MAP I-1537

33112-D1-PP-01M

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PETROLEUM POTENTIAL OF WILDERNESS LANDS, ARIZONA

By Robert T. Ryder

MISCELLANEOUS INVESTIGATIONS SERIES
Published by the U.S. Geological Survey, 1983

RYDER—PETROLEUM POTENTIAL OF WILDERNESS LANDS, ARIZONA 1:1,000,000 MAP I-1537

Petroleum Potential of Wilderness Lands in Arizona

By Robert T. Ryder

PETROLEUM POTENTIAL OF WILDERNESS LANDS IN THE WESTERN UNITED STATES

GEOLOGICAL SURVEY CIRCULAR 902-C

This chapter on the petroleum geology and resource potential of Wilderness Lands in Arizona is also provided as an accompanying pamphlet for Miscellaneous Investigations Series Map I-1537

CONTENTS

ILLUSTRATIONS

Petroleum Potential of Wilderness Lands in Arizona

By Robert T. Ryder

ABSTRACT

On the basis of in-depth geologic framework and petroleum geology studies, the oil and gas potential of Wilderness Lands in Arizona is rated qualitatively on a scale from high to zero. A high rating is assigned to Wilderness Lands that are located near or along the projected trend of hydrocarbon production and have all the geologic attributes of the producing area. A medium rating is assigned to Wilderness Lands that have all the attributes, including shows, of an oil and gas producing area, but presently lack commercial production. In contrast, low, low to zero, and zero ratings are assigned, respectively, to Wilderness Lands that have few or no attributes of an oil and gas producing area. Usually a zero rating is reserved for regions having autochthonous igneous and metamorphic rocks at or near the surface.

The Wilderness Lands in Arizona are grouped into 12 clusters, each containing one or more tracts that have the same or similar geologic characteristics and the same hydrocarbon potential. Of the 6,183,665 acres of Wilderness Lands in Arizona the potential acreage can be summarized as follows: high potential, none; medium potential, 192 thousand acres; low potential, 1,375.3 thousand acres; low to zero potential, 3,528.8 thousand acres; and zero potential, 1,087.8 thousand acres.

INTRODUCTION

Arizona produces limited quantities of oil and gas from fields in the northeasternmost part of the State and has the potential for yielding modest undiscovered oil and gas resources (Dolton and others, 1981). Much of Arizona is still a frontier area in terms of oil and gas exploration; however, much of the State is unsuitable for oil and gas accumulations because basement rocks are situated at or near the surface. Future oil and gas discoveries in the sedimentary basins of Arizona will likely depend on imaginative, but geologically sound, interpretations of the complex structural, depositional, and magmatic history of the State and on the testing of these interpretations with reflection seismic profiles and deep drilling. To date, drilling outside the region of known production has been disappointing. The purpose of this investigation is to provide qualitative estimates, complete with written documentation, of the future oil and gas potential of the 6,183,665 acres of Wilderness Lands in Arizona. These estimates are based largely on data derived from current published literature. Future estimates may vary as new data and concepts become available.

This report is divided into three parts. The first part, the geologic framework section, is intended to acquaint the reader with the complex physiographic and geologic provinces of Arizona and the complex tectonic and magmatic history that shaped the provinces and ultimately helped control the distribution of oil and gas. The second part, the petroleum geology section, consists of a general treatment of several key elements related to the generation and entrapment of oil and gas in

Arizona. The third and final part, the petroleum potential of Wilderness Lands, contains the qualitative estimates of the oil and gas potential of the Wilderness Lands of Arizona.

GEOLOGIC FRAMEWORK

PHYSIOGRAPHIC PROVINCES

Arizona is divided into two major physiographic provinces, the Colorado Plateau province in the northeast half of the State and the Basin and Range province in the southwest half of the State with a transitional zone between (fig. 1*A*). The Colorado Plateau province is characterized by a highly dissected landscape comprised of broad, high plateaus and mesas and intervening steep-walled canyons (Fenneman, 1931). The Basin and Range province is characterized by narrow, northwest-trending mountain ranges and adjoining basins. In the northwest corner of Arizona the mountain ranges change in orientation to north and north-northeast trends (fig. 1*B*). The northwest-trending, 50–60-mile-wide transitional zone, as here defined, is wider than the transitional zone defined by Wilson and Moore (1959).

WILDERNESS LANDS

The 6,183,665 acres of Wilderness Lands in Arizona are distributed over the two physiographic provinces and the transitional zone (fig. 1*A*). About 70 percent of the Wilderness Lands is located in the Basin and Range province with the remaining 30 percent about equally divided between the Colorado Plateau province and the transitional zone.

TECTONIC PROVINCES AND TECTONIC HISTORY

The physiographic provinces, and to a large extent the hydrocarbon accumulations within them, are controlled by the tectonic framework of the underlying rocks. The major tectonic features which shaped Arizona's physiographic provinces are identified and discussed in the following section.

COLORADO PLATEAU PHYSIOGRAPHIC PROVINCE

The Colorado Plateau province represents a part of the North American craton which has been relatively stable since the Middle Proterozoic.

EXPLANATION
(For figures 1A, B, and C)

- Metamorphic and igneous rocks—Precambrian
- Metamorphic and intrusive igneous rocks—Mesozoic and Tertiary
- Volcanic rocks—Quaternary, Tertiary, and Mesozoic
- Wilderness Lands
- Oil, natural gas, and helium fields
- × Oil seep
- ○ Drill hole
- 1○ Phillips Arizona State No. 1–A drill hole
- △ Outcrop section
- F F′ Line of geologic cross section—Dashed line and circle indicate a drill hole projected into line of section
- Boundary between physiographic provinces
- Boundary between USGS petroleum provinces
- Boundary between tectonic provinces
- Approximate leading edge of Cordilleran fold and thrust belt, Drewes (1979, 1980, 1981)

Existing structural features are typified by broad areas of flat-lying to gently tilted strata bound by monoclines and (or) high-angle faults (figs. 2, 3). First-order structural features include the Black Mesa basin, Defiance uplift, Echo Cliffs uplift, Four Corners platform, Kaibab uplift, Kaiparowits basin, and Zuni basin, all of probable Laramide age (Davis, 1978), the Holbrook basin of Pennsylvanian and Early Permian age (Barwin and others, 1971; Heylmun, 1981), and the Paradox basin of Pennsylvanian age (Peterson and Ohlen, 1963) (fig. 1*A*). Thick evaporites of Permian-Pennsylvanian age and of Pennsylvanian age occupy, respectively, the central part of the Holbrook basin in Arizona and the Paradox basin in southeast Utah and southwest Colorado. Many of the first-order structural features have been controlled by an underlying basement-block mosaic which probably developed in the Precambrian and was reactivated by later episodes of crustal instability (Kelley, 1955; Lucchitta, 1974; Davis, 1978; Shoemaker and others, 1978).

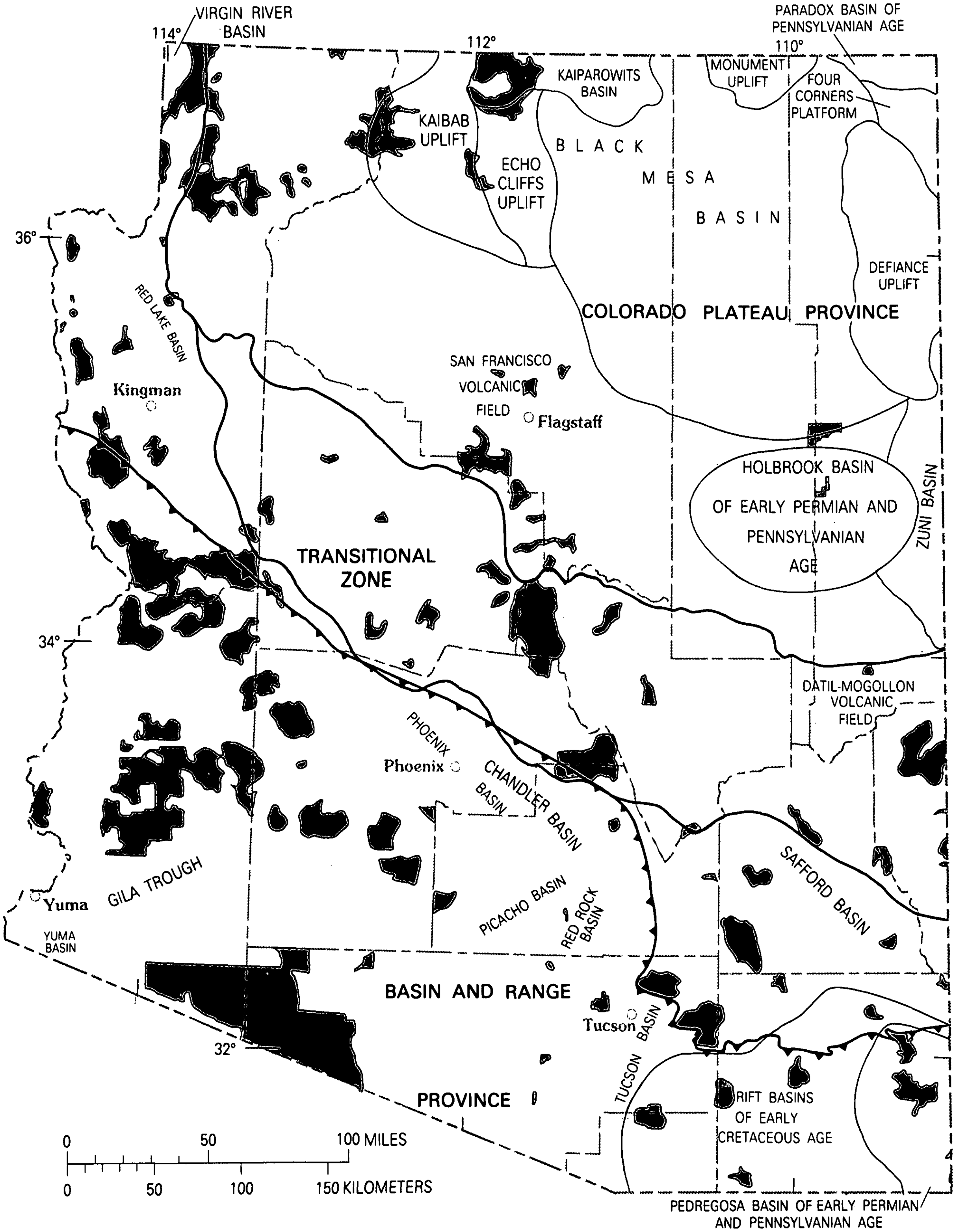

FIGURE 1A.—Physiographic and tectonic provinces.

