry' relatively cold igneous material. Minor contact metamorphic halos, measured in inches, are typical throughout this country. Strategically positioned dikes relative to fold axes may in themselves provide additional structural closure for the accumulation of oil and gas without affecting the quality of the reservoir." Landes (1970) has concluded, "The Dineh-bi-Keyah discovery called attention to oil and gas possibilities along the east flank of the Defiance uplift, and future discoveries can be anticipated there, including the portion in northwestern New Mexico. The next most obvious place to prospect is the west flank, and on out into the Black Mesa basin. The objectives here can range down through the section from Cretaceous to Cambrian."

The greater BMB exhibits one of the largest positive and continuous residual Bouguer gravity and isostatic gravity anomalies in Arizona in terms of areal extent; these anomalies appear to correspond to aeromagnetic anomalies. Anomalies may reflect strata of the OT, but more likely accentuate or model the northeast-northwest fault pattern of the Precambrian basement. References for selected geophysical maps are cited in the PRECAMBRIAN section of this report.

<u>Timing and Migration</u>

Using Lopatin's methodology, MacMillan (1980) concluded that petroleum generation in the adjacent SJB and PB of the FC area began in the Early Cretaceous. If generation and migration began at this same time in the

BMB but terminated prior to the Laramide folding, then structural traps of Laramide origin may not contain oil and gas unless older traps were involved. On the other hand, Kashfi (1983) proposed that oil generation was most intense during the late Cretaceous or early Tertiary during a time of maximum burial for the Devonian source rocks.

Depth of Occurrence

Depths to the top of the Devonian range from 3,300 feet near the DU to 7,200 feet in BMB proper and 5,700-6,700 feet in the BB. Production has been from 6,370-6,384 and 6,758-6,793 foot well-depth intervals. In the eastern half of the Tyende Saddle top depths range from 3,300 feet near the DU to 5,500 feet near the center of the Oraibi trough. In the western half of the Tyende Saddle, top depths are 5,300-6,500 feet. For BMB proper, Devonian depths are 5,600-6,500 feet in the north, 6,500-7,200 feet in the center, and 3,500-6,100 feet in the south. Depths to potential reservoirs, however, will vary considerably around specific structures because of the Precambrian paleotopography.

Exploration Status

The nearest Devonian petroleum production is within the play at Walker Creek (McCracken reservoir), and Tohache Wash (Aneth dolomite resevoir). Oil is mainly about 40^{o} gravity with a presumed Aneth source (Spencer, 1978b). Porosity is low, between 4 percent for carbonates and 8 percent for clastics; however, increases may be found farther to the south along the western edge of the DU within the deltaic facies. Before being abandoned these one-well fields produced a combined maximum of about 100,000 BBLS from structural traps.

Minor Devonian gas containing 5-6 percent helium has been produced at DBK (Danie, 1978). Two small fields in northwestern New Mexico, Akah Nez and Tom, have produced from the McCracken Sandstone Member. Akah Nez, 6 miles east of Arizona, was discovered in 1967 as a structural trap and produced 17,200 BBLS of oil and 5,945 MCFG before abandonment in 1972. Its net pay zone was 31 feet, porosity was 9-18 (ave. 11) percent, and the average reservoir depth was 4,116 feet (Dawson, 1983). Tom field was discovered in 1976 and abandoned in 1982 after producing 1,605 BBLS of oil and 8,183 MCFG from a structural trap. Porosity was only 3-8 (ave. 5) percent, the net pay zone was 28 feet, and the reservoir depth averaged about 6,450 feet (Malinowski, 1983). Eighty miles north of the OT play, McCracken Sandstone oil is produced from a faulted anticline at Lisbon Field in the northeastern PB (Clark, 1978; Gustafson, 1981; Clem and Brown, 1984).

Exploration by drilling in northeastern Arizona has concentrated on shallow targets around the periphery of the greater BMB. Between 1 and 2 percent of the entire play has been explored by drilling to at least the Coconino level. Less than one percent of the play has been drilled to the Devonian. Drilling density averages about one borehole per 78 square miles. Slightly less than 650,000 total feet of strata have been penetrated by about 115 boreholes. Average depth per borehole is about 5,700 feet. The deepest borehole (dry and abandoned) in the play was drilled to 8,461 feet in 1969 in northeast Apache County (sec.1, T39N, R29E). It bottomed in an igneous sill in the upper Devonian Ouray Formation. Twenty sills were encountered in this well. Less than 25 boreholes, which penetrated about 100,000 feet of strata, have been drilled to date in BMB proper; average depth per well is about 4,350 feet and drilling density is about one borehole per 190 square miles. However, in the BB part of this play, drilling density is higher, i.e. about one borehole per 7 square miles. Nearly half of the cumulative footage drilled is in the 5 percent of the play within the BB of Arizona; the average depth per well is about 5,770 feet here.

The greater BMB remains very sparsely explored by the drill at all stratigraphic levels, and particularly for Devonian reservoirs. Given the large size of this play, it may be a long time before the Devonian potential can be either condemned or totally exploited.

Western Flank of the Defiance Uplift Play

Location and Size

This 1,800-square-mile play includes the northern, western, and southern flanks of the Defiance uplift (DU) in central and northern Apache County (fig. 2 and 3). Dineh-bi-Keyah (DBK), Arizona's largest oil field, is located in the northern play area.

General Statement

Outcrops include extensive strata of Triassic and Jurassic age, and lesser exposures of Cenozoic age. Thickness of the entire stratigraphic section may attain 4,500-5,500 feet -- about 1,500-3,750 feet of Paleozoic strata and 1,500-2,000 feet of Mesozoic strata. The overall thickness of Cambrian through Mississippian rocks is 0-700 feet, and 100-1,000 feet for Pennsylvanian rocks except at the BB shelf-edge where it reaches a maximum of 1,500 feet. Permian rocks are 1,200-2,000 feet thick (Peirce, 1967). The Permian and Triassic are the only systems covering the crest of the DU. Both the Triassic and Jurassic Systems are each about 500-2,000 feet thick.

The west flank of the DU merges with the east flank of BMB (fig. 48) in the Chinle Valley and Beautiful Valley area. This play contains Arizona's largest oil field, DBK, which is in the monocline area (fig. 49) of the Lukachukai Mountains of the northern part of the Chuska Mountains (5-6 miles west of the New Mexico border, 12-15 miles north-northeast of Canyon DeChelly National Monument, and 15 miles east of Round Rock, AZ.).

The basis of this play is to "extrapolate" conditions of known oil occurrence in the north at DBK to similar, but more speculative, locations to the south. The play's southern limit is approximately the Puerco River north of Pinta Dome (PD) helium field near Chambers, AZ.

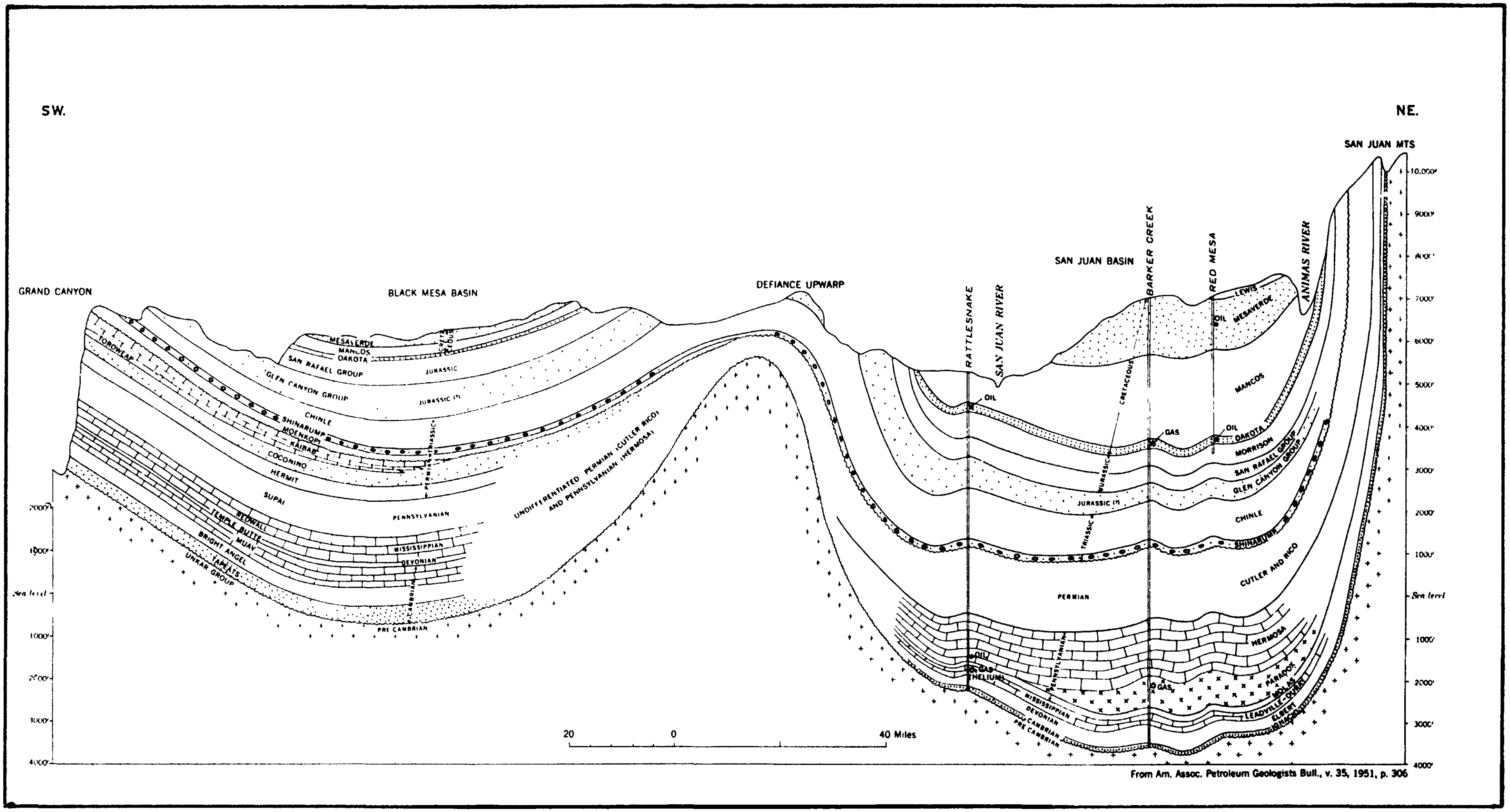


Fig. 48--Cross section across Black Mesa and San Juan basins. (From Hunt, 1956).

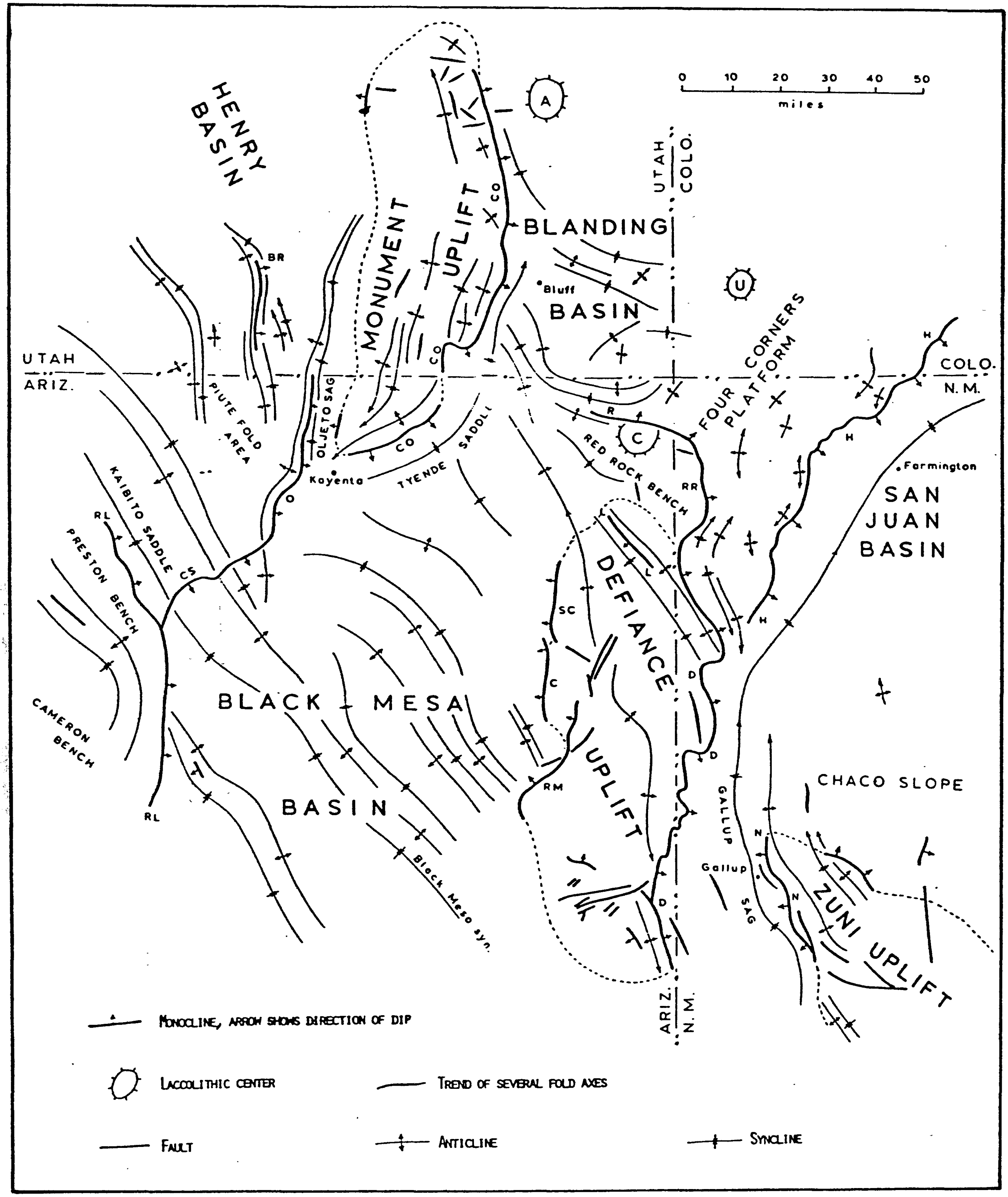


Fig. 49– *Generalized tectonic map of Four Corners region of Colorado Plateau (modified from Kelley, 1955b). Abbreviations for monoclines are: BR, Balanced Rock; C, Chinle; CO, Comb; CS, Cow Springs; D, Defiance; H, Hogback; L, Lukachukai; N, Nutria; O, Organ Rock; R, Rattlesnake; RL, Red Lake; RM, Rock Mesa; RR, Red Rock; SC, Sheep Creek. Abbreviations for laccolithic centers are: A, Abajo; C, Carrizo; U, Ute. Dashed lines indicate boundaries of uplifts.* (From Woodward, 1973).

The 100-mile-long axis of the DU, a basement-cored Paleozoic horst, plunges north-northwest. The uplift separates large-scale structures of Laramide origin, i.e. the petroliferous SJB from the BMB. It has been a broad anticlinal feature, or mildly positive submarine arch (Ijirigho, 1977), with an indefinite outline throughout much of the Paleozoic Era; it manifests a structural relief of 3,000 to 5,000 feet or more in Arizona.

Source Rocks and Geothermal Maturity

Regionally, the thermal maturity of outcrops is immature with respect to oil, or about 0.50 to 0.60 R_o. Higher values would be expected locally around laccolithic bodies, such as the Carrizo Mountains, and the numerous sills, some of which crop out in the northern play area.

Present-day geothermal gradients in the play (see references page 47) range from 1.2-2.0^oF/100ft (22.0-36.5^oC/km) with the higher values toward the core of the DU near Canyon DeChelly. Data in the area between the Puerco River and 35^o N. lat., document temperature gradients of 1.62, 2.75, and 3.15^oF/100ft (29.4, 49.8, and 57.0^oC/km, respectively). At least 30 boreholes, mostly shallow, in this southern area have gradients higher than 2.76^oC/ft (50^oC/km). Some of these with the very highest gradients are aligned northeasterly, manifesting the basement fracture pattern.

Heat flow in the area described above is determined to be moderately high with values of 2.19 to 3.8 HFUs. Studies of geothermal resource potential, HFU, and temperature gradients indicate an anomalous heat source in the area of Ganado, AZ., and also near the southern to southeastern end of the play and extending eastward into New Mexico. Also, in the southern end, Eggleston and Reiter (1984) have published some of the highest heat flow units in northeastern Arizona, i.e. up to 3.82. At least one heat flow datum to the east, just across the state line in New Mexico, is slightly higher at 3.89 HFU. Excess heat can be a negative factor in the exploration for petroleum, but for the most part in this play the effect of heat is a desireable attribute. Some workers who have recognized the positive relationship among igneous intrusions, thermal maturation, and trap creation include Hunt (1942), Ekren and Houser (1958), Heylmun (1958b), Turner (1961), Thompson (1976), and Butler (1987).

The source rocks of the play are immature black shales of the Paradox Formation -- the same general stratigraphic interval that contains organic matter at DBK field and other smaller northeastern Arizona fields. Tucker (1983) has measured the TOC content of one sample of the Hermosa shale at DBK. Her value of 0.64 appears to be lower than expected, and may not be indicative of the best source rocks present. Also, the sample may be low because it has already generated and expelled petroleum. DBK field, about 85 percent depleted, has an estimated ultimate primary recovery of 20 million BBLS of oil. The potential of the play is believed to be higher in the northern part, given its thicker section of source rocks, known igneous intrusions, and current production.

Reservoir Rocks

The "type section" of this play, DBK, produces 43^{o}-gravity oil from fractured seyenite sills of Oligocene age sourced by carbonaceous black shale of the Paradox Formation (Pohlmann, 1967; McKenny and Masters, 1968; O'Sullivan, 1969; Landes, 1970; Peirce and others, 1970; Danie, 1978; Thomaidis, 1978; Peirce, 1982). Porosity in the sill is unusually high, up to 14 percent (C.W. Spencer, pers. commun.). More typical reservoirs, such as the productive algal carbonates of the Hermosa Group in the FC area, may also provide good porosity in the northernmost part of the play.

Traps and Seals

DBK's production is controlled by the northwest-plunging, 37-mile-long and 5-mile-wide Toadlena (Lukachukai fig. 49) anticline. Other structures, however, are worth evaluating. North-south trending monoclines of Laramide origin on the west flank of the DU mark the eastern play boundary. This segment of the east boundary is a series of three north-trending monoclines (Rock Mesa, Chinle, and Sheep Creek) having a combined length of about 75 miles. These monoclines dip west with several hundred feet of structural relief. Dips on the west flank are 1-3^{o}, except where folded into prevalent asymmetric structures.

Although potential accumulations may involve the abundant Laramide folds of the area, a component of stratigraphic trapping may also be necessary. This is generally the mode of trapping in the Pennsylvanian oil fields of the FC area where productive biohermal facies occur associated with structures. Although production from this play has been derived from unusual and localized igneous reservoirs, there is also some potential for petroleum generation in the deeper part of the greater BMB and eastward updip migration along the flank of the DU into combination stratigraphic-structural traps.

Some steep normal faults occur in the Canyon DeChelly area east of the play; exposed faults seem to be neither a positive or negative factor in the potential accumulation of petroleum. Basement fractures, however, could have directed the magmatic heat necessary to convert kerogen into petroleum. Emplacement of igneous intrusions has probably occurred at intersections of these lineaments (Kelley, 1955a; Wilson, 1962: Case and Joesting, 1972). Helium recovery at DBK and PD could reflect the deep-seated origin of these faults which probably act as conduits for the gas (O'Sullivan, 1969; Peirce and others, 1970; Casey, 1983; Spencer, 1983). The Late Cretaceous laccolithic bodies of the Carrizo Mountains are thought to have intruded at fault intersections. Pyroclastic and flow rocks in the nearby Chuska Mountains are the result of Pliocene volcanism (Appledorn and Wright, 1957).

Magnetic anomaly maps (see PRECAMBRIAN section for geophysical references) show several areas, particularly in the central play area west and southwest of Canyon DeChelly, with an intense magnetic field. These anomalies could be the signature of buried intrusions and consequently a likely place to evaluate further as prospects. Residual Bouguer gravity and isostatic residual gravity maps show positive anomalies in the northern play area. This dual geophysical evidence, plus geothermal anomaly data, support the hypothesis that igneous rock may be close to the surface.

Timing and Migration

Although oil accumulations could have pre-dated the sill, petroleum was most likely generated during the Oligocene intrusive event; hence, a short igration was required only to fill the fractured and porous syenite. Another plausible viewpoint, however, could require updip migration from the greater BMB during maximum burial of the Pennsylvanian source rocks during the late Cretaceous.

Depth of Occurrence

Depths of different parts of the productive igneous sill at DBK are 2,800-4,100 feet. Elsewhere in the play, the Pennsylvanian system has relatively shallow depths of 1,500 to 3,500 feet.

Exploration Status

Apache County is the most highly drilled county in Arizona with about 250 oil and gas wells. It is the only county, however, which has petroleum production at present and most of this drilling is not representative of the play area. Excluding the DBK field, drilling density is about one borehole per 45 square miles; nearly all drilling has been in the northern third of the play. Virtually no drilling for petroleum has been attempted between BMB proper and the DU in Chinle Valley. Thirteen fields have produced petroleum from about 75 wells, about half being at DBK. PD helium field, close to the southern end of the play, also accounts for much of the county's drilling; about 30 wells produce helium from the Coconino Sandstone. No borehole has been drilled deeper than 2,500 feet south of

Canyon DeChelly National Monument in the play area. Because so few deep wells have been drilled in the southern part of this play, adequately describing the nature of the Pennsylvanian System is conjectural at best.

See the HYDROCARBON OCCURRENCES section for data pertaining to nearby Pennsylvanian fields in Arizona. Northwestern New Mexico has also produced some oil and gas from a Pennsylvanian reef at Tocito Dome which is a field due east of DBK (15 miles east of Arizona and 35 miles south of Colorado in T26N, R18W). The location is on the edge of the SJB and the FC platform. Discovered in 1963, Tocito Dome produces from the Barker Creek zone/substage of the Paradox Formation in a combination stratigraphic-structural trap. The reservoir is a fossiliferous, biohermal carbonate with claystone and siltstone interbeds at top depths of 6,296 and 6,338 feet. Porosity is 6-14 (average 8.6) percent with a net pay zone of 17 feet (oil) and 10 feet (gas). Through 1985 12.8 million BBLS of oil and 26.1 BCF of gas have been recovered. This field is further evidence that substantial petroleum resources may be found in isolated, unconventional settings around the DU area in relatively shallow reservoirs.

Finding other DBK-type fields will be difficult according to Barwin and others (1971). On the other hand, Conley (1974) concluded in his review of oil and gas development, "With the exception of a few relatively small areas, there have been no well-planned and efficiently-executed exploratory programs in northern Arizona. This part of the state has many large unexplored or incompletely explored areas having the basic factors normally considered requisite for oil and gas accumulation. Numerous shows of oil noted in igneous sills intruded into rocks of Paleozoic age in the northeastern corner of the state suggest the possibility that there are other 'non-normal' oil accumulations similar to the one at Dineh-bi-Keyah. Northern Arizona can be considered as an attractive unexplored onshore area offering potentially large accumulations of oil from a variety of traps in

Paleozoic rocks." Similarly, Conley and Giardina (1979) concluded, "...the posssibility exists that there are some unique accumulations similar to Dineh-bi-Keyah."