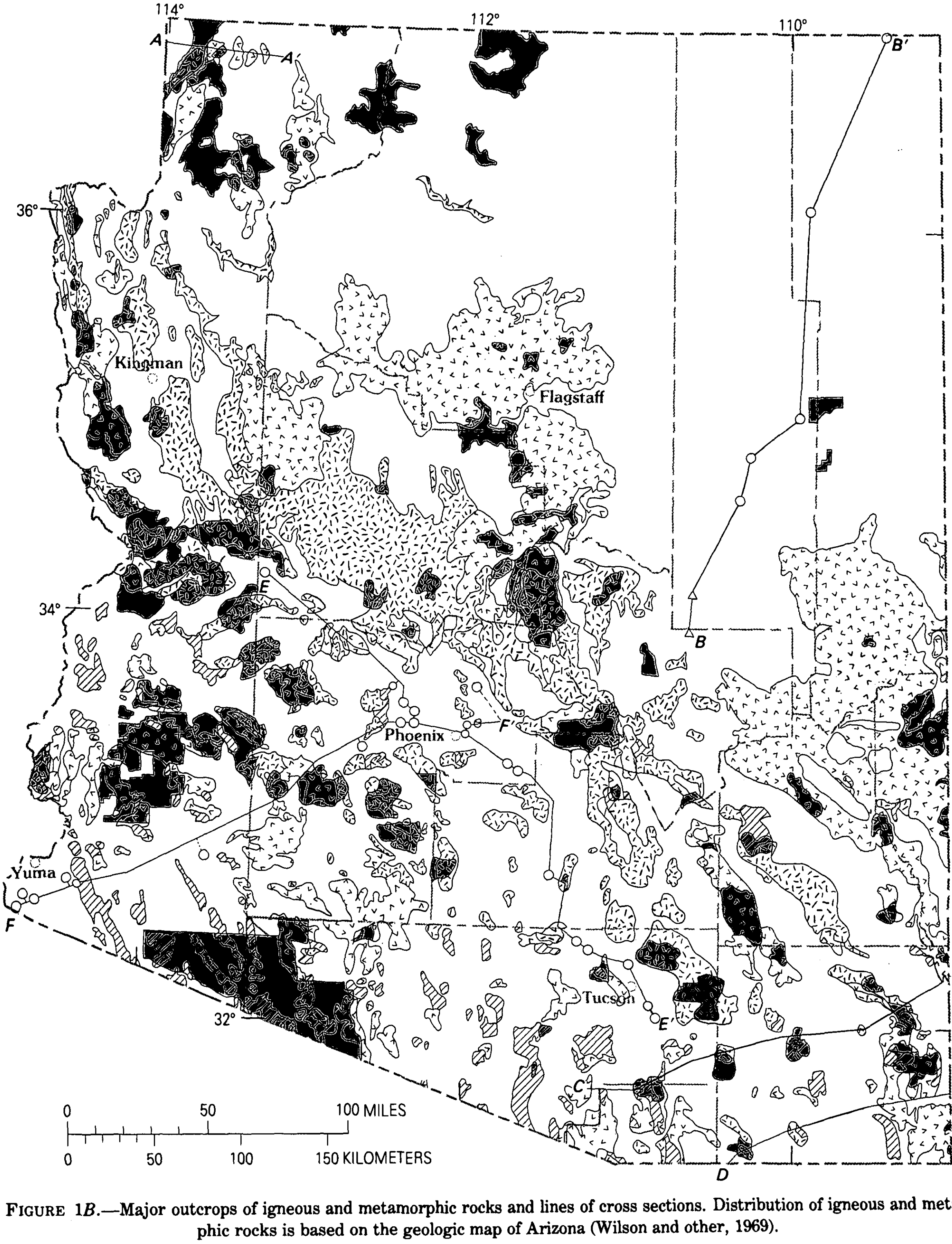

FIGURE 1*B*.—Major outcrops of igneous and metamorphic rocks and lines of cross sections. Distribution of igneous and metamorphic rocks is based on the geologic map of Arizona (Wilson and other, 1969).

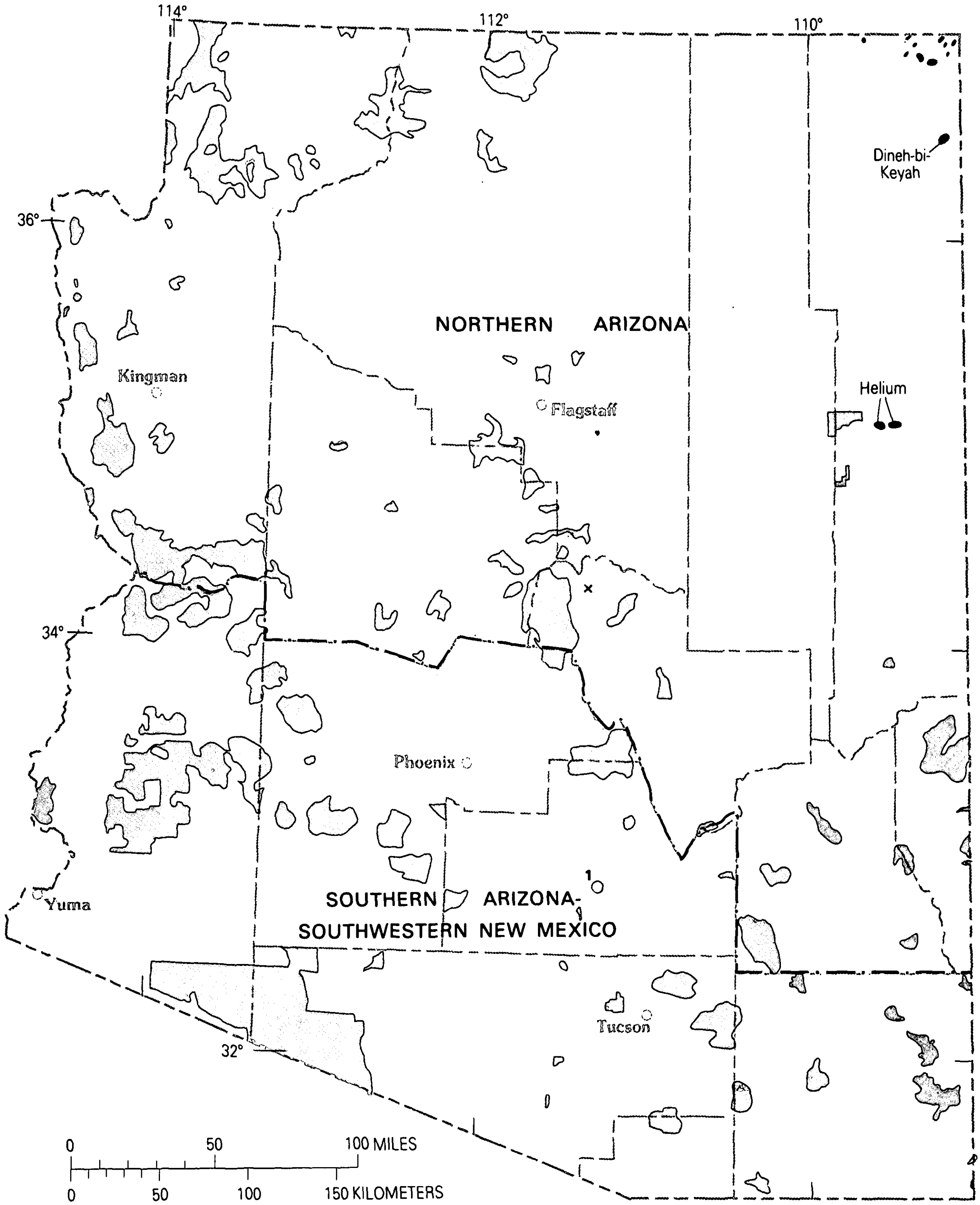

FIGURE 1C.—Oil and gas data and USGS petroleum provinces (Dolton and others, 1981). Oil and gas fields are from Fassett (1978).

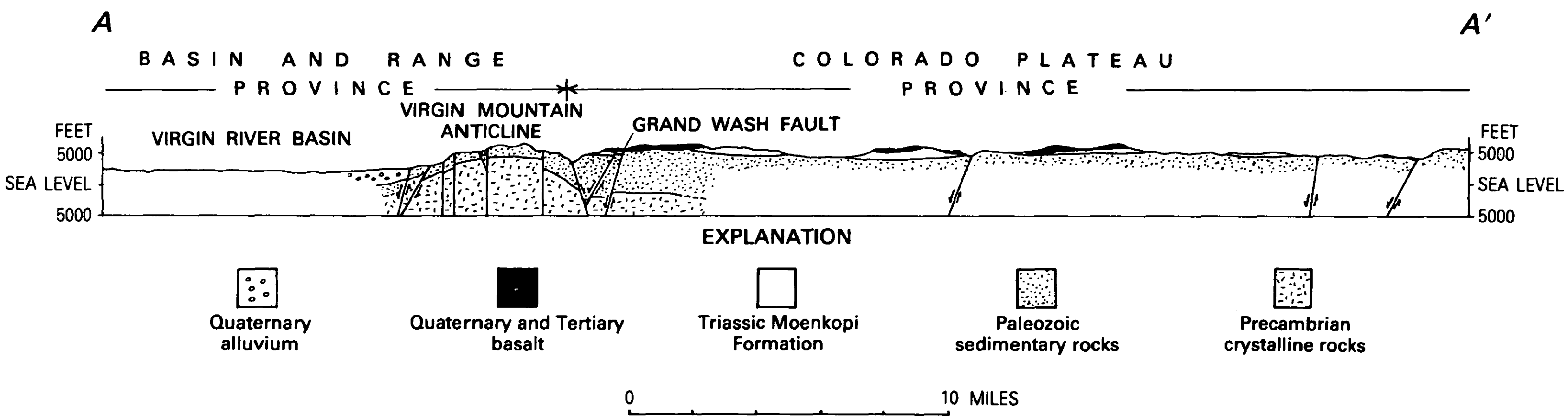

FIGURE 2.—Geologic cross section *A–A′* through the Basin and Range and Colorado Plateau provinces of northwest Arizona. Line of cross section is shown in figure 1*B*. Cross section from Moore (1972). Not all place names used in this figure appear on figure 1.