Southern Margin of the Paradox Basin Play

Location and Size

The southern margin of the Paradox basin (PB), i.e. Blanding basin (BB) sub-province, in the Four Corners (FC) area of northern Apache County is 350-400 square miles. (The entire PB province is being evaluated in a similar U.S. Geological Survey report). Two to three percent of the area of the PB lies in Arizona. The play is within an area (fig. 3) bounded by $36^{o}50'$ to $37^{o}00'$ N. lat. and $109^{o}03'$ to $109^{o}50'$ W. long.; the southern boundary follows the Paradox Formation wedge-edge (as drawn, e.g., by Lessentine, 1965; Woodward-Clyde, 1983).

General Statment

Outcrops in the western play area include the Glen Canyon Group of Triassic-Jurassic age. The Morrison Formation of Jurassic age and small exposures of upper Cretaceous strata are found in the eastern part. The basis of this hydrocarbon play, within the Paradox Formation of middle Pennsylvanian age, is a combination of rich source rocks (black sapropelic pelletal mudstone and dolomite) encasing discontinuous porous carbonate mounds, "reefs", or algal bioherms on the southern shelf edge of the PB. Paleozoic strata are about 4,000-4,600 feet thick, and the entire stratigraphic section is 5,500-7,000 feet thick.

Source Rocks and Geothermal Maturity

Outcrops in and near the play area indicate a geothermal maturity from 0.56 to 0.80 R_o (mature with respect to the oil window of occurrence). Present-day geothermal gradients are about 1.5 to $1.8^{o}F/100ft$ (27.5 to $33^{o}C/km$). Heat flow is measured at 1.13 to 1.56 HFU with most readings being 1.56. See pages 47-48 for references on thermal data.

Kerogen in black shales of the Paradox Formation is a mixed type II and III, according to Hite and others (1984). Their samples averaged 2.5 percent TOC by weight; values increase northward from the penesaline to saline facies in the center of the PB (fig. 50) where reducing environments preserved more organic matter. Hite and others (1984) analyzed samples (black silty calcareous dolomitic shales) from the central PB for TOC and found these source rocks average 3.3 weight percent TOC and yield about 5,000 BBLS oil per acre from reservoirs 32 feet thick. The upper range for some samples is 13 weight percent TOC. Spencer (1975) reported maximum TOCs of about 9 weight percent in the PB. Other published geochemistry on Arizona fields is meager but includes work by Tucker (1983) who suggested that long-distance secondary migration along the regional fracture system may be responsible for Paleozoic accumulations of petroleum in extreme northeastern Arizona. Her evidence of hydrogen-deficient organic matter suggested that Pennsylvanian strata are mostly gas-generating with only limited oil-generating capacity, thus making suspect the widely-held idea that Pennsylvanian reservoirs are locally sourced by Pennsylvanian rocks. However, if the Pennsylvanian is not a good type II or mixed type II and III source rock in northeastern Arizona, accounting for all previous oil production is difficult. This production approaches an estimated 20 million BBLS ultimate recovery from the Barker Creek zone which sources reservoirs as far south as DBK.

Stevenson (1983a) calculated that over 386.5 million BBLS of oil and 575 BCF of gas have been produced from the Paradox Formation in the greater FC area through 1982. Production in the play to date from the seven fields with Pennsylvanian reservoirs is estimated to be 1.4 BBLS oil and 15.25 BCF of gas, giving a combined gas-oil ratio of roughly 11,000 CFG/BBL. Gas-oil ratios of Arizona's Pennsylvanian fields, excluding gas-only fields and

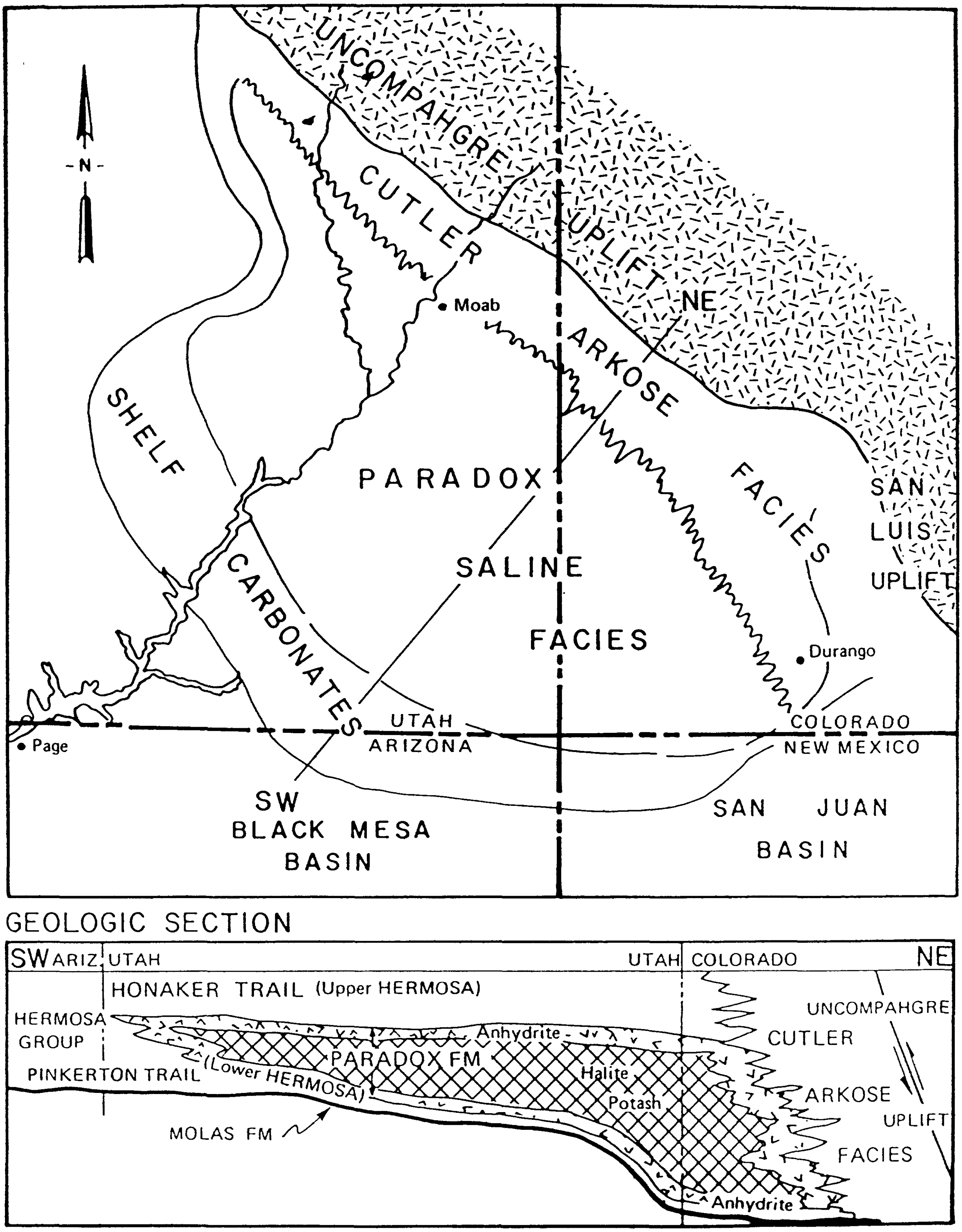


Fig. 50--Map showing generalized sedimentary pattern of Pennsylvanian-age rocks in the Paradox basin. (From Woodward-Clyde Consultants, 1983).

DBK, range from about 3,000 to 11,500 CFG/BBL. The largest field, East Boundary Butte, has a ratio of about 11,200 CFG/BBL. Gas-oil ratios apparently decrease northward into southeastern Utah and southwestern Colorado where values range between 950 to 1,750 CFG/BBL. If the effect of thermal maturity is hypothetically eliminated as a factor, then perhaps this relationship in petroleum types is due to a difference in kerogen types from predominately type III (woody humic) deposited in a shallower, intertidal part of the basin to type II (herbaceous) deposited in deeper water from south to north, respectively.

Reservoir Rocks

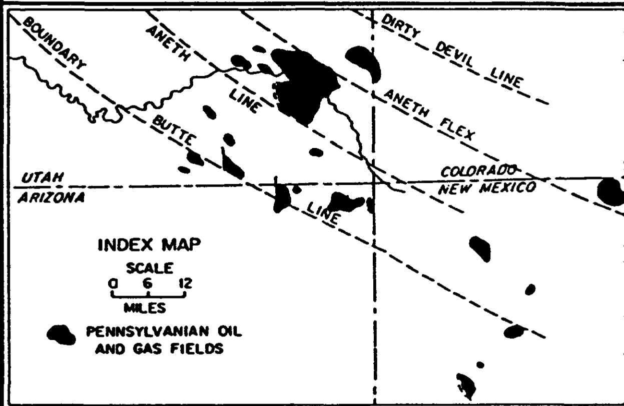
Pennsylvanian strata are about 1,500-1,800 feet thick. The Hermosa Group represents cyclic carbonate, shale, and evaporite rocks (see Szabo and Wengerd, 1975 for formation and marker zone descriptions), and is one of the prolific producers in the PB, such as demonstrated at Aneth Field. This group has good potential in the FC of Arizona (fig. 51). Evaporites in the PB are basin-centered (fig. 52). Individual algal mounds attain 40 feet in thickness, but they also occur as stacked reservoirs.

Porosity in the Paradox Formation carbonates ranges from 6 to 24 percent (Fassett, 1978) and is developed as primary and secondary types. Plates of the phylloid alga *Ivanovia sp.* make up much of the fossiliferous material in the carbonate mounds and bioherms; such overlapping plates plus other bioclastic constituents sustain the greatest pore space (McComas, 1963). Oolite banks are also productive in the FC area. With repeated rise and fall of sea level, the carbonates were subjected to subaerial leaching and brecciation forming vuggy calcirudite. This process plus dolomitization provided extra porosity. Both structure and fracturing are other important reservoirs attributes for production.

Traps and Seals

Trapping is stratigraphic but with a strong structural component (fig.

PALEOZOIC OIL AND GAS FIELDS-FOUR CORNERS REGION



LEGEND
(A) - Arizona
(C) - Colorado
(N) - New Mexico
(U) - Utah

TOP TYPES
— Time Surface
Facies
Disconformity

AGE	UNIT	GROUP / FORMATION	MAP	UNIT NAMES	FIELDS
PERMIAN	KAI			KAIBAB	
PERMIAN	COC	LEONARD		COCONINO	
PERMIAN	CUT	CUTLER		CUTLER	
PERMIAN	CEM	WOLFCAMP / CUTLER		CEDAR MESA	
PERMIAN	WOL	WOLFCAMP		WOLFCAMP	
PERMIAN	(WOL-CAR)	WOLFCAMP		ELEPHANT CANYON	
PERMIAN	RIC			(RICO)	
PENNSYLVANIAN	HER	HERMOSA GROUP / UPPER HONAKER TRAIL	MAJOR OIL POTENTIAL	HERMOSA	
PENNSYLVANIAN	TRA	HERMOSA GROUP / HONAKER TRAIL	MAJOR OIL POTENTIAL	TRANSITION	East Boundary Butte (A)
PENNSYLVANIAN	ISM	HERMOSA GROUP	MAJOR OIL POTENTIAL	ISMAY	Ismay (U), Anido Creek (U), Boundary Butte (U), Akah (U), Greater Aneth (U), Tohanadla (U), Gothic Mesa (U), Bluff (U), Recapture (U), Broken Hills (U), Turner Bluff (U), Bluff Bench (U), Unnamed 37S-21E (U), Flodine Park (C), Cache (C), Marble Wash (C), Towaoc (C), Unnamed 30N-18W (N), Four Corners (N), Twin Falls (A), Bita Peak (A), East Boundary Butte (A), Pan. Am. 1-F 40N-28E (A), Cowboy (U)
PENNSYLVANIAN	UNK	HERMOSA GROUP	MAJOR OIL POTENTIAL	UNKNOWN	
PENNSYLVANIAN	PAR	HERMOSA GROUP / PARADOX	MAJOR OIL POTENTIAL	PARADOX	
PENNSYLVANIAN	DES	HERMOSA GROUP / PARADOX	MAJOR OIL POTENTIAL	DESERT CREEK	Desert Creek (U), Greater Aneth (U), Tohanodla (U), Chinle Wash (U), Gothic Mesa (U), Bluff Bench (U), Cowboy (U)
PENNSYLVANIAN	AKA	HERMOSA GROUP / PARADOX	MAJOR OIL POTENTIAL	AKAH	Cliff (U), Akah (U)
PENNSYLVANIAN	BAR	HERMOSA GROUP / PARADOX	MAJOR OIL POTENTIAL	BARKER CREEK	Alkali Gulch (C), Barker Creek (N), Ute Dome (N), Hogback (N), Table Mesa (N), Amerada 29N-17W (N)
PENNSYLVANIAN	PIN	HERMOSA GROUP	MAJOR OIL POTENTIAL	PINKERTON TRAIL	Long Canyon (U), Shafer Canyon (U), Tocito Penn "D" (N), Rattlesnake (N)
PENNSYLVANIAN	LIM (MOL)	(MOLAS)	MAJOR OIL POTENTIAL	LIME RIDGE	
MISS	MIS (D, C, B, A)		MAJOR OIL POTENTIAL	LEADVILLE (REDWALL) MADISON	Lisbon (U), NW Lisbon (U), Salt Wash (U), Big Flat (U), SE Lisbon (C), Dry Mesa (A)
DEVONIAN	OUR			OURAY	
DEVONIAN	ELB			ELBERT	
DEVONIAN	MAC			MC CRACKEN	Texaco 1-Z 41 N-30E (A) Abandoned
Ꞓ	CAM			ANETH	
Ꞓ	CAM			LYNCH etc.	
PRECAMBRIAN					

Fig. 51--Paleozoic oil and gas fields - Four Corners region. (From Fassett, editor, 1975).