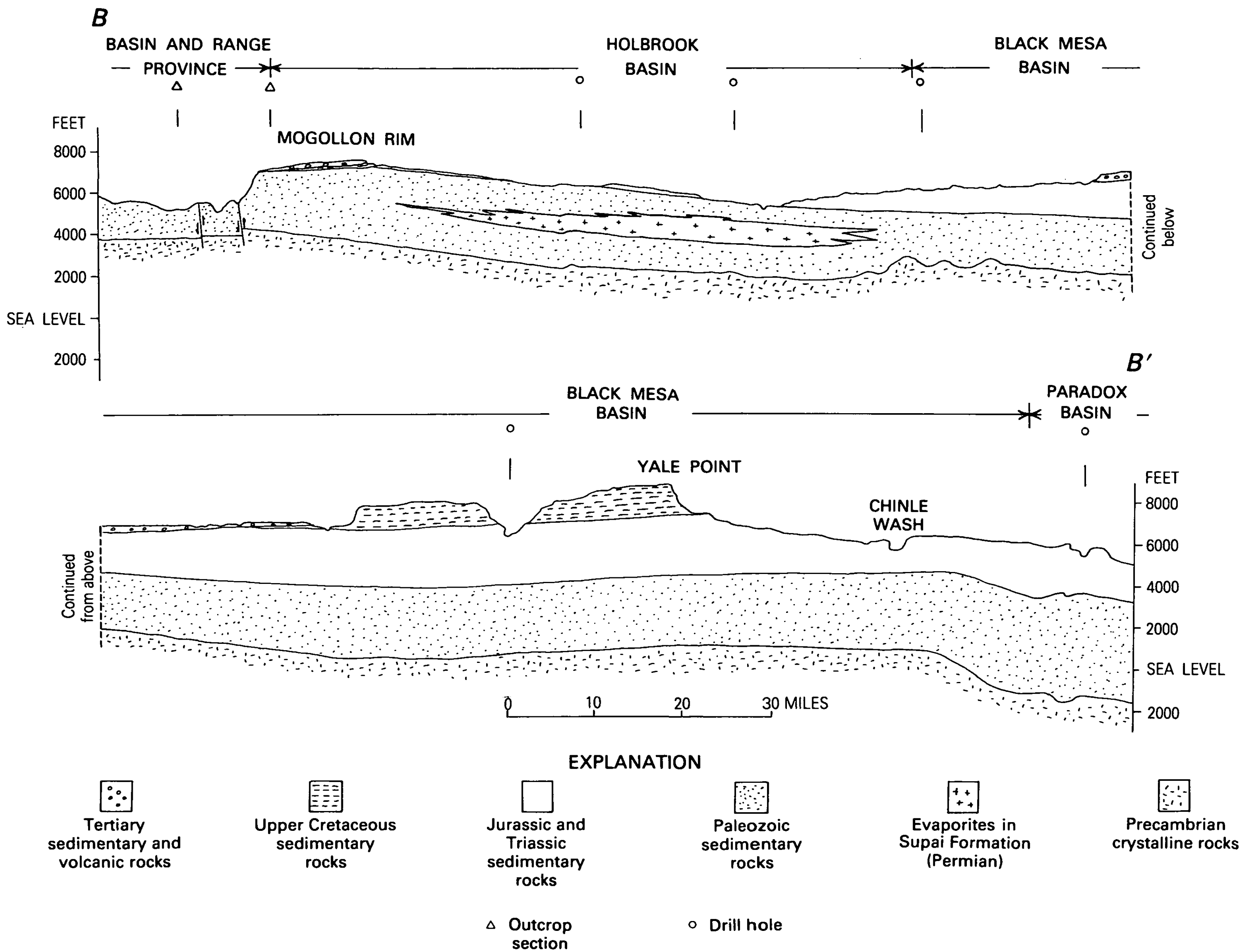

FIGURE 3.—Geologic cross section *B–B′* through the Black Mesa and Holbrook basins of northeast Arizona. Line of cross section is shown in figure 1*B*. Cross section from Brown and Lauth (1957). Not all place names used in this figure appear on figure 1.

BASIN AND RANGE PHYSIOGRAPHIC PROVINCE

The Basin and Range province, with its complex history of crustal extension, plutonism, and volcanism, is a far more mobile sector of the North American craton than the Colorado Plateau province. Major crustal instability of the craton in southern Arizona first appeared with the development of the Pedregosa basin, a late Paleozoic negative feature which trends northwestward from its depocenter in north-central Chihuahua, Mexico, through southwesternmost New Mexico, into southeasternmost Arizona (Greenwood and others, 1977) (fig. 1*A*). The northwest extent of the Pedregosa basin is partially masked by complex structures and plutonism (figs. 4, 5). Over 3,000 feet of Pennsylvanian and Early Permian marine carbonate rocks accumulated in the Arizona part of this basin (Ross, 1973).

In Mesozoic time, the North American craton in southern Arizona was deformed by Jurassic, middle Cretaceous, and latest Cretaceous magmatic arcs (Hamilton, 1978; Coney, 1978; Dickinson, 1981), a Jurassic left-lateral megashear (Silver and Anderson, 1974), Early Cretaceous rifting (Bilodeau, 1982), and Laramide compression (Drewes, 1978; Davis, 1979). Many of the geologic complexities that resulted from these tectonic and magmatic events are illustrated in figures 4 and 5.

Drewes (1978, 1980, 1981) believes that many of the thrust faults and folds in southeast Arizona represent a structural link between the Cordilleran fold and thrust belt of southern Nevada and southeast California and the Chihuahua fold and thrust belt of northern Mexico. Hamilton (1978), Davis (1979), and Matthews (1982) disagree with such a linkage on the grounds that neither the stratigraphic facies nor the structural features are present. The 7,000 to 7,500 feet of Paleozoic rocks (Peirce and others, 1970) and the 1,500 to 1,800 feet of lower Mesozoic rocks (Stewart and others, 1972) deposited in northwesternmost Arizona appear to represent the only hingeline or near-hingeline deposits in the State. The leading edge of the Cordilleran fold and thrust belt as defined by Drewes (1978, 1980, 1981) is shown in figure 1*A*.

The Early Cretaceous rifting resulted in west- to northwest-trending fault-bounded basins filled with thick nonmarine and marine deposits (Bilodeau, 1978, 1982). These basins were superimposed on the Pedregosa basin and the adjacent terrane in southeast Arizona (fig. 1*A*). Collectively known as the Bisbee Group, the nonmarine and marine deposits of the rift basins attained a thickness between 10,000 and 15,000 feet (Hayes, 1970; Kottlowski, 1971; Greenwood and others, 1977).

Crustal extension, volcanism, and nonmarine sedimentation dominated what is today the Basin and Range physiographic province of Arizona from latest Oligocene time to the Holocene (Hamilton, 1978; Dickinson, 1981). Coney (1978) recognizes a middle Tertiary and a late Tertiary phase of crustal extension.

The middle Tertiary phase resulted in the belt of metamorphic-core complexes described by Davis and Coney (1979), rhyolitic to andesitic volcanism generally ranging between 20 to 40 m.y. ago (Elston, 1976) with a peak between 20 and 26 m.y. ago (Damon and Bikerman, 1964; Damon and Mauger, 1966; Eberly and Stanley, 1978), and coarse-grained nonmarine sedimentary rocks derived from adjacent highlands. The interbedded volcanic rocks, arkosic conglomerate and sandstone, and local lake beds formed during the middle Tertiary phase of crustal extension are assigned by Eberly and Stanley (1978) to unit I (figs. 6, 7). The combined thickness of unit I may be as much as 8,000 feet in the Gila trough (fig. 7), but elsewhere in southern Arizona the rocks of unit I are generally less than 3,000 feet thick (figs. 6, 7).

The late Tertiary phase of crustal extension—beginning between 12 and 13 m.y. ago (Eberly and Stanley, 1978) and 15 m.y. ago (Coney, 1978; Dickinson, 1981) and ending about 10 m.y. ago (Eberly and Stanley, 1978)—resulted in the characteristic block faulting of the Basin and Range physiographic province. Thick sequences of generally nonmarine sedimentary rocks defined by Eberly and Stanley (1978) as unit II (figs. 6, 7) and scattered basaltic volcanism also accompanied the late Tertiary phase of crustal extension. The thickness of unit II is greater than unit I in most localities, particularly in five basins between Phoenix and Tucson where unit II commonly exceeds 7,500 feet in thickness (figs. 6, 7). Several of these basins also contain thick evaporite deposits (Eaton and others, 1972; Peirce, 1974; Eberly and Stanley, 1978) (figs. 6, 7).