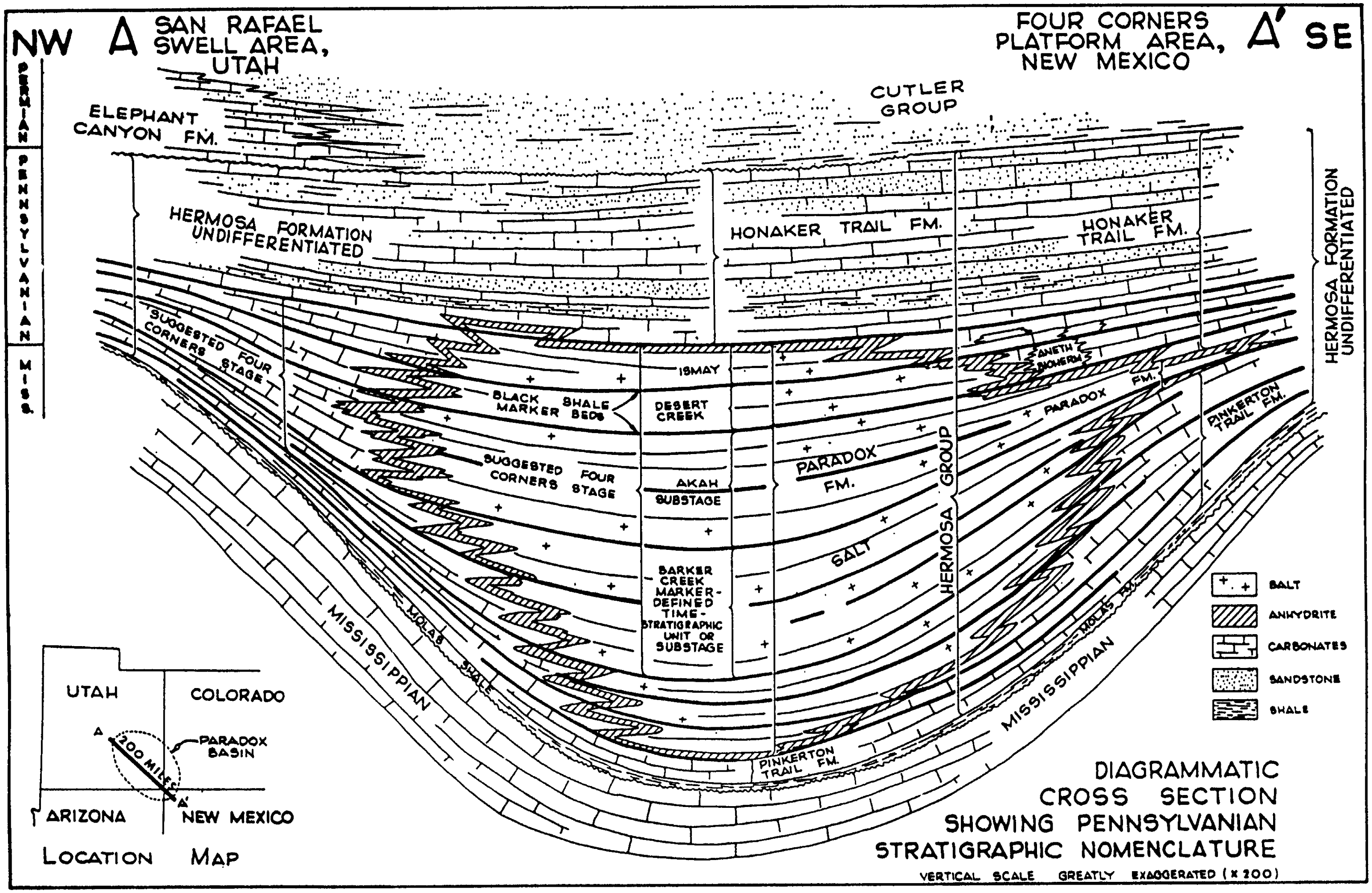


Fig. 52--Cross-section of Hermosa Group, Four Corners area. (From Baars and others, 1967).

53). Upright anticlines, synclines, and monoclines with slightly curved to sinuous axes are the dominate surface structures of the play. The major fold is the Defiance anticline whose axis trends and plunges north-northwest into the western play area where it dies out toward Mexican Water, AZ. Folds, such as the Boundary Butte and Rattlesnake anticlines, have roughly east-west axes and are curved toward the Arizona-Utah state line and BB. Folds near Comb Ridge monocline more-or-less parallel the northeast structural trend of that feature. Some normal faults are associated with the folds and may be partially responsible for the localization of the petroleum fields. In the southeastern corner of the play, the intrusion of laccolithic bodies has domed the entire stratigraphic section; folds in the intruded area, such as the Bita Peak anticline, have no clear-cut relationship to the igneous centers. Good structural traps probably exist along the flanks of the laccolith bodies.

A puzzling geophysical feature, centered over the Arizona-Utah state line in the Boundary Butte oil and gas field area, is an intense positive aeromagnetic anomally (e.g., see Sauk and Sumner, 1971; Zietz, 1982). This anomally is much higher than over the exposed laccoliths of the CP. The magnetic signature may be related to diagenetic magnetite formed in a reducing environment caused by a leaking petroleum trap. Traps such as this are usually structural types (EG&G Geometrics, 1984).

Timing and Migration

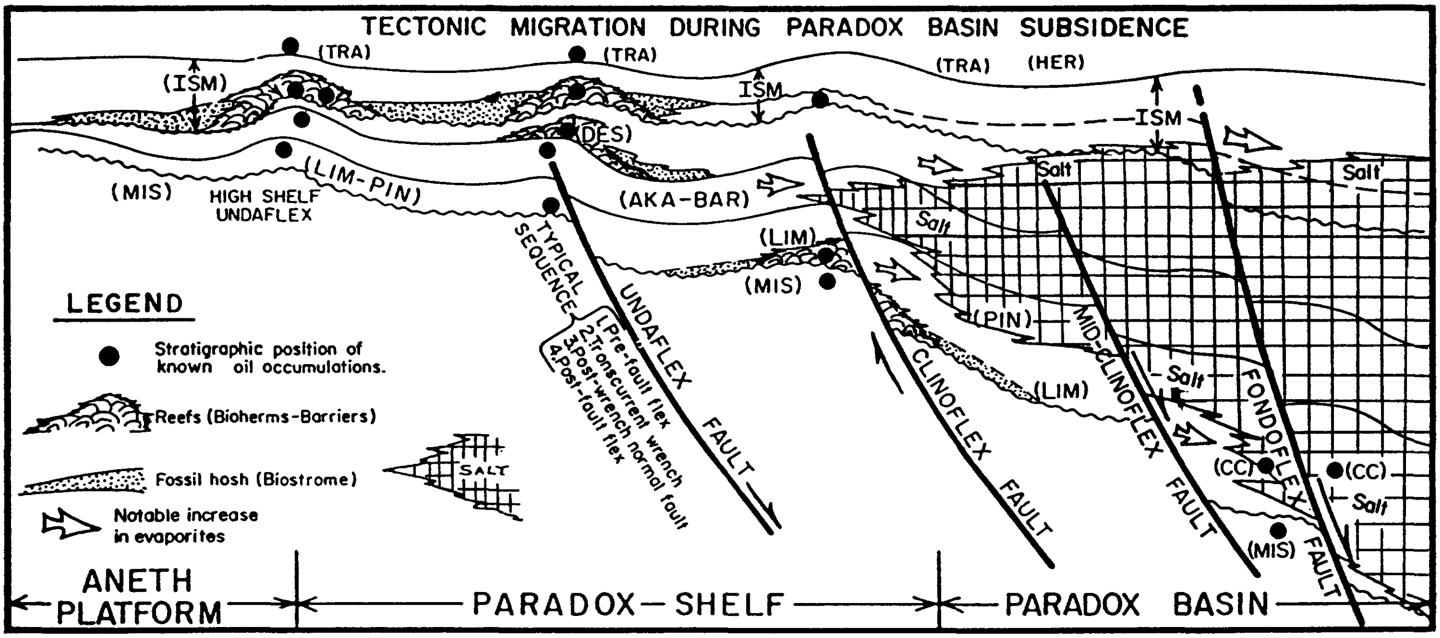
Migration of petroleum probably occurred during Laramide time after thick Cretaceous sediments buried and matured the source rocks.

Depth of Occurrence

Top depths to the Paradox Formation are 4,500-5,000 feet.

Exploration Status

Several PB oil and gas fields are worthy of mention with respect to the potential for this play. Only 10-15 miles north of this play is the



A summary of probable subsidence flexing and subsequent faulting along one cross section from the high-shelf Aneth platform on the left across the Paradox shelf to Paradox Basin on the right. Major cycle designations are shown, not to represent a true-scale section, but to depict relations of some flexes and faults to sedimentary patterns important to oil accumulations in different parts of the Paradox Basin and its western shelf, southeast of the Monument Upwarp. Structural genesis of the subsiding basin controlled sedimentation of the southwest shelf of the Paradox Basin as well as the accumulation of oil in Pennsylvanian strata. This diagram depicts barrier carbonate trends and reef-associated and detrital quartz sand sediments. Potentially oil-productive situations similar to this are logically expectable northwest of the Monument Upwarp on the Paradox shelf. Basinward development of Paradox evaporites is well documented northeast of the clinoflex faults—in the thickest Paradox sections. Thus this typical sequence of structural deformation is usually developed along clinoflex faults northeast of the Aneth alignment in areas of thicker Paradox salt.

HER = Hermosa; TRA = Honaker Trail; ISM = Ismay; DES = Desert Creek; AKA = Akah; BAR = Barker Creek; CC = Cane Creek member of Alkali Gulch; PIN = Pinkerton Trail; LIM = Lime Ridge; MIS = Mississippian

Fig. 53 --Schematic cross-section of Paradox basin shelf. (From Gorham, 1975).

edge of the Greater Aneth field (classified as a giant producer) in southwestern San Juan County, Utah. Since its discovery in 1954, it has produced about 350 million BBLS of oil and about 325 BCF of gas from the bioherms of the Pennsylvanian Paradox Formation. Outcrops of these bioherms are exposed in the walls of the entrenced San Juan River valley of southern San Juan County, Utah. Such exposures are thought to be fossil oilfields, and they trend southeastward into northeastern Arizona. The Lisbon Field, about 80 miles to the north of the Arizona play, is another large field in the Paradox salt-anticline fold-and-fault belt of southeastern Utah. It, however, produces from the Mississippian Leadville Limestone, and to lesser extents from the Devonian McCracken Sandstone and Paradox Formation under an entirely different plumbing system and structural framework (Clark, 1978; Parker, 1981). Some petroleum geologists feel the source rock at Lisbon is the Paradox Formation, although this is unsubstantiated. Mexican Hat is an abandoned, very small, shallow (minimum 50- to 200-foot reservoir top depths) oil field at the edge of the PB (Woodruff, 1910; Ball Associates, 1965; Curtis, 1972; Lauth, 1978). It lies 12 miles north of the west end of this play. Mexican Hat was discovered in 1907 and produced about 95,000 BBLS of oil from stratigraphic traps of the Hermosa Group (? "Rico" Formation).