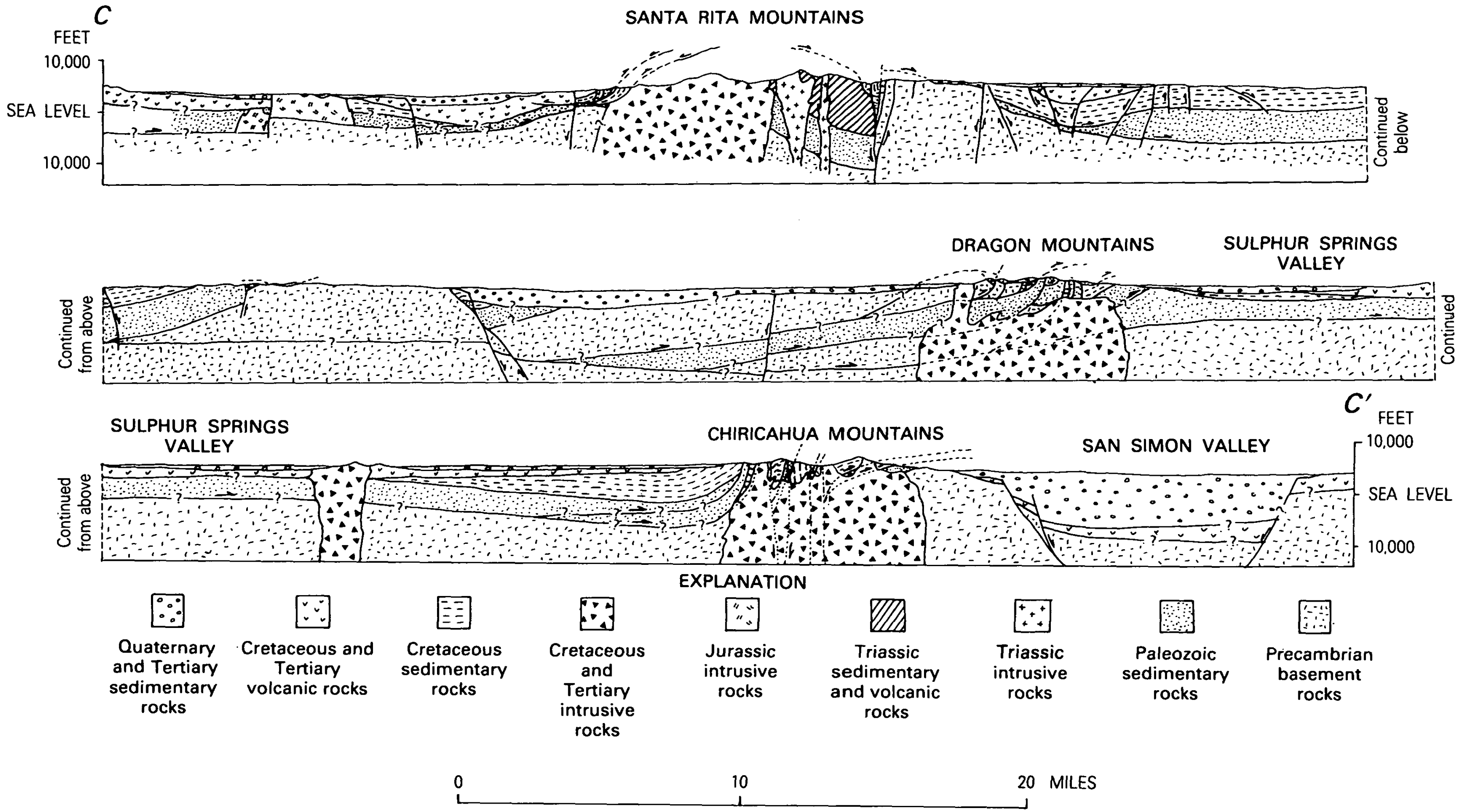

FIGURE 4.—Geologic cross section *C–C′* through the Pedregosa basin and superimposed Early Cretaceous rift basins of southeast Arizona. Line of cross section is shown in figure 1*B*. Cross section from Drewes (1980). Place names used in this figure do not appear on figure 1.

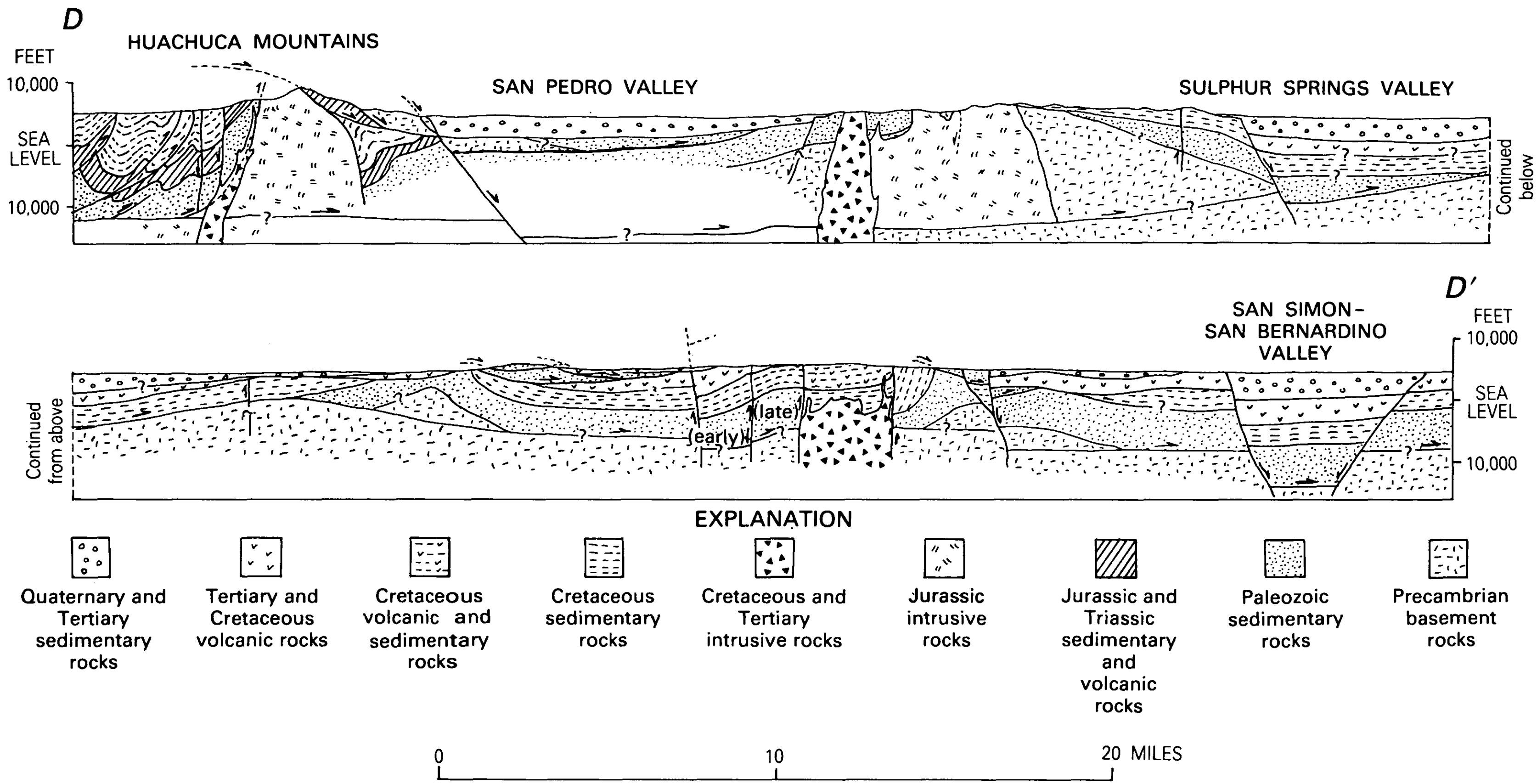

FIGURE 5.—Geologic cross section *D–D′* through the Pedregosa basin and superimposed Early Cretaceous rift basins of southeast Arizona. Line of cross section is shown in figure 1*B*. Cross section from Drewes (1980). Place names used in this figure do not appear on figure 1.

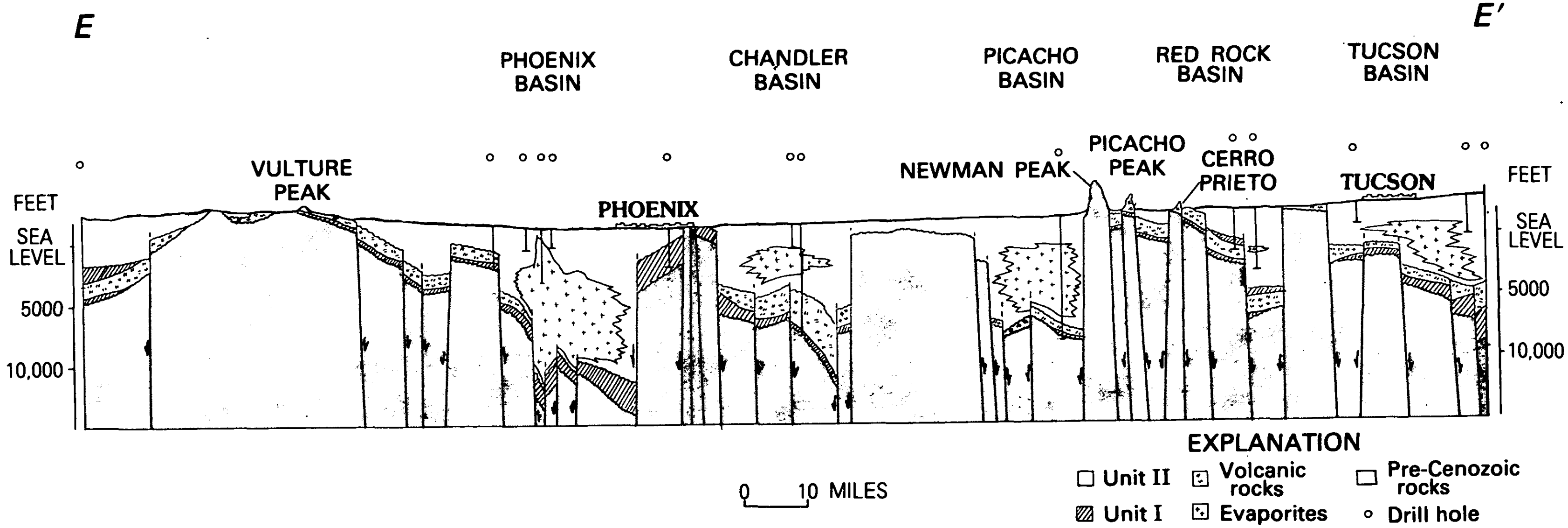

FIGURE 6.—Geologic cross section E–E' through the Basin and Range province of southwest Arizona. Line of cross section is shown in figure 1B. Cross section from Eberly and Stanley (1978). Not all place names used in this figure appear on figure 1.

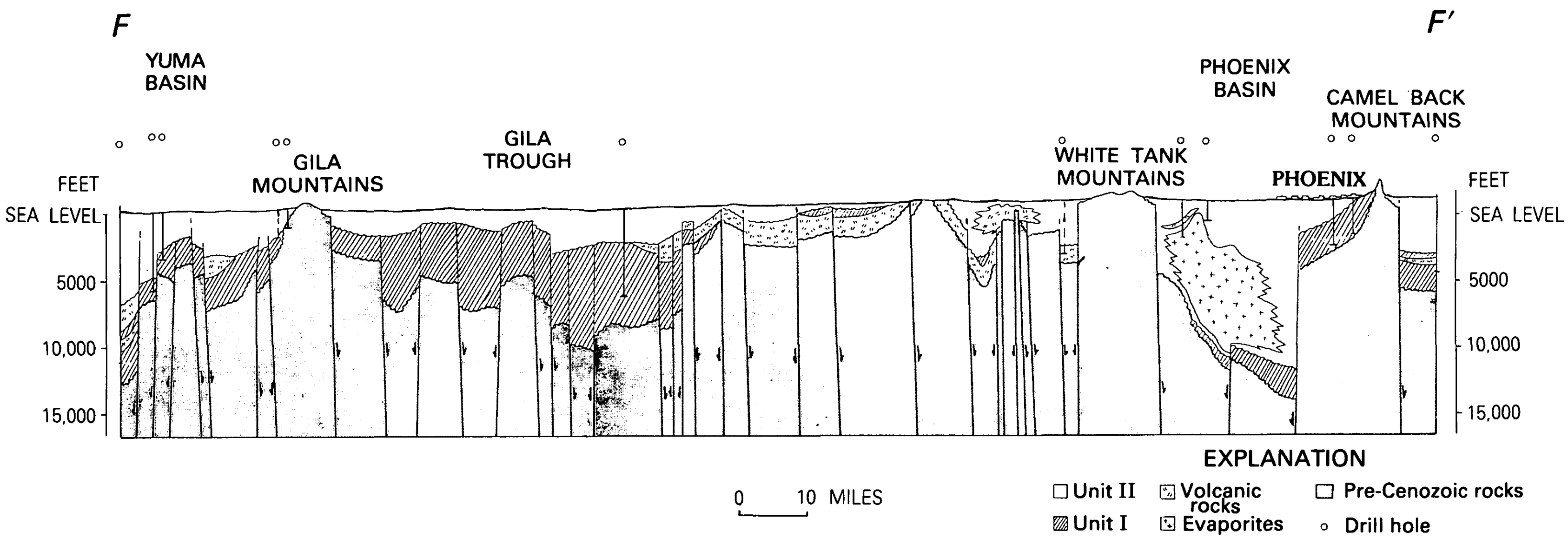

FIGURE 7.—Geologic cross section F–F' through the Basin and Range province of southwest Arizona. Line of cross section is shown in figure 1*B*. Cross section from Eberly and Stanley (1978). Not all place names used in this figure appear on figure 1.

TRANSITIONAL ZONE

The transitional zone between the Colorado Plateau and the Basin and Range physiographic provinces, the central Arizona transition zone of Lucchitta (1978), has been the site of extensive volcanism (San Francisco and Datil-Mogollon volcanic fields; fig. 1*A*, *B*), orogeny, deep erosion, and mineralization (Lucchitta, 1978). From southeast to northwest along this zone the present day basin-and-range structure changes in trend from northwest to north-northeast. Lucchitta (1978) suggests that this zone may mark a former plate boundary which could extend as far to the northwest as the southern terminus of the Cascade Range in northern California.

PETROLEUM GEOLOGY

USGS PETROLEUM PROVINCE BOUNDARIES

The State of Arizona is subdivided into two provinces established by the U.S. Geological Survey for which quantitative oil and gas resource estimates have been prepared (Dolton and others, 1981). The northern Arizona petroleum province approximates the Colorado Plateau physiographic province and the transitional zone, whereas the southern Arizona-southwestern New Mexico petroleum province nearly coincides with the Basin and Range physiographic province (fig. 1*A*, *C*). The match between the petroleum provinces and the physiographic provinces is imperfect because the USGS petroleum provinces follow county lines to simplify the tabulation of oil and gas resource data.

OIL AND GAS FIELDS

Oil and gas production in Arizona is restricted to a few fields discovered between 1954 and 1971 along the western margin of the Four Corners platform and the southwestern margin of the Paradox basin (fig. 1*C*). The fields are small, having ultimate recoveries of less than 1 million barrels of oil and 10,000 million cubic feet of gas, except for the Dineh-bi-Keyah field (fig. 1*C*) where the ultimate recovery has been estimated at 20 million barrels of oil (Molenaar, 1972). Helium was produced from one well in the Paradox basin (Spencer, 1978) and from two fields along the southern margin of the Black Mesa basin (Allen, 1978) (fig. 1*C*).

Algal-plate mounds in the Pennsylvanian Paradox Formation form the reservoirs for the small oil and gas fields in Arizona. At Dineh-bi-Keyah the reservoir is a Tertiary igneous sill which has intruded Pennsylvanian rocks (McKenny and Masters, 1968; Danie, 1978). Oil and gas reservoirs of lesser importance are the Devonian McCracken Sandstone Member (of Knight and Cooper, 1955) of the Elbert Formation, the Devonian Aneth Formation (of Knight and Cooper, 1955), and the Mississippian Leadville Limestone. The Pennsylvanian oil and gas accumulations, including Dineh-bi-Keyah, have been trapped by an updip reduction of porosity and permeability associated with a nose or flank of an anticlinal structure. Oil and gas accumulations in the lower Paleozoic reservoirs and helium accumulations in the Permian Coconino Sandstone (Allen, 1978) are trapped along the crests of anticlinal structures.

THICKNESS AND ORIGIN OF SEDIMENTARY ROCKS

The combined thickness of Paleozoic, Mesozoic, and Tertiary sedimentary rocks exceeds 8,000 feet in (1) parts of the Black Mesa basin, (2) northwesternmost Arizona near the Paleozoic hingeline in southern Nevada, (3) the Pedregosa basin and the superimposed rift basins of Early Cretaceous age, and (4) at least six Tertiary basins in the Basin and Range province.

BLACK MESA BASIN

Approximately 3,500 to 4,000 feet of Paleozoic rocks are present in the Black Mesa basin, of which over half are Permian in age (Brown and Lauth, 1957; Barwin and others, 1971; Peirce, 1976) (fig. 3). Cambrian through Mississippian rocks are as much as 1,600 feet thick in the basin and consist of shelf carbonate rocks, shallow marine sandstone, and local dark marine shale (Lessentine, 1965). Pennsylvanian rocks thin from about 1,000 feet in the northeast part of the Black Mesa basin to zero along the west side of the basin (Lessentine, 1965). The lithology of the Pennsylvanian rocks also changes markedly from northeast to southwest from basinal carbonate rocks and black shale to shelf carbonate rocks to nonmarine beds of sandstone and red shale (Lessentine, 1965). Triassic and Jurassic rocks in the Black Mesa basin are nonmarine and attain a combined thickness of approximately 3,000 feet

(Brown and Lauth, 1957; Barwin and others, 1971). Up to 1,500 feet of Cretaceous rocks are present in the Black Mesa basin, owing largely to the deposition of offshore marine shale, nearshore marine sandstone, paludal shale, sandstone and coal, and alluvial-plain sandstone and shale at or near a northeastward prograding shoreline (Repenning and Page, 1956; O'Sullivan and others, 1972; Molenaar, 1983). Tertiary rocks in the basin are negligible.

PALEOZOIC HINGELINE AREA

Paleozoic and lower Mesozoic rocks deposited in northwesternmost Arizona, near the Paleozoic hingeline between miogeoclinal and cratonic strata in southern Nevada (Hamilton, 1978), have a combined thickness of 8,500 to 9,300 feet (Peirce and others, 1970; Stewart and others, 1972). These rocks are buried beneath Tertiary sedimentary rocks and Quaternary sediments which are at least 1,000 feet thick in the Virgin River basin (Moore, 1972) (fig. 2).

PEDREGOSA BASIN

At least 15,000 feet of sedimentary rocks are present in the Pedregosa basin and the overprinted Lower Cretaceous rift basins (Greenwood and others, 1977). Approximately one-third of these strata are represented by Pennsylvanian and Permian shelf carbonate rocks and basinal black shale and carbonate rocks, the remainder being Lower Cretaceous, with a thick alluvial-fan conglomerate at the base followed by shallow marine limestone, shale, and sandstone (Hayes, 1970). Cambrian through Mississippian rocks with a maximum combined thickness of up to 3,000 feet (Kottlowski, 1971; Greenwood and others, 1977) and Tertiary sedimentary and volcanic rocks locally up to 5,000 feet thick (Thompson and others, 1978) further contribute to the already thick sedimentary section in southeast Arizona. Because of the complex history of uplift, erosion, and plutonism, the Pennsylvanian, Permian, and Lower Cretaceous rocks are not uniformly distributed throughout the area (figs. 4, 5). Nonetheless, the overall thickness of this depocenter is impressive.

TERTIARY RIFT BASINS

Five rift basins of Tertiary age in the vicinity of Tucson and Phoenix (Chandler, Phoenix, Picacho, Red Rock, and Tucson) are filled with at least 8,000 feet of Tertiary sedimentary rocks and Quaternary sediments (Eberly and Stanley, 1978; Scarborough and Peirce, 1978) (figs. 1*A*, 6). Up to several thousand feet of Paleozoic rocks are probably present in some of these Tertiary rift basins (Greenwood and others, 1977). The pre-rift Paleozoic rocks consist of predominantly shelf carbonate rocks with secondary shallow marine sandstone and black marine shale. The Gila trough and Yuma basin in southwest Arizona (Eberly and Stanley, 1978) (fig. 7) and the Red Lake basin in northwest Arizona (Scarborough and Peirce, 1978) also contain 8,000 feet or more of Tertiary sedimentary rocks and Quaternary sediments. The Tertiary sedimentary rocks in all of these basins are nonmarine except in the Yuma basin where approximately 3,800 feet of marine rocks of an unnamed late Miocene unit and the Miocene and Pliocene Bouse Formation were encountered by drilling (Mattick and others, 1973; Eberly and Stanley, 1978).

POTENTIAL SOURCE ROCKS, HYDROCARBON SHOWS, AND THERMAL MATURITY

Except for Pennsylvanian black shales in the Paradox basin-Four Corners platform area (Lessentine, 1965; Barwin and others, 1971) and Devonian black shales in the Paradox basin and northeast part of the Black Mesa basin (Parker and Roberts, 1963), good oil and gas source rocks in the Paleozoic section appear to be sparse in the Colorado Plateau province of Arizona. Paleozoic source rocks of secondary importance in the Colorado Plateau province and transitional zone may include dolomite beds in the Devonian Martin Formation of central Arizona, interbedded limestone and shale of the Permian-Pennsylvanian Naco Limestone in the Holbrook basin, and possibly interbedded dolomite and evaporite rocks of the thick Permian-Pennsylvanian Supai Formation in the Holbrook basin (Barwin and others, 1971; Heylmun, 1981). A fetid dolomite unit in the Martin Formation may be responsible for the lower Paleozoic oil shows reported in the subsurface southwest of Flagstaff, as well as for oil seeps in Devonian rocks in the north-central part of the transitional zone (Scurlock, 1971) (fig. 1*C*); however, this unit cannot be a major source rock in the Colorado Plateau province because it extends only a few miles north of the Colorado Plateau-transitional zone boundary before pinching out (Teichert, 1965). Minor oil and gas shows in Paleozoic and lower Mesozoic rocks of the block-faulted plateaus in northwestern Arizona (Giardina, 1979) probably resulted from the long-range migration of hydrocarbons from organic-rich Paleozoic rocks west of the hingeline. Coals in the Upper Cretaceous Mesaverde Group and black shales in the Upper Cretaceous Mancos Shale of the Black Mesa basin have good source rock potential, but they are thermally immature.