Drilling density equals about one borehole per 7 square miles; the average depth of all wells drilled is 5,770 feet. The number of wells that produce from the Hermosa Group in the play is believed to be about thirty-five. Many papers have reported the numerous Pennsylvanian shows in the general play area, and are cited under HYDROCARBON OCCURRENCES. Mature and organic-rich source rocks, primary and secondary porosity development, and stratigraphic pinchouts with structural traps all indicate the play has favorable potential for additional oil and gas discoveries.

Holbrook Basin (Holbrook Anticline and Petrified Forest Plays)

Location and Size

The Holbrook basin (HB) in southern Navajo and southern Apache Counties contains two plays of 550 and 350 square miles in the southwestern and northeastern parts of the basin, respectively. The entire HB covers a region of about 2,300 square miles (Peirce, 1982) and is located at the south-central edge of the CP. The Little Colorado River drains northwest through the center of the basin. Two plays, the Holbrook Anticline and the Petrified Forest areas, are approximately within a 1,700 square-mile, kidney-shaped, central basin area bounded by 34°30′-35°00′ N. lat. and 109°30′-110°45′ W. long. (see fig. 3). Towns that approximately outline the two plays are in counterclockwise order: Show Low, Concho, St. Johns, Pinta, Holbrook, Winslow, and Snowflake.

General Statement

The HB lies in a Precambrian depression, or possible rift, which has a total structural relief of 1,000-1,500 feet (Conley and Giardina, 1979, map G-9), and is connected in the northwest to the northeast-trending OT of Devonian age in the BMB area. Precambrian basement rises out of the basin to the south-southwest near the edge of the MR where it is exposed in the Sierra Ancha Mountains. Basement also rises to the northeast toward the DU where Pennsylvanian strata thin to zero. Only about 250-500 feet of pre-Pennsylvanian strata occur in the subsurface in the western part of the basin. Mostly Permian and Triassic rocks crop out in the HB. Strata of Pennsylvanian age are about 500-1,500 feet thick (Kottlowski, 1962; Barwin and others, 1971; Peirce, 1979; Ross and Ross, 1986); strata of Permian age are about 2,200-3,000 feet thick (Kottlowski and Havenor, 1962; Blakey, 1980; Nydegger, 1982). Thickness of all strata in the general play vicinity is about 3,300 to 4,500 feet (McKee, 1951; Peirce and others, 1970; Jensen, 1972). The stratigraphy of the HB has been generalized in appendix A, and the late Paleozoic stratigraphy, particularly, has been characterized by Winters (1963), Brew (1965), and Peirce and Gerrard (1966).

The bases of the two HB plays are: a) numerous Pennsylvanian-Permian oil shows, b) cyclic fine-clastic and carbonate strata of late Paleozoic age showing rapid facies changes plus updip pinchouts, and c) common but incompletely-tested surface folds. Wells in the Pennsylvanian-Permian section of the HB have encountered up to eight shows of oil per hole (Conley, 1977). Factors, however, which may militate against a higher petroleum resource potential include thin source rocks that may be geothermally immature and TOC deficient. Although hydrocarbon shows have also been reported in Devonian and Mississippian strata of the HB, their limited lateral extent precludes defining them as separate plays.

Source Rocks and Geothermal Maturity

In addition to the widespread Supai Formation (see isopach map of upper part, fig. 54), the subjacent Naco Group is also considered to have some potential as a source rock (Ryder, 1983); the Naco has provided occasional oil shows (Bahr, 1962). However, because little or no publicly-available geochemical data have been reported on Pennsylvanian rocks of this area, the assumption is made that until proven otherwise, these rocks have a fair to good potential to source limited but economic petroleum deposits.

Geothermal maturity of outcrops in the HB is slightly below the oil threshold of occurrence and may be a detriment to finding economic accumulations in an area with relatively thin strata. Vitrinite reflectance data are between about 0.55 and 0.60 percent. Present-day geothermal gradients range from 1.2 to 1.6^{o}F/100ft (22 to 29^{o}C/km). Gradients over 2.75^{o}F/100ft (50^{o}C/km) are common in shallow wells about 25 to 30 miles east-northeast of Holbrook in the helium-producing PD area.

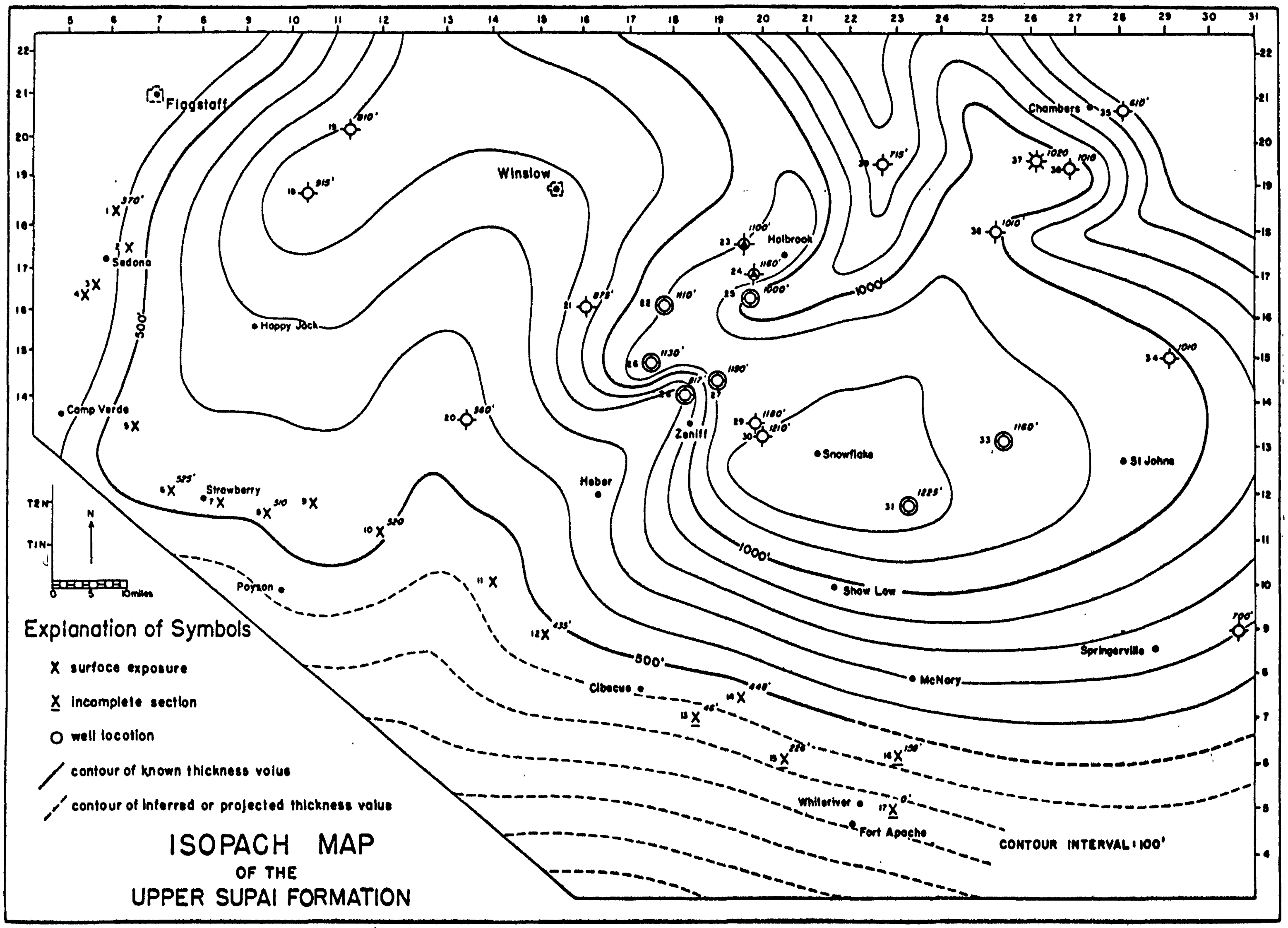


Fig. 54--Isopach map of upper part of Supai Formation in east-central Arizona. (From Gerrard, 1966). Contour interval = 100 feet.

Heat flow data in the greater HB range from 0.94 HFU in the west to 2.62 HFU in the northeast to 3.58 HFU in the southeast. Several regions in central to southern Apache County, particularly in the PD to Springerville area, have good to high geothermal resouce potential, and perhaps enhanced shallow petroleum potential due to increased thermal maturity.

Reservoir Rocks

Based on the many good shows of oil recorded in wells drilled on the Holbrook anticline, Brown and Lauth (1957) concluded, "The Fort Apache Member of the Supai, the DeChelly member of the Cutler, and the Coconino sandstone have excellent potentials for shallow production." Clastic units of the Supai Formation are indeed favorable, as are superjacent Permian clastic strata, but their drawback is a possibility of being flushed by fresh water. In 1961 Turner reported 16 flammable gas shows in wells penetrating Permian strata of the Holbrook-Mogollon Slope region. Numerous live oil shows occur in the middle Fort Apache member of the Supai Formation (Bahr, 1962) with some also occurring in the upper Supai clastics, carbonates, and evaporites section (Peirce and others, 1970; Conley, 1977. Fetid odors are common in outcrops and well samples of the Fort Apache unit along the east-west MR about 25 miles to the southwest; oil seeps are also common in outcrops.

The Coconino Sandstone reservoir produced helium with about 90-92 percent nitrogen and other non-flammable gases from a faulted anticline at PD (including Navajo Springs and East Navajo Springs) from 1961 to 1976 (Allen, 1978; Spencer, 1983).

Traps and Seals - Holbrook Anticline Play

The sinuous, northwest-trending Holbrook anticline has a 40- to 60-mile-long axis of intermittent continuity (see maps in Doeringsfeld and others, 1958; Bahr, 1962; Peirce and others, 1970; Scurlock, 1971; Conley and Giardina, 1979; Heylmun, 1981). A diversity of structural and stratigraphic traps exist. Some of the many fold structures of the HB may be a result of continuing collapse caused by evaporite solution, and some are consequences of the Laramide orogeny which mildly compressed and flexed strata - perhaps twice. Most folds, however, including the Holbrook anticline, have a somewhat complex history and are probably products of both processes. First-order folds trend northwest and superimposed second-order folds trend northeast. Evaporite rocks and porosity pinchouts may both act as potential seals in this area.

The Holbrook anticline is in an area of coalescing sinkholes and thus may not be a fold as created in the normal compressive sense. Dissolution of the Permian evaporites by groundwater may have caused depression of the overlying strata (Bahr, 1962; Pye, 1967). If so, the fold does not persist to crystalline basement; this is suggested by cross-sections by Peirce and others (1970) and Conley (1977). However, the northwest anticlinal axis is perpendicular to the principal Laramide stress direction supporting a compressional origin. Topography and structure have close agreement. The north flank of the anticline has a regional dip of about 2^{o} and the southern flank has an average dip of about 15^{o}, but is vertical in some places. Structural contours on top the Coconino Sandstone (and equivalents) by Scurlock (1971) and Conley and Scurlock (1976) indicate the Holbrook anticline has a relief of about 400-500 feet with an estimated 200-250 feet of closure. Bahr (1962) presented evidence that collapse is presently occurring. Nonetheless, if oil was generated contemporaneously with collapse there is still potential for trapping by the Holbrook anticline because "diapiric salt" may be flowing into pre-existing upwarp structures that may serve as traps. The timing for the generation and migration of potential oil or gas is unknown.