Conodont Alteration Index (CAI) values indicate that Paleozoic rocks in the Colorado Plateau province and transitional zone have a favorable thermal history for the generation of oil and gas (B. R. Wardlaw and A. G. Harris, unpub. data). The oil and gas fields and shows found in the Paleozoic rocks of northeastern Arizona were probably locally derived and were only generated after the Paleozoic source beds were buried beneath several thousand feet of Upper Cretaceous rocks. Oil and gas which presumably migrated eastward from near the hingeline into northwestern Arizona were probably generated in Late Jurassic to Early Cretaceous time.

Black shales and limestone of the Permian-Pennsylvanian Horquilla Limestone and the Devonian Percha Shale of the Pedregosa basin appear to be the best oil and gas source rocks in the Basin and Range province of Arizona (Kottlowski, 1971; Greenwood and others, 1977; Ross, 1973; Thompson and others, 1978). The dark basinal facies of the Horquilla Limestone is limited to the southeasternmost part of the Pedregosa basin whereas the Percha Shale extends over much of southeast Arizona (Greenwood and others, 1977). Thick black shales in the Apache Canyon Formation of the Lower Cretaceous Bisbee Group also may be good oil and gas source rocks (Heylmun, 1979).

Hydrocarbons were probably generated from the above-mentioned units during or slightly after the Early Cretaceous rifting phase and readily account for the modest number of shows and seeps in the Pedregosa basin (Thompson and others, 1978) and adjacent Tertiary rift basins (Heylmun, 1978, 1979). Some of the hydrocarbon shows in southeastern Arizona basins, however, may have been derived from lower Tertiary lacustrine rocks such as in the Pantano Formation (Heylmun, 1978). Subsurface oil shows in Tertiary strata (unit I of Eberly and Stanley, 1978) in the Gila trough (Petroleum Information Well History Control System (WHCS) file) also may have been derived from lacustrine rocks.

On the basis of CAI values, Paleozoic rocks in the vicinity of the Pedrogosa basin have had a thermal history favorable for the generation and entrapment of gas and possibly some oil (B. R. Wardlaw and A. G. Harris, unpub. data). Elsewhere in the Basin and Range province of Arizona, the Paleozoic rocks have been elevated to extremely high temperatures, particularly in the vicinity of metamorphic-core complexes (B. P. Wardlaw and A. G. Harris, unpub. data). The degree to which the lower and middle Tertiary sedimentary rocks of unit I (Eberly and Stanley, 1978) have been affected by this thermal event is unknown.

RESERVOIRS AND TRAPS

Paleozoic carbonate units provide the best oil and gas reservoirs in the Colorado Plateau province and transitional zone. Good reservoir rocks which are in proximity to possible source rock units include the Mississippian Redwall Limestone, Pennsylvanian shelf carbonate rocks, dolomite of the Devonian Martin and Elbert Formations, and Fort Apache Member of the Permian-Pennsylvanian Supai Formation (Brown and Lauth, 1957; Lessentine, 1965; Barwin and others, 1971).

Shelf-margin dolomite of the Horquilla Limestone (Pennsylvanian-Permian), Epitaph Dolomite (Permian), and Concha Limestone (Permian) appears to be the best reservoir unit in the Pedregosa basin (Greenwood and others, 1977; Thompson, 1980). Reservoirs of secondary importance in the vicinity of the Pedregosa basin include local rudistid reefs in the Mural Limestone (Lower Cretaceous), marine sandstones in the Cintura Formation (Lower Cretaceous), the El Paso Limestone (Ordovician), and the Montoya Dolomite (Ordovician) (Thompson and others, 1978).

A wide variety of structures is available for hydrocarbon traps in Arizona. However, commonly it is difficult to determine the timing of trap development with respect to major phases of hydrocarbon generation, migration, and redistribution. This problem is particularly acute in the Basin and Range province. Stratigraphic traps are also available, and in some cases may be less susceptible to flushing by freshwater and leakage than complex structures.

SUMMARY STATEMENT

Although most of Arizona is considered to be a frontier area in terms of oil and gas exploration, the probability of discovering major hydrocarbon resources here is low. Pennsylvanian and older rocks will probably yield commercial hydrocarbons in the already productive Paradox basin and Four Corners platform and in the presently unproductive Holbrook basin, Black Mesa basin, and block-faulted plateaus of northeast Arizona; however, the local extent of rich source rocks severely limits the future potential of these provinces. Oil and gas, which may have migrated from west of the hingeline into northwest Arizona, were probably largely flushed by freshwater introduced after the uplift and erosional dissection of the region in late Tertiary time.

The Pedregosa basin and the superimposed Early Cretaceous rift basins—with good source rocks, good reservoirs, and local hydrocarbon shows and seeps—appear to hold the most promise for significantly increasing the oil and gas reserves of Arizona. Unfortunately, most of the oil and gas in this area probably were generated during or shortly after a thick section of sedimentary rocks was deposited in the Lower Cretaceous rift basins; thus oil and gas accumulations were subject to migration or destruction by the Laramide, middle Tertiary, and late Tertiary tectonic and magmatic episodes that followed. Much of the oil and gas escaped during its probable redistribution from primary traps to secondary and Tertiary traps. The best exploration opportunities in the Pedregosa basin are in the Tertiary rift basins where hydrocarbons that may have been trapped in Paleozoic and Lower Cretaceous rocks are least affected by later tectonism and flushing by freshwater. Known centers of plutonism and volcanism should be avoided for petroleum exploration. Tertiary strata near the flanks of Tertiary rift basins may also have trapped hydrocarbons that either migrated from older traps or were generated from adjacent lacustrine source rocks.

Other parts of the Basin and Range province of Arizona, such as the Gila trough, Yuma basin, and several basins near Tucson and Phoenix, may also yield commercial oil and gas. Strata in units I and II of Eberly and Stanley (1978) are the most likely exploration targets.

A recent drill hole (Phillips Arizona State No. A–1, fig. 1*C*), northwest of Tucson, tested what was believed to be a thick section of Mesozoic and Paleozoic sedimentary rocks beneath an allochthonous cover of Precambrian crystalline rocks (Hansen and others, 1980). This test and the overthrust-hingeline play received much attention in the petroleum industry (Keith, 1979; Hansen and others, 1980). The Phillips Arizona State No. A–1 drilled into crystalline rocks of a metamorphic core complex and remained in them to a total depth of 18,013 feet. Distinct seismic reflectors thought by Hansen and others (1980) to represent unmetamorphosed sedimentary rocks were caused instead by well-developed zones of brecciation and compositional banding in metamorphic rocks (Reif and Robinson, 1981). Despite the failure of the well being productive, the drilling of the Phillips Arizona State No. A–1 exemplifies the type of action that will need to be taken if commercial hydrocarbons are to be found in the Basin and Range province of Arizona.

The question of whether or not the Cordilleran fold and thrust belt extends across Arizona and adjacent New Mexico is still unresolved. However, the results of the Phillips Arizona State No. A–1 drill hole strongly suggest that if the thrust belt does extend across Arizona it is not expressed as a major allochthon of crystalline rocks that overlie a thick, previously unknown and unexplored section of Paleozoic and Mesozoic sedimentary rocks. Therefore, this unanswered question concerning the presence or absence of the thrust belt probably does not significantly affect the overall assessment of the oil and gas potential of southwest Arizona.

PETROLEUM POTENTIAL OF WILDERNESS LANDS

On the basis of the geologic framework and petroleum geology outlined in the previous sections, the hydrocarbon potential of the Wilderness Lands in Arizona is rated qualitatively on a scale from high to zero. No Wilderness Lands in Arizona are rated as having a high potential because a high rating is reserved for land that is located near hydrocarbon production and has all the geologic attributes of the producing area. A medium rating is assigned to Wilderness Lands that have all the attributes, including shows, of a future petroleum producing area, but presently lack commercial production. In contrast, low and zero ratings are assigned, respectively, to Wilderness Lands that have few or no attributes of a future petroleum producing area. Usually a zero rating is reserved for regions characterized by autochthonous igneous and metamorphic rocks.

For ease of discussion, the Wilderness Lands in Arizona are grouped into 12 clusters (fig. 8), each containing one or more tracts that have the same or similar geologic characteristics and the same hydrocarbon potential.

Cluster 1

Cluster 1 contains a single tract of Wilderness Land located along the Vermilion Cliffs in northwest Arizona near the Arizona-Utah border (figs. 1, 8). Rocks of the Jurassic-Triassic Glen Canyon Group are exposed throughout the tract (Wilson and others, 1969). The hydrocarbon potential of the cluster is rated medium because of the proximity of the cluster to the now-abandoned Virgin oil field in southwest Utah (Bahr, 1963; Giardina, 1979). Furthermore, several oil shows are reported from holes drilled less than 20 miles south of the tract. Good source rocks are absent from the area and thus the reported oil must have migrated into the area from the west, probably from at least as far west as the Paleozoic hingeline. The reservoir unit in the now-abandoned Virgin oil field was the Triassic Timpoweap Limestone Member of the Moenkopi Formation (Bahr, 1963). The shows south of cluster 1 are located in the Permian Kaibab Limestone, Mississippian Redwall Limestone, and the Timpoweap Member. Broad anticlines and facies-change stratigraphic traps are the most likely variety of traps in the tract. The hydrocarbon potential of cluster 1 is not considered to be high because the available reservoir rocks are susceptible to flushing by freshwater.

Cluster 2

Cluster 2 is in northwest Arizona along the Grand Wash fault (Wilson and others, 1969) (figs. 1, 2, 8), and except for a greater concentration of Tertiary faults has the same characteristics as cluster 1. This greater concentration of Tertiary faults—which facilitate the leakage and flushing of earlier-trapped hydrocarbons—makes cluster 2 slightly less desirable for hydrocarbon exploration than cluster 1. The hydrocarbon potential of cluster 2 is rated medium.

Cluster 3

Cluster 3 is located in northeast Arizona near the southern part of the Black Mesa basin and the adjacent Holbrook basin (figs. 1*A*, 8). Rocks of the Triassic Chinle Formation crop out across the tracts of this cluster (Wilson and others, 1969). The hydrocarbon potential of this cluster is rated medium because of several oil and gas shows reported from nearby wells and because of the potentially favorable source and reservoir characteristics of the Permian-Pennsylvanian Naco Limestone and part of the Permian-Pennsylvanian Supai Formation.

Cluster 4

Cluster 4 contains a single tract of Wilderness Land on the northeast flank of the Safford basin in southeast Arizona (figs. 1*A*, 8). The Safford basin locally contains at least 7,000 feet of Tertiary sedimentary rocks and Quaternary sediments (Scarborough and Peirce, 1978; Oppenheimer and Sumner, 1981). The hydrocarbon potential of this cluster is rated medium on the strength of the oil shows reported from several shallow wells drilled within the boundaries of the wilderness tract (Petroleum Information WHCS file). All the oil shows are in Tertiary sedimentary rocks. Very little is known about the organic richness and reservoir quality of the underlying Paleozoic rocks.

Cluster 5

Cluster 5 consists of 26 tracts of Wilderness Lands spread across the Colorado Plateau province (figs. 1*A*, 8). The hydrocarbon potential of cluster 5 is rated low.

Those tracts in the northwest part of cluster 5 have a geologic framework similar to clusters 1 and 2, but the degree of late Tertiary and Holocene erosional dissection is much greater in cluster 5 than in clusters 1 and 2. Thus, the tracts in the northwest part of cluster 5 are more susceptible to flushing by freshwater than are clusters 1 and 2. A few oil shows have been reported from wells drilled in the northwest part of cluster 5.

South and southwest of Flagstaff, the tracts in cluster 5 have lower Paleozoic rocks at the surface. Subsurface oil shows and several oil seeps have been reported from these rocks (Scurlock, 1971; fig. 1*C*). The hydrocarbon potential of this part of cluster 5 is considered low because of the extensive erosion and exposure of the rocks with

FIGURE 8.—Map showing the qualitative estimates of petroleum potential for Wilderness Lands in Arizona. The heavy lines and associated numbers define clusters of Wilderness Lands that have the same or similar geologic characteristics and the same hydrocarbon potential.

reservoir potential to freshwater flushing. Moreover, these oil shows probably were generated from the fetid dolomite unit in the Martin Formation, a unit having only local geographic extent.

The small isolated tract at the extreme southeast end of cluster 5 has volcanic rocks at the surface. Lower Paleozoic rocks with the same characteristics as the lower Paleozoic rocks in the Flagstaff area probably underlie the volcanic rocks.

Cluster 6

Cluster 6 is represented by tracts in the transitional zone and in the Basin and Range province of southeast Arizona (figs. 1*A*, 8). Thick Tertiary volcanic rocks crop out here and probably cover a thin section of Paleozoic rocks. The hydrocarbon potential of cluster 6 is rated low to zero because any hydrocarbons originally trapped in the Paleozoic rocks probably escaped during ensuing phases of rifting and volcanism. In the easternmost tracts of cluster 6 the rocks of the Datil-Mogollon volcanic field may be underlain by Tertiary plutons (Elston and others, 1976).

Cluster 7

Cluster 7 is in the Basin and Range province of northwest Arizona (figs. 1*A*, 8). The hydrocarbon potential of cluster 7 is rated low to zero because extensive exposures of Precambrian gneiss, granite, and schist and Tertiary volcanic rocks extend across most of the wilderness tracts of this cluster. Commercial hydrocarbons, if found at all in these tracts, would be located in those parts of the tracts that overlap the flanks of Tertiary basins.

Cluster 8

Cluster 8 is in the southeasternmost part of the Basin and Range province where thick sedimentary deposits of the Pedregosa basin and the Early Cretaceous rift basins are present (figs. 1*A*, 8). The source rocks, reservoir rocks, and thermal history are at least locally favorable for the generation and entrapment of hydrocarbons. According to B. R. Wardlaw and A. G. Harris (unpub. data), the thermal history of the region favors gas over oil.

Hydrocarbons generated in strata within cluster 8 would have been highly prone to leakage and thermal destruction because the adjacent rocks have been cut by several generations of faults and plutons, many of which appear to postdate the major phase of oil and gas generation and migration. The location of the tracts in cluster 8 along structurally high fault blocks further contributes to the leakage and flushing of previously trapped hydrocarbons. The hydrocarbon potential of cluster 8 is rated low.

Cluster 9

Cluster 9 is in the Basin and Range province of southwest Arizona (figs. 1*A*, 8). Because the tracts in cluster 9 overlie Tertiary basins, they have a greater hydrocarbon potential than the tracts in adjacent clusters 7 and 11. The southernmost tract in cluster 9 adjoins the Gila trough, where lower to middle Tertiary sedimentary rocks, possibly up to 6,000 feet thick, are present. Minor oil shows have been reported from holes drilled in the Gila trough (Petroleum Information WHCS file). The hydrocarbon potential of cluster 9 is ranked low because the organic richness, reservoir quality, and thermal history of the rocks are probably unfavorable to the generation and entrapment of significant volumes of hydrocarbons.

Cluster 10

Cluster 10 is represented by tracts in the transitional zone and in the Basin and Range province of southeast Arizona (figs. 1*A*, 8). The hydrocarbon potential of cluster 10 is rated low to zero. The two northern tracts in this cluster have extensive exposures of Tertiary volcanic rocks that probably conceal a thin section of Paleozoic rocks. Any hydrocarbons that were originally trapped in these tracts probably would have escaped in postgeneration and postmigration episodes of rifting and volcanism.

The southernmost tract in cluster 10 is in the Pedregosa basin and the Early Cretaceous rift basins where a thick section of sedimentary rocks is preserved (figs. 1*A*, 8). However, the tract is complexly faulted, contains several outcrops of Precambrian crystalline rocks, and is intruded by Tertiary plutons.

Cluster 11

Cluster 11 is comprised of 34 tracts of Wilderness Lands in the Basin and Range province of southwest Arizona (figs. 1*A*, 8). The hydrocarbon potential of cluster 11 is rated low to zero. The numerous horst blocks located in cluster 11 are composed of Mesozoic and Precambrian gneiss, schist, and granite, Cretaceous and Tertiary granite, Tertiary volcanic rocks, and local Mesozoic sedimentary rocks (Wilson and others, 1969). Grabens and half grabens between the horst blocks are filled with Tertiary sedimentary rocks and Quaternary sediments generally no greater than about 5,000 feet thick (Oppenheimer and Sumner, 1981). These shallow basins are the only part of cluster 11 where commercial hydrocarbons could be found. Oil shows have been reported from one shallow well drilled near the middle part of cluster 11 (Petroleum Information WHCS file).

Cluster 12

Cluster 12 consists of a broad, northwest-oriented zone of wilderness tracts in the transitional zone and the Basin and Range province of Arizona (figs. 1*A*, 8). This cluster of tracts has zero potential. Outcrops of Precambrian, Mesozoic, and Tertiary granite are widely distributed throughout cluster 12. Some sedimentary rocks are present in the southeast part of cluster 12, but they have been pervasively intruded by Mesozoic and Tertiary granites. Commercial hydrocarbons could be found in cluster 12 only if the extensive crystalline rocks at the surface were allochthonous. Such a notion is unlikely in view of the granitic and gneissic rocks encountered by the recent 18,013-foot Phillips Arizona State No. A–1 drilled near Tucson (Reif and Robinson, 1981) (fig. 1*C*).

SUMMARY

Of the 6,183,665 acres of Wilderness Lands in Arizona the potential acreage can be summarized as follows: high potential, none; medium potential, 192 thousand acres; low potential, 1,375.3 thousand acres; low to zero potential, 3,528.8 thousand acres; and zero potential, 1,087.8 thousand acres. The petroleum potential by acreage of all Wilderness Land categories in the Western United States is shown in this circular by B. M. Miller in table 1, chapter P.

REFERENCES CITED

Allen, W. E., 1978, Navajo Springs and Pinta Dome, *in* Fassett, J. E., ed., Oil and gas fields of the Four Corners area, Four Corners Geological Society, p. 80–89.

Bahr, C. W., 1963, Virgin oil field, Washington County, Utah, *in* Intermountain Association of Petroleum Geologists Guidebook to the geology of southwestern Utah: Salt Lake City, Utah Geological and Mineralogical Survey, p. 169–171.

Barwin, J. R., King, R. W., and Hassenfratz, C. A., 1971, Future oil and gas potential of northeast Arizona, *in* Cram, I. A., ed., Future petroleum provinces of the United States—their geology and potential, American Association of Petroleum Geologists Memoir 15, v. 1, p 449–469.

Bilodeau, W. L., 1978, The Glance conglomerate, a Lower Cretaceous syntectonic deposit in southeastern Arizona, *in* New Mexico Geological Society Guidebook, 29th Field Conference, Land of Cochise, p. 209–214.

——1982, Tectonic models for Early Cretaceous rifting in southeastern Arizona: Geology, v. 10, no. 9, p. 466–470.

Brown, S. C., and Lauth, R. E., 1957, Oil and gas potentialities of northern Arizona: Geology of southwestern San Juan basin, 2nd Field Conference, Four Corners Geological Society Guidebook, p. 77–84.

Coney, P. J., 1978, The plate tectonic setting of southeastern Arizona, *in* New Mexico Geological Society Guidebook, 29th Field Conference, Land of Cochise, p. 285–290.

Damon, P. E., and Bikerman, Michael, 1964, Potassium-argon dating of post-Laramide plutonic and volcanic rocks within the Basin and Range province of southeastern Arizona and adjacent areas: Arizona Geological Society Digest, v. 7, p. 63–78.

Damon, P. E., and Mauger, R. L., 1966, Epeirogeny and orogeny viewed from the Basin and the Range province: Society of Mining Engineers AIME Transactions, v. 235, p. 99–112.

Danie, T. C., 1978, Dineh-bi-Keyah, *in* Fassett, J. E., ed., Oil and gas fields of the Four Corners area, Four Corners Geological Society, p. 73–76.