Because of the alteration of the Holbrook anticline by solution, Bahr (1962) suggested that the subsurface crest of the fold may be up to five miles south of its surface expression. Peirce and others (1970) assessed the area as follows: "Exploration opportunities have not been exhausted in the Mollogon slope region. Although much exploration effort has been expended in the vicinity of the Holbrook 'anticline' there is reason to question the subsurface extent of the anticlinal aspect. Of much greater potential significance is the structural condition imposed by subsidence associated with the development of upper Supai evaporites. It is suggested that the Fort Apache Member and all older Paleozoic strata are deflected downward on the order of 600-700 feet along a narrow zone parallel to but southwest of the Holbrook 'anticline'. The zone may have stratigraphic importance in that a Fort Apache Member dolomitization and porosity trend may be associated with the edge of the saline basin. Numerous dark dolomitic zones are interbedded with the evaporites and may constitute some potential in zones of structure."

Traps and Seals - Petrified Forest Play

Updip stratigraphic pinchouts (fig. 55) and local anticlines in the northeast part of the HB provide abundant traps. One of the primary differences between the Holbrook anticline play and this play is the absence of pre-Pennsylvanian strata in this play. Although this play is based principally on stratigraphic trapping, numerous folds with northeast and northwest- trending axes also offer trapping possibilities. Upper Paleozoic strata thin northeastward toward the DU area at a rate of 1,000 feet per 15-20 miles -- a fairly rapid lateral stratigraphic change. Major exposed faults in the HB are rare and thus probably insignificant to the localization of potential petroleum accumulations. A thick plastic salt layer in the upper Supai Formation may prevent the manifestation of surface faults. Porosity pinchouts and evaporites provide a sealing mechanism.

Depth of Occurrence

Permian top depths are from 500 to 1550 feet, but mostly from 1,000 to

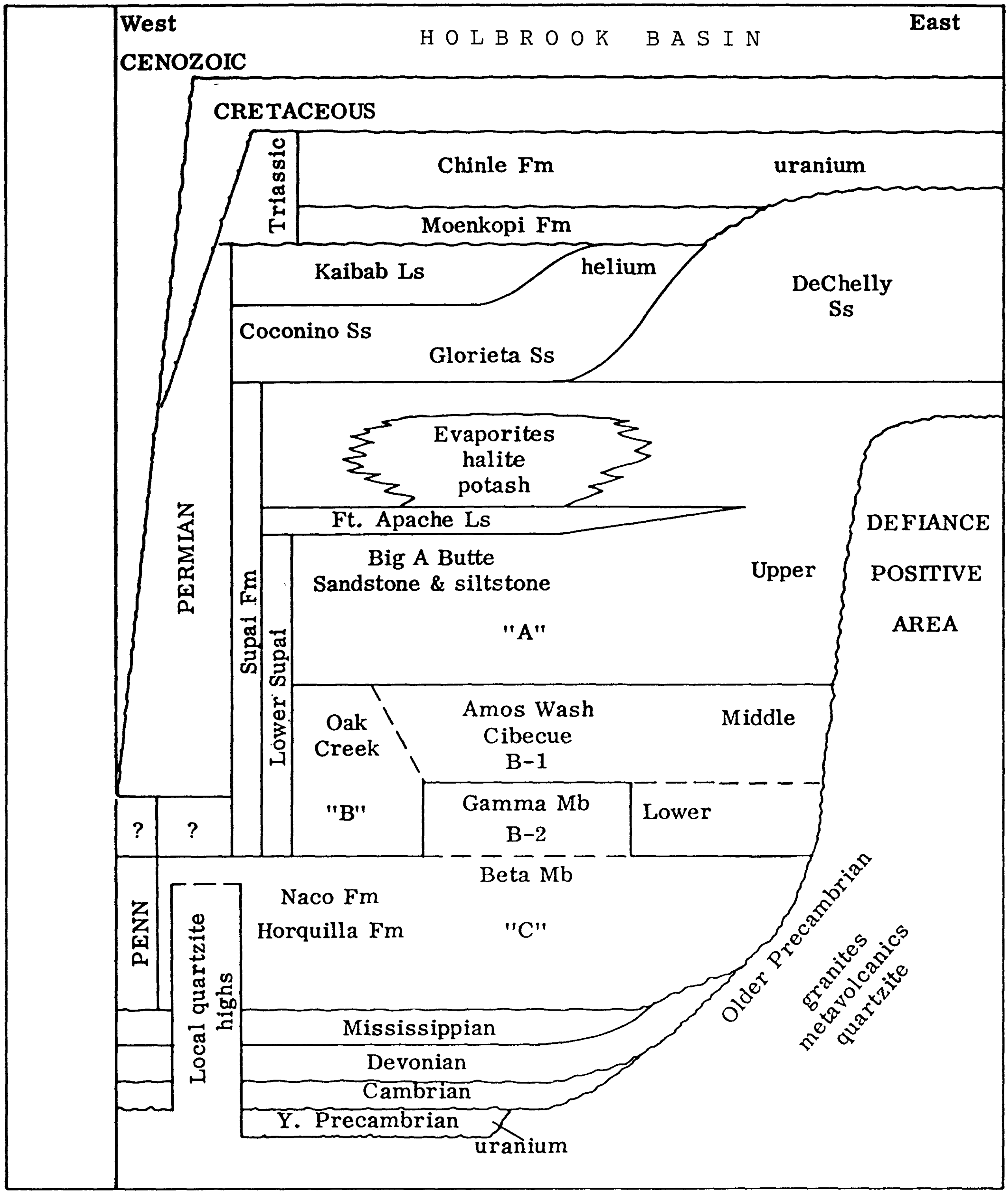


Fig. 55-- **Diagrammatic representation of the regional general geologic setting showing some nomenclatural variations** in the Holbrook basin. (From Peirce and others, 1977).

1,400 feet. Tops of evaporites within the Supai Formation occur at depths of 1,000 to 2,450 feet. Potential reservoirs within the Supai and Naco formations range widely from 1,000-3,775 feet, but are mostly 2,000-2,500 feet. Abundant shows occur at depths between 1,100 and 3,200 feet.

Exploration Status

The HB is immaturely explored having a drilling density of about one borehole per 45 square miles. Conley (1974) indicated that at least 126 holes have been drilled in the general Holbrook area, but these were drilled primarily in the search for shallow potash in the Supai Formation. Only about 15 boreholes have exceeded 3,600-foot depths in the HB, and almost all of these have been in its northeastern part. Many of the mapped anticlines have not been tested along their full axial lengths. Both O'Sullivan (1969) and Conley (1974) felt that much of the early drilling in northern Arizona was done haphazardly, and as such, there is some hydrocarbon potential and need for additional exploration. On the other hand, the Oil and Gas Journal (1979), paraphrasing Conley and Giardina (1979), stated, "Those [wells] drilled in the Mogollon slope area, mostly on surface structural anomalies in the general Holbrook area of Navajo County have been dry holes. Although numerous shows of oil on cuttings, plus some indications of the presence of porous zones, have been logged in thin Permian Fort Apache carbonates, the prospects for finding economic hydrocarbon accumulations in these beds are not encouraging at this point." Although dry and abandoned, one of the most recent significant wells in Arizona, according to Nations and others (1983a), was drilled off-surface-structure in the HB. This well was sited in sec.29, T11N, R22E and bottomed at 4,155 feet. The site is a few miles south of the play boundary. The rationale for the site may have been to locate the crest of the possibley "shifted" axis of the Holbrook anticline in the subsurface. Three other boreholes drilled between 1959 and 1983 encountered from 4,100 to 4,700 feet of strata before reaching basement. One of the three dry and abandoned boreholes (sec.17, T12N R26E) encountered oil shows in the Supai Formation. These four holes have thus initially, but not completely, tested the Holbrook anticline in the southeastern part of play.

Foster (1964) briefly assessed the petroleum potential of northern Catron County, NM., about 30-plus miles east of this play. He determined that additional testing of the Permian San Andreas, Glorieta, and Yeso formations is warranted, and noted, "Numerous dolomites, limestones, and sandstones of Permian age are porous and permeable and were deposited and existed under a reducing environment, three favorable exploratory factors." Barwin and others (1971) concluded the HB has potential based on good porosity and shows in Pennsylvanian and Permian rocks. Nations and others (1983a) have stated, "Several wells have been drilled in the Holbrook basin without success, but interest and activity continue there due to the thick upper Paleozoic section, structural and stratigraphic complexity associated with evaporitic facies in the upper Supai Formation, and the presence of older Paleozoic strata."

According to Stremel (1984), the HB remains an attractive exploration area where large structures remain to be tested and where more geochemical and geophysical work is being planned. An appropriate concluding overview of petroleum potential, pertinent to the HB, offered by Peirce and others (1970) states, "Arizona has an oil, gas and helium potential that is largely untested. There are extensive regions of favorable country in the [Colorado] Plateau region within which to search for detailed prospects. Much of the potential is likely to be stratigraphic in nature such that random drilling on an isolated anticline may not prove to be a conclusive test. The overall geologic setting is sufficiently complex to require a careful examination of the significance and interrelationships between all forms of available geologic data." As with any frontier area where some attributes for petroleum accumulation exist and where drilling has been unsuccessful, such as the promising HB, more drilling -- not condemnation -- is warranted.

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APPENDIX A: GENERAL STRATIGRAPHIC FRAMEWORK

Stratigraphy is described by noting formations and their thicknesses for the six local areas where the seven plays occur; this is opposed to characterizing individual geologic systems. A wide distribution of play localities serves to summarize the entire northern Arizona assessment province. Formations below are noted in ascending stratigraphic order. Stratigraphic columns (fig. 5 and 6), illustrate the east-west stratigraphic changes across northern Arizona.

Cordilleran Overthrust Belt

Formations include: the Tonto Group (1,600-3,000 feet thick) of early to late Cambrian age consisting of the Tapeats Sandstone (Prospect Mountain), Bright Angel (Pioche) Shale, and the Muav Limestone; possible thin (100 or less feet thick) Pogonip(?) or Goodsprings(?) carbonates of Ordovician age in regional angular discordance with subjacent and superjacent strata; the Temple Butte Limestone (Muddy Peak or Crystal Pass Formation to the west) of Late Devonian age ranging from 200 to 1000 (most commonly 500) feet thick; the Mississippian Redwall Limestone (Monte Cristo Limestone or Group, Rogers Springs, and partially overlying Battleship Wash-Chainman formations to the west) ranging in thickness from about 600 to 1500 feet (most commonly 750-1,150 feet) and bounded by subjacent and superjacent disconformities (a karst regolith on top the Redwall may contain the Molas Formation of Pennsylvannian age); the Illipah and Callville Limestone-lower Supai Formation-Bird Spring subtidal sequence of Pennsylvanian age ranging from 500 to 1350 feet thick but most commonly 800-1,100 feet; and, the Supai Group (Pakoon Limestone and Esplande/Queantoweap Sandstone), Hermit Shale, Coconino Sandstone, Toroweap Formation (limestone and dolomite), and Kaibab Limestone (dolomite) all of Permian age ranging from 1,500 to 3,400 (most commonly 1800) feet thick consisting of (oldest to youngest) alluvial plain, shoreline dune, and carbonate shelf environments. The entire Paleozoic section in this play is at least 6,500 feet thick and generally becomes thicker to the west where it is about 7,500-8,000 feet or more thick

Unconformably overlying the Paleozoic strata are the Moenkopi Formation of early Triassic age and the superjacent Shinarump Conglomerate. Both formations together are about 1,600-2,200 feet thick and consist of calcareous fine clastic and evaporite rocks deposited in a tidal flat environment shoaling upwards. The Chinle Formation of late Triassic age, plus the superjacent Glen Canyon Group, probably total 1,500 feet in thickness (about 3,500 feet in southwestern Utah) and represent floodplain to fluvial environments of deposition. Restored Triassic and Jurassic isopach maps by Lessentine (1965) show thicknesses of about 4,000 feet and 2,500 feet, respectively.