Davis, G. H., 1978, Monocline fold pattern of the Colorado Plateau, *in* Matthews, Vincent III, ed., Laramide folding associated with basement block faulting in the western United States, Geological Society of America Memoir 151, p. 215–233.

——1979, Laramide folding and faulting in southeastern Arizona: American Journal of Science, v. 279, no. 5, p. 543–569.

Davis, G. H., and Coney, P. J., 1979, Geologic development of the Cordilleran metamorphic core complexes: Geology, v. 7, no. 3, p. 120–124.

Dickinson, W. R., 1981, Plate tectonic evolution of the southern Cordillera, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. XIV, p. 113–135.

Dolton, G. L., Carlson, K. H., Charpentier, R. R., Coury, A. B., Crovelli, R. A., Frezon, S. E., Khan, A. S., Lister, J. H., McMullin, R. H., Pike, R. S., Powers, R. B., Scott, E. W., and Varnes, K. L., 1981, Estimates of undiscovered recoverable conventional resources of oil and gas in the United States: U.S. Geological Survey Circular 860, 87 p.

Drewes, Harald, 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, no. 5, p. 641–657.

——1980, Tectonic map of southeast Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1109.

——1981, Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 100 p.

Eaton, G. P., Peterson, D. L., and Schumann, H. H., 1972, Geophysical, geohydrological, and geochemical reconnaissance of the Luke salt body, central Arizona: U.S. Geological Survey Professional Paper 753, 28 p.

Eberly, L. D., and Stanley, T. B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, no. 6, p. 921–940.

Elston, W. E., 1976, Tectonic significance of mid-Tertiary volcanism in the Basin and Range province: a critical review with special reference to New Mexico, *in* Elston, W. E., and Northrop, S. A., eds., Cenozoic volcanism in southwestern New Mexico: New Mexico Geological Society Special Publication 5, p. 93–102.

Elston, W. E., Rhodes, R. C., Coney, P. J., and Deal, E. G., 1976, Progress report on the Mogollon Plateau volcanic field southwestern New Mexico, No. 3—surface expression of a pluton, *in* Elston, W. E. and Northrop, S. A., eds., Cenozoic volcanism in southwestern New Mexico: New Mexico Geological Society Special Publication 5, p. 3–28.

Fassett, J. E., ed., 1978, Oil and gas fields of the Four Corners area: Four Corners Geological Society, 727 p.

Fenneman, N. M., 1931, Physiography of western United States: McGraw-Hill Book Company, Inc., New York and London, 534 p.

Giardina, Salvatore, Jr., 1979, Geologic review of northwestern Arizona for petroleum exploration investigations: Arizona Oil and Gas Conservation Commission Publication 4, 72 p.

Greenwood, Eugene, Kottlowski, F. E., and Thompson, Sam III, 1977, Petroleum potential and stratigraphy of Pedregosa basin: comparison with Permian and Orogrande basins: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1448–1469.

Hamilton, Warren, 1978, Mesozoic tectonics of the western United States, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States, Pacific Coast Paleogeography Symposium 2, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 33–70.

Hansen, A. R., Moulton, Floyd, and Owing, B. F., 1980, Utah-Arizona overthrust-hingeline belt: Oil and Gas Journal, v. 78, no. 47, p. 188, 191–192, 195–196, 198–199.

Hayes, P. T., 1970, Cretaceous paleogeography of southeastern Arizona and adjacent areas: U.S. Geological Survey Professional Paper 658–B, 41 p.

Heylmun, E. B., 1978, Southeastern Arizona: Oil and gas possibilities: Oil and Gas Journal, v. 76, no. 28, p. 176–177.

——1979, The Sonoita basin of Arizona: Oil and Gas Journal, v. 77, no. 20, p. 180–182.

——1981, Geology of promising Holbrook basin: Oil and Gas Journal, v. 79, no. 1, p. 117–118, 123.

Keith, S. B., 1979, The great southwestern Arizona overthrust oil and gas play: Fieldnotes from the State of Arizona, Arizona Bureau of Geology and Mineral Technology, v. 9, no. 1, p. 10–14.

Kelley, V. C., 1955, Monoclines of the Colorado Plateau: Geological Society of America Bulletin, v. 66, p. 789–804.

Knight, R. L., and Cooper, J. C., 1955, Suggested changes in Devonian terminology of the Four Corners area, *in* Four Corners Geological Society Guidebook, 1st Field Conference, p. 56–58.

Kottlowski, F. E., 1971, Petroleum potential of southwest New Mexico and south Arizona, *in* Cram, I. A., ed., Future petroleum provinces of the United States—their geology and potential, American Assocation of Petroleum Geologists Memoir 15, v. 1, p. 431–448.

Lessentine, R. H., 1965, Kaiparowits and Black Mesa basins: stratigraphic synthesis: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1997–2019.

Lucchitta, Ivo, 1974, Structural evolution of northwest Arizona and its relation to adjacent Basin and Range province structures, *in* Karlstrom, T. N. V. and others, eds., Geology of Northern Arizona, part 1—regional studies: Flagstaff, Northern Arizona University Bookstore, p. 336–354.

——1978, The central Arizona transition zone: a Precambrian plate boundary? (abs): Geological Society of America abstracts with programs, v. 10, no. 3, p. 114.

Matthews, Vincent III, 1982, Just the opposite?, *in* Letters to editor: Oil and Gas Journal, v. 80, no. 21, p. 12.

Mattick, R. E., Olmsted, F. H., and Zohdy, A. A. R., 1973, Geophysical studies in the Yuma area, Arizona and California: U.S. Geological Survey Professional Paper 726–D, 36 p.

McKenny, J. W., and Masters, J. A., 1968, Dineh-bi-Keyah field, Arizona: American Association of Petroleum Geologists Bulletin, v. 52, no. 10, p. 2045–2057.

Molenaar, C. M., 1972, Petroleum and natural gas, The Paradox basin, *in* Geologic Atlas of the Rocky Mountain Region, Rocky Mountain Association of Geologists, Denver, Colorado, p. 282–284.

——1983, Major depositional cycles and regional correlations of Upper Cretaceous rocks, southern Colorado Plateau and adjacent areas, *in* Reynolds, M. W., and Dolly, E. D., eds., Mesozoic paleogeography of the west-central United States; Rocky Mountain Paleogeography Symposium 2, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 201–224.

Moore, R. T., 1972, Geology of the Virgin and Beaverdam Mountains, Arizona: Arizona Bureau of Geology and Mineral Technology Bulletin 186, 65 p.

Oppenheimer, J. M., and Sumner, J. S., 1981, Gravity modeling of the Basin and Range province, Arizona: Arizona Geological Society Digest, v. XIII, p. 111–115.

O'Sullivan, R. B., Repenning, C. A., Beaumont, E. C., and Page, H. G., 1972, Stratigraphy of the Cretaceous rocks and the Tertiary Ojo Alamo sandstone, Navajo and Hopi Indian reservations Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521–E, 69 p.

Parker, J. W., and Roberts, J. W., 1963, Devonian and Mississippian stratigraphy of the central part of the Colorado Plateau, *in* Bass, R. O., ed., Shelf carbonates of the Paradox basin, Four Corners Geological Society Symposium, p. 31–60.

Peirce, H. W., 1974, Thick evaporites in the Basin and Range province, Arizona: Northern Ohio Geological Society Symposium on Salt, 4th, v. 1, p. 47–55.

———1976, Elements of Paleozoic tectonics in Arizona: Arizona Geological Society Digest, v. X, p. 37–57.

Peirce, H. W., Keith, S. B., and Wilt, J. C., 1970, Coal, oil, natural gas, helium, and uranium in Arizona: Arizona Bureau of Geology and Mineral Technology Bulletin 182, 289 p.

Peterson, J. A., and Ohlen, H. P., 1963, Pennsylvanian shelf carbonates, Paradox basin, *in* Bass, R. O., ed., Shelf carbonates of the Paradox basin, Four Corners Geological Society Symposium, p. 65–79.

Reif, D. M., and Robinson, J. P., 1981, Geophysical, geochemical, and petrographic data and regional correlation from the Arizona State A–1 well, Pinal County, Arizona: Arizona Geological Society Digest, v. XIII, p. 99–109.

Repenning, C. A., and Page, H. G., 1956, Late Cretaceous stratigraphy of Black Mesa, Navajo and Hopi Indian reservations, Arizona: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 255–294.

Ross, C. A., 1973, Pennsylvanian and Early Permian depositional history, southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 57, no. 5, p. 887–912.

Scarborough, R. B., and Peirce, H. W., 1978, Late Cenozoic basins of Arizona, *in* New Mexico Geological Society Guidebook, 29th Field Conference, Land of Cochise, p. 253–259.

Scurlock, J. R., 1971, Geologic structure map of northern Arizona: Arizona Oil and Gas Conservation Commission.

Shoemaker, E. M., Squires, R. L., and Abrams, M. J., 1978, Bright Angel and Mesa Butte fault systems of northern Arizona, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 341–368.

Silver, L. T., and Anderson, T. H., 1974, Possible left-lateral early to middle Mesozoic disruption of the southwestern North American craton margin (abs.): Geological Society of America abstracts with programs, v. 6, no. 7, p. 955–956.

Spencer, C. W., 1978, Tohache Wash Area, *in* Fassett, J. E., ed., Oil and gas fields of the Four Corners area, Four Corners Geological Society, p. 92–93.

Stewart, J. H., Poole, F. G., and Wilson, R. F., 1972, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 691, 195 p.

Teichert, Curt, 1965, Devonian rocks and paleogeography of central Arizona: U.S. Geological Survey Professional Paper 464, 181 p.

Thompson, Sam III, 1980, Pedregosa basin's main exploration target is Pennsylvanian dolostone: Oil and Gas Journal, v. 78, no. 42, p. 202, 207, 210, 215.

Thompson, Sam III, Tovar R., J. C., and Conley, J. N., 1978, Oil and gas exploration wells in the Pedregosa basin, *in* New Mexico Geological Society Guidebook, 29th Field Conference, Land of Cochise, p. 331–342.

Wilson, E. D., and Moore, R. T., 1959, Structure of Basin and Range province in Arizona, *in* Heindl, L. A., ed., Southern Arizona Guidebook II for 55th Annual Geological Society of America Cordilleran Section Meeting, Arizona Geological Society, p. 89–105.

Wilson, E. D., Moore, R. T., and Cooper, J. R., 1969, Geologic map of Arizona: Arizona Bureau of Mines and U.S. Geological Survey, scale 1:500,000.