Erosion, commencing in late Jurassic to early Cretaceous time, has removed an estimated 6,000-7,500 feet of strata from this area. Formations stripped from the upper thrust plate(s) or wedge-blocks include: 2,00-2,500 feet of late Triassic to early Jurassic eolian Navajo Sandstone (Aztec and Nugget Sandstone equivalent) of the Glen Canyon Group; the San Rafael Group consisting of the Carmel Formation evaporite rocks of middle Jurassic age, plus the Entrada Sandstone of middle Jurassic age; and, up to 5,000 feet of undifferentiated (Dakota, Mancos, Mesaverde equivalents), mixed marine-nonmarine, fine-to-coarse clastic strata of Cretaceous age. Slices of these units, however, may be present beneath the allochthonous plates.

Up to several thousand feet of mostly Miocene, Pliocene, and Quaternary rocks, consisting of conglomerate, sandstone, siltstone, travertine, dolomite, limestone, gypsum, and gravel, were deposited in the Grand Wash trough (present-day Virgin River Valley in the western half of the play). These rocks were deposited in fluvial, lacustrine, playa, and alluvial fan environments. In the eastern play area late Miocene and Quaternary basalts cover some of the section.

Hurricane Cliffs - Uinkaret Plateau

Major sedimentary units consist of: 1,200-1,500 feet of lower to upper Cambrian rocks (150-250 feet of Tapeats Sandstone, 300 feet of Bright Angel Shale, and 475-650 feet of Muav Limestone); 275-500 feet of upper Devonian rocks (Temple Butte Limestone/Martin Formation); 500-1,000 feet of Mississippian rocks (Redwall Limestone); 500-1,000 feet of Pennsylvanian rocks (Molas Formation[?], Callville Limestone, and lower Supai Formation); 1,850-3,000 feet of Permian rocks (950-1,250 feet of Supai Formation or Group equivalent in part to the Pakoon Limestone and overlying 400-500 feet of Queantoweap Sandstone, plus the remaining Permian units consisting of 800-1,050 feet of Hermit Shale, 50-300 feet of Coconino Sandstone, 450 feet Toroweap Formation, and 500-575 feet of Kaibab Limestone); and, 0-1,600 feet of Triassic Moenkopi Formation. The Moenkopi's original thickness of 1,500-2,000 feet has been reduced by erosion in most outcrops. Limited exposures of the upper Triassic Shinarump Conglomerate Member of the Chinle Formation, 0-100 feet thick, crop out in the northeastern corner of the play.

The term Callville is occasionally used in this area for Pennsylvanian strata between the Redwall and the Pakoon formations. The four formations of the Supai Group from oldest to youngest are: Watahomigi, Manakacha, Wescogame, and Esplanade (Queantoweap equivalent). Thickness of the entire Paleozoic stratigraphic section generally increases from east-southeast to west-northwest.

The Glen Canyon and San Rafael groups plus undifferentiated Cretaceous strata were entirely eroded during the Cenozoic Era. Basalts mostly less than 5 m.y. old cover the southern to southeastern half of this play (Luedke and Smith, 1978; Best and others, 1980). These basalts should have little or no effect on the presence of petroleum, and this play includes all subsurface areas below the lava flows.

Lithologically, the general character of the stratigraphic section is as follows. The ledge-forming Tapeats Sandstone is a grayish- to reddish-brown orthoquartzite and coarse-grained sandstone with small-scale crossbeds; this transgressive beach deposit rests unconformably on Precambrian rocks. The slope-forming Bright Angel Shale is a greenish, glauconitic, fissile shale with interbedded red-brown, medium-grained sandstone. The Mauv Limestone is a gray, very fine grained dolomite and limestone with some calcareous siltstones. This formation is thinly and irregularly bedded. Unconformably overlying the Cambrian strata are the dark-gray to olive-gray, medium-grained, silty supratidal carbonates of the Temple Butte Limestone which have a strong fetid odor and are irregularly bedded. Thick-bedded, massive, light-gray Redwall carbonates overlie the Upper Devonian beds. The Redwall is dolomitic and cherty in its lower part. A karst erosional surface with channels marks the contact to the superjacent Supai Group red beds consisting of sandy to oolitic carbonates, calcareous shale, and red to purple crossbedded siltstones and sandstones. The clastic component increases upwards in this low- to high-energy intertidal to deltaic deposit. The ledge-forming, red siltstones and sandstones plus gypsiferous shales of the Esplande (Queantoweap), and the Pakoon Limestone intertongue with the upper Supai Group. The slope-forming Hermit Shale represents fluvial, floodplain and distal alluvial fan deposits consisting of reddish sandstone, siltstone, and shale. Above these beds is the conspicuous cliff-forming, white to buff, eolian sands of the Coconino. Wind ripples and large-scale crossbeds are common in the well-sorted sandstones. Stratigraphically higher is the resistent, gray, fine-grained, fossiliferous limestone of the Toroweap Formation. Its lower part has interbedded carbonates and gypsum with fine-grained sandstone, siltstone, and mudstone. Deposition was in low-energy marine to sabkha environments. The Kaibab rests disconformably over thin, red and white sandstones, siltstones, and gypsum in the Toroweap. Gray, fossiliferous, cherty, medium-bedded, aphanitic limestones of the Kaibab form both cliffs and the top of the CP in the Colorado River region of northwestern Arizona. The slope-forming Moenkopi beds consist of interbedded cyclic (marine-nonmarine) red, fluvial siltstone and shale with lesser conglomerate and shallow marine limestone.

Greater Black Mesa Basin (Devonian Oraibi Trough)

Paleozoic formations include: the Tonto Group consisting of the Tapeats Sandstone (0-175 feet), the Bright Angel Shale (50-100 feet), the Muav Limestone (0-150 feet), and Lynch(?) ("Supra Mauv") Dolomite (0-225? feet) all of Cambrian age; the Aneth Formation (0-150 feet and possibly 250 feet locally), the McCracken Sandstone Member of the Elbert Formation (0-265 feet, usually about 50-150 feet), the upper member of the Elbert Formation (50-400 feet, usually about 150-300 feet), and Ouray Limestone (0-200 feet, usually about 75 feet) all of Devonian age; the Redwall Limestone, (0-500 feet, usually about 175-300 feet thinning southeastward) of Mississippian age; the Molas Formation (80-100 feet), the Hermosa Group (550-1500 feet, usually 600-700 feet) which is best developed and thickest in the PB and consists of the Pinkerton Trail Formation (0-400 feet), Paradox Formation (0-500? feet), Honaker Trail Formation (400-800 feet), and Rico Formation(?) (225-575 feet) all of Pennsylvanian age; the Cutler/Supai Group undifferentiated (500-1,400 feet) of Pennsylvanian-Permian age; the Coconino/DeChelly Sandstone (250-550 feet), the Toroweap Formation (0-200 ? feet), and the Kaibab Limestone (0-200 feet) all of Permian age.

Mesozoic and Cenozoic strata include the eastward-thinning Moenkopi Formation (30-250 feet, usually about 100-200 feet), the Shinarump Member of the Chinle Formation (0-150 feet), the Chinle Formation (1,000-1,400 feet), the Glen Canyon Group thinning eastward and consisting of the Wingate Sandstone (200-600 feet, usually about 350 feet), the Moenave Formation (0-300 feet), the Kayenta Formation (50-250 feet) all of Triassic age, and the eastward-thinning Navajo Sandstone (400-950 feet, usually about 525-675 feet) of Triassic(?)-Jurassic age; the San Rafael Group (300-600 feet) consisting of the Carmel Formation (0-125 feet, usually about 50 feet), the Entrada Sandstone (100-600 feet), and the Cow Springs (partial Bluff and Summerville equivalent) Sandstone (0-250? feet) all of Jurassic age; the southwestward-thinning Morrison Formation, undifferentiated, (0-600 feet) of Jurassic age; the Dakota Sandstone (50-125 feet), the southwestward-thinning Mancos Shale (600 feet), and the Mesaverde Group consisting of the Toreva Sandstone (up to 150 feet), the Wepo Formation (up to 600 feet), and the Yale Point Sandstone (up to 100 feet) all of Cretaceous age; the Pliocene Bidahochi Formation (0-500 or 700 feet) in the southeastern play area (Repenning and Irwin, 1954).

Many of the stratigraphic relationships in the play are unclear and complex intertonguing, particularly within Pennsylvanian, Permian, and Jurassic strata, may artificially inflate their perceived stratigraphic thicknesses. The total Cambrian section is from 0-500 feet thick; Cambrian isopach lines trend northeast and increase from zero near the axis of the Oraibi trough to about 500 feet at Comb Ridge. The Devonian section is about 100-650 feet thick, thinning east to southeast toward the DU. The Pennsylvanian is from 500-2,000 feet thick and the Permian is from 1,000-3,000 feet thick. Together the Pennsylvanian-Permian strata comprise about 2,000-3,500 feet of section. The Triassic section varies from about 1,000 to 2,000 feet, and the Jurassic from zero to 1,500-2,500 feet (averaging about 1,250 feet). Cretaceous rocks have been severely eroded in the greater BMB, thus leaving from zero to 1,750-2,000 feet from an original thickness of about 5,000 feet near FC. There was an original thickness of 3,000-4,000 feet of Cretaceous strata near the southwest part of the play (Peterson and Smith, 1986). About 1,500 feet of Cretaceous strata have been removed from BMB proper.

Numerous nomenclature problems exist in the greater BMB, and particularly outside the BB subprovince, because various formation names are projected into the essentially unexplored subsurface from sourrounding outcrops. Equivalent upper Cambrian strata in southwestern Colorado are mapped as the Ignacio Quartzite. To the south and west of the play, the Martin and Temple Butte formations, respectively, are equivalent to the Elbert Formation. The use of Ouray Limestone is questionable and is restricted to southwestern Colorado by some geologists (Kirk, 1931). The Redwall Limestone is mostly equivalent to the Leadville Limestone to the east to northeast, and the Escabrosa Limestone to the south. The Naco Group and overlying Supai Group/Formation are in part equivalent to the Hermosa Group. The name Coconino Sandstone is used in north-central Arizona whereas DeChelly Sandstone is used in northeastern Arizona and Cutler Group undifferentiated (500-2,000 feet thick) is prevalently used in the MV and FC areas (see Strobell, 1958).

Major erosional unconformities occur between: 1) the Precambrian and middle Cambrian, 2) the upper Cambrian and upper Devonian, 3) the middle Mississippian and lower Pennsylvanian, 4) the middle Permian and lower Triassic, 5) the upper Jurassic and upper Cretaceous, and 6) the upper Cretaceous and Pliocene, or upper Cretaceous and Quaternary alluvium. All Paleozoic stratigraphic units thin and some wedge-out to zero thickness against the DU; Permian strata cover it in outcrop.

Western Flank of the Defiance Uplift

A lack of subsurface data for late Paleozoic and Mesozoic strata of the play, plus rapid facies changes has made regional stratigraphic syntheses by most workers exceptionally difficult. Paleozoic sedimentary units of the play are as follows: the southeastward-thinning Tapeats Sandstone or Ignacio Quartzite near FC (0-100 feet) of late Cambrian age; Aneth Formation (0-125 feet), McCracken Sandstone Member of the Elbert Formation (0-150 feet), southwestward-thinning upper Elbert Formation (0-125 feet), and Ouray Limestone (0-50 feet) all totalling 0-350 feet of late Devonian age and restricted to the northern half of the play area; Redwall Limestone (0-250 or 300 feet, present only in northern play area where it is often termed the Leadville Limestone) of Mississippian age; Molas Formation (0-125 feet), Naco-Hermosa Group undifferentiated (100-500 feet of Naco in the southern part, 100-300 feet in the central part, and 900-1,500 feet of Hermosa in the northern part), and some thin beds part of the lower Supai Group-Rico Formation(?)-lower Cutler Formation equivalents, all of Pennsylvanian age; Upper Supai Group-Abo and superjacent Yeso formations (in northwest New Mexico)-Cutler Formation equivalents (800-2,000 feet), including members of Halgaito Shale, Cedar Mesa Sandstone, Organ Rock Shale (100-400 feet), and DeChelly Sandstone (250-800 feet, about 300-400 feet and Coconino-Glorieta Sandstone equivalents to the south and southwest) all of early to middle Permian age.

Mesozoic and Cenozoic sedimentary units include: the Moenkopi

Formation (0-350 feet, mostly in southern part), Shinarump Conglomerate Member of the Chinle Formation (50-100 feet), and Petrified Forest and Owl Rock members of the Chinle formation (500-2,000 feet, generally about 750-1,000 feet and thickest in the south except where eroded) of Triassic age; the Glen Canyon Group (up to 1,500 feet) consisting of the Wingate Sandstone (225-850 feet, sometimes differentiated into Lukachukai and Rock Point members), Moenave Formation (? feet, highly variable), Kayenta Formation plus intertonguing Navajo Sandstone (0-100 feet, present only in the northern part and 15 feet near Chinle, AZ., in the central part) of late Triassic(?) or early Jurassic(?) age; the southwest-thinning San Rafael Group consisting of Carmel Formation (0-185 feet), Entrada Sandstone (50-275 feet), westward-thinning Todilto Limestone (25-100 feet, mostly sandstone in Arizona), Cow Springs-Summerville (50-100 feet, thicker in the north)-Bluff Sandstone (0-75, average 50 feet, possibly assignable to Morrison Formation) equivalents, and the southwestward-thinning Morrison Formation, undifferentiated, (50-800 feet) of Jurassic age; (About 1,000-3,500 feet of Cretaceous strata were eroded from the play area during the middle Tertiary to present); Chuska Sandstone (0-1,200 feet) in the northeast and Bidahochi Formation (0-600, most commonly 200 feet) in the southwest, both highly variable in thickness and of late Tertiary (probably Pliocene) age.

The overall thickness of Cambrian through Mississippian rocks is 0-700 feet, 100-1,000 feet for Pennsylvanian rocks, and 1,200-2,000 feet for Permian rocks. Relative to this play's boundaries, the Hermosa is best defined and thickest in the north at the edge of the PB. This edge is considered to be the zero-thickness line of the Paradox Salt. The Naco Group is best recognized to the south in the depostional regimes of the HB and Pedregosa basin. As currently envisioned, a shallow sea connected the northern and southern areas. More-than-usual confusion in terminology, caused in part by disagreements between "lumpers" and "splitters", exists for Permian and Mesozoic formations of northeastern Arizona. Nomenclature problems are due to the complex intertonguing and rapid lateral changes of units. Hence, stratigraphic relationships are speculative and correlation is also difficult in these essentially unfossiliferous deposits of continental origin. The Supai Group thickens towards the HB and the Cutler Group thickens toward the PB. From half to two-thirds of the late Paleozoic strata are red beds. Both the Triassic and Jurassic are each about 500-2,000 feet thick.

Southern Margin of the Paradox Basin

Although units are in general order of superposition, poorly understood intertonguing and facies relationships make many of the tops and bottoms of adjacent units lateral equivalents. Formations are as follows: the Tapeats Sandstone (100-350 feet, thinning eastward) and equivalent or subjacent to the Ignacio Quartzite (0-150 feet, best developed in southwestern Colorado) both of middle Cambrian age; Lynch Dolomite(?) or "Supra-Mauv Dolomite" (50 feet) Upper Cambrian; Aneth Formation(50-150 feet), the McCracken Sandstone Member (50-275 feet, usually about 100-150 feet) of the Elbert Formation, the Upper Elbert Formation (150-300 feet), and the Ouray Limestone (25-100 feet) all of late Devonian age with a combined range of thicknesses from 400-650 feet; the Redwall/Leadville Limestone (150-500 feet, usually 200-350 feet and thinning southeastward) of Mississippian age; Molas Formation (75-200 feet) of limey shale and shaly carbonate deposited on a karst surface, the Hermosa Group (1,500-1,800 feet, thinning south-southwestward and equivalent to the Supai Group to the west and south) consisting of the Pinkerton Trail Formation (100-200 feet), Paradox Formation (700-900 feet), and Honaker Trail Formation (600-800 feet) all of Pennsylvanian age.

Because of its bioherms, the Paradox Formation in the greater FC area has an irregular surface; also, the formation is highly variable both laterally and thickness-wise, and includes up to 40 cycles of black shales, basin-centered evaporites, and carbonates. The major zones are variously called informal stages, sub-stages, cycles, intervals, facies, formations, and members in the literature. "Zones" recognized by most workers include the Alkali Gulch (100-200 feet), Barker Creek (150-250 feet), Akah (200 feet), Desert Creek (50 feet), and Ismay (120-150 feet); they are usually correlated by internal, black, sapropelic, fetid shale marker beds (Baars and others, 1967). A transitional unit between the essentially marine Hermosa Group and the superjacent non-marine Cutler Group (Elston, 1960) of probably Pennsylvanian or Pennsylvanian-Permian age (partial upper Supai Formation equivalent) has been defined as the "Rico Formation"; however, many non-U.S. Geological Survey geologists do not consider it a valid formation because of its supposed non-mappability (for elaboration see Baker and others, 1927, Herman and Sharps, 1956, Pratt, 1968, and Baars and Ellingson, 1984).

As with the upper Pennsylvanian formations, Permian strata likewise intertongue complexly and include: the Cutler Group (2,00-2,500 feet, the lower part equivalent to the upper Supai Formation to the south and Abo Formation to the east) consisting of the Halgaito Shale (east) and Elephant Canyon Formation (west), the Cedar Mesa Sandstone (the latter three 800-1,000 feet), the Organ Rock Shale Member (600-700 feet), the DeChelly Sandstone (250-500 feet, White Rim and Coconino Sandstones equivalent), and the Hoskinnini Tongue (a possible Kaibab Limestone or Lower Moenkopi Formation equivalent). The Cutler Group may be difficult to differentiate in this locality.

Mesozoic strata include: the Moenkopi Formation(?) (if present, very thin and restricted to far western play area) of early Triassic age, the Chinle Formation (900-1,100 feet) consisting of the Shinarump Conglomerate, Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock members all of late Triassic age; the Glen Canyon Group (600-1,250 feet thinning eastward) consisting of the Wingate Sandstone (400 feet with Rock Point and Lukachukai members), Kayenta (25-100 feet thinning northeastward), and Navajo Sandstone (100-500 feet, thinning eastward) formations of late Triassic(?) or early Jurassic(?) age; the Jurassic San Rafael Group (1,000-2,000 feet) consisting of the Carmel Formation (25-150 feet), Entrada Sandstone (85-450? feet), Todilto Limestone (25-100 feet, possibly absent in the east), Summerville Formation (100-200 feet, usually 125 feet and Cow Springs equivalent to the west), and Bluff Sandstone (25-250 feet and Junction Creek Sandstone equivalent); the Morrison Formation (750-900 feet, but 1,500 feet possible locally, thinning northeastward) of Jurassic age and including Salt Wash, Recapture, Westwater Canyon, and Brushy Basin members; the Burro Canyon Formation (0-75 feet) of early Cretaceous age, and the Dakota Sandstone (0-200 feet) of late Cretaceous age.

Missing sedimentary rocks represented by major regional unconformities in the above stratigraphic column, include: Late Proterozoic and lower Cambrian, Ordovician to upper Devonian, upper Mississippian, lower Pennsylvanian, upper Permian, middle Triassic, some beds between the Glen Canyon and San Rafael groups, and middle Cretaceous.

Holbrook Basin

Stratigraphic units in the HB are listed as follows: Tapeats Sandstone (0-50 feet), a transgressive-shoreline, basal, micaceous quartzose sandstone with some shale and conglomerate of middle(?) and/or late(?) Cambrian age equivalent to the transgressive Bliss and regressive Bolsa formations to the south; Martin Formation (0-300 feet with rapid northeastward thinning), thin variegated shale, siltstone, and sandstone and dense fetid dolomite all of late Devonian age and equivalent to the Temple Butte Formation to the west; Redwall Limestone (0-150 feet with northeastward thinning, absent in play two), cherty, open-shelf, fossiliferous massive carbonates of Mississippian age and equivalent to the Escabrosa Limestone of southeastern Arizona; the Redwall may have shaly terra rosa deposits of Pennsylvanian age (Molas Formation, 10-80 feet thick) mantling its upper karst surface; Naco Group (0-1,000 feet), interbedded and alternating fossiliferous micritic limestone and shale with minor siltstone, sandstone, and carbonaceous clastics deposited in nearshore shelf to algal mudflat environments of Pennsylvanian age and equivalent to the Horquilla Limestone to the south and Hermosa Formation to the north; lower Supai Formation sometimes called Big A Sandstone (0-1,000 feet or more, the lower 200 feet or so being of probable Pennsylvanian age and the upper 750-800 feet being of Permian age), reddish clastics of mudstone, siltstone, sandstone and limestone-pebble conglomerate of shoaling, deltaic, and alluvial plain origin and equivalent to the Earp Formation to the south and Hermit Formation to the northwest; Fort Apache Member of the Supai Formation (50-125 feet), impure dark petroliferous carbonates with anhydrite and shale all of Permian age; upper Supai Formation, sometimes called Corduroy Sandstone, sabkha deposits (1,000-1,300 feet), red beds of siltstone and sandstone with grey to brown petroliferous carbonates and thick evaporites of gypsum, anhydrite, potash, and halite all of Permian age and equivalent to the Abo Formation and superjacent Yeso Formation to the east and the Colina Limestone and superjacent Epitaph Dolomite to the south; Coconino Sandstone (150-500 feet, thinning southward), a clean, light-colored, fine-grained, locally-petroliferous, crossbedded permeable sandstone of eolian and beach origin of Permian age -- it is also a helium reservoir and equivalent to the Glorieta Sandstone to the east and the DeChelly Sandstone to the north and northwest and Scherrer Formation to the south; Toroweap Formation and Kaibab Limestone (0-200 feet, present only in western part of basin), mostly intertidal deposits of interbedded impure carbonates, dolomitic mudstones, sandstone and minor evaporites of middle Permian age, locally petroliferous, and equivalent to the San Andreas Formation of New Mexico and Concha Limestone and Rainvalley Formation to the south.

Mesozoic and Cenozoic units include: Moenkopi Formation (25-250 feet), nonmarine supratidal to intertidal clastics with red beds of calcareous siltstone and mudstone and thin gypsum all of Triassic age; Shinarump Conglomerate Member of Chinle Formation (0-50 feet), conglomeratic, helium-bearing sandstone of Triassic age; Chinle Formation (0-850 feet, restricted to northeastern part of the HB), variegated fluvial to floodplain mudstone, sandy shale, and silty to conglomeratic sandstone with uranium deposits and minor chemical rocks, ash, and petrified logs of Triassic age. Up to 3,000-4,000 feet (McGookey, 1972; Peterson and Smith, 1986) of Cretaceous arkosic- and greywacke-type sandstones, conglomerate, siltstone, shale, volcanic tuffs, and minor coal measures have been eroded from this area. The Bidahochi Formation (0-200 feet) includes calcareous sandstone interbedded with silty mudstone and volcanic ash, unconformably overlies Triassic strata in the northeast HB. Mid-Miocene to Pliocene and Quaternary basalt and tuff crop out at the southeastern and western edges of the greater HB. Quaternary alluvium has been deposited throughout the basin in the present drainage pattern.

APPENDIX B: LAND STATUS OF ARIZONA PLAY AREAS. Values in percent.
(compiled mostly from numerous U.S. Dept. of Interior maps, 1979 and 1981)

Play Name	BLM	Indian Reserv.	Wilderness	National Monument	State	Private
Cordilleran Overthrust	87				9	4
Hurricane Fault-Uinkaret Plateau	87				10	3
Black Mesa Basin	1	96	1			2
West Flank Defiance Uplift		90				10
Paradox Basin		100				
Holbrook Basin	6			7	16	71