UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology and petroleum resources, Paradox basin Province

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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GEOLOGY AND PETROLEUM RESOURCES, PARADOX BASIN PROVINCE

By J.A. Peterson

INTRODUCTION

The Paradox basin province assessment area is located in southeastern and south-central Utah and southwestern Colorado (figs. 1,2). The area encompasses all or parts of several major Laramide structural provinces of the central and western Colorado Plateau, including: 1) the Paradox basin proper, except for the portions extending into northwestern Mexico and northeastern Arizona; 2) the Uncompahgre and San Juan uplifts; 3) the San Rafael, Circle Cliffs and Monument uplifts; 4) the Kaiparowits and Henry Mountains basins; and 5) the Wasatch and Paunsaugunt Plateaus, which occupy the western margins of the province. The area covers approximately 35,000 mi^2 (90,000 km^2).

HISTORY

The Four Corners area (Utah, Colorado, Arizona and New Mexico) of the southwestern U.S. has undergone sporadic petroleum exploration activity since the early 1900's. The initial play was in the Paradox basin, where the first oil (1908) was found at shallow depths in fractured clastic rocks at the Mexican Hat oil field near the San Juan River on the Monument upwarp (fig. 4). In the early 1900's, gas was discovered in Cretaceous sandstone reservoirs in the San Juan basin of northwestern New Mexico (Matheny, 1978). This discovery later developed into the basinwide Blanco/Ignacio-Blanco and other gas fields of the San Juan basin (fig. 1). Between 1920 and 1940, sporadic drilling occurred in the adjoining Paradox basin, but except for minor oil and gas production (1929) from Pennsylvanian reservoirs in northwestern New Mexico, little success resulted. Interest in the potential of Pennsylvanian rocks was stimulated by the 1945 discovery of large volumes of gas in carbonate reservoirs of the Paradox Formation at Barker Creek dome in northwestern New Mexico near the Colorado border. With subsequent oil and gas discoveries at Boundary Butte in Utah (1948), the search for Pennsylvanian petroleum traps took on broader proportions.

Most of the earlier discoveries had been based on exploration of surface structures, but in the early 1950's the search moved farther out into the Paradox basin where more sophisticated geophysical work was required. Most of this activity was on Navajo Indian tribal lands. Several major oil companies initiated an extensive seismic program, which delineated several subsurface structural closures in southeastern Utah. Two of the better structures, Bluff and Desert Creek, were drilled by Shell Oil Co. in 1953 (fig. 5). Although economic failures, both of these initial wells encountered encouraging oil shows and porosity in carbonate rocks above the salt section in what later came to be known as the Desert Creek and Ismay (Bluff) zones. A second well was drilled downflank on each of these structures in 1954. The downflank wells encountered improved reservoir rocks, resulting in a discovery at Desert Creek, the first in the Aneth area, and a marginal discovery at Bluff. These successes, although small, motivated a large sealed-bid sale of Navajo Indian lands. Participating in the sale were several major companies, including Shell, Texaco, Superior, Carter, Phillips, and others. The Texaco C-1 Navajo

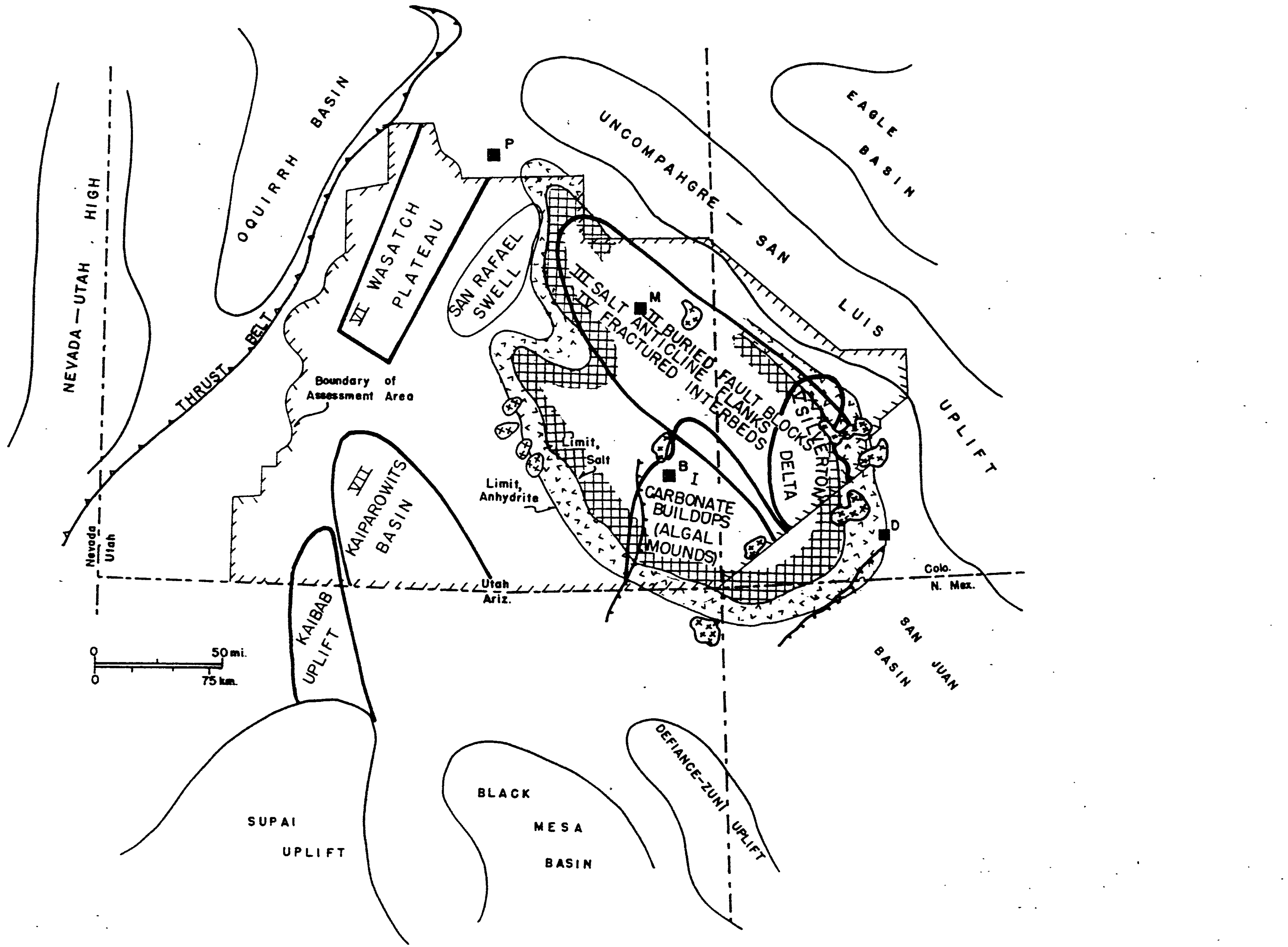


Figure 1.--Index map, Paradox basin province, showing assessment boundary and main plays I through VII.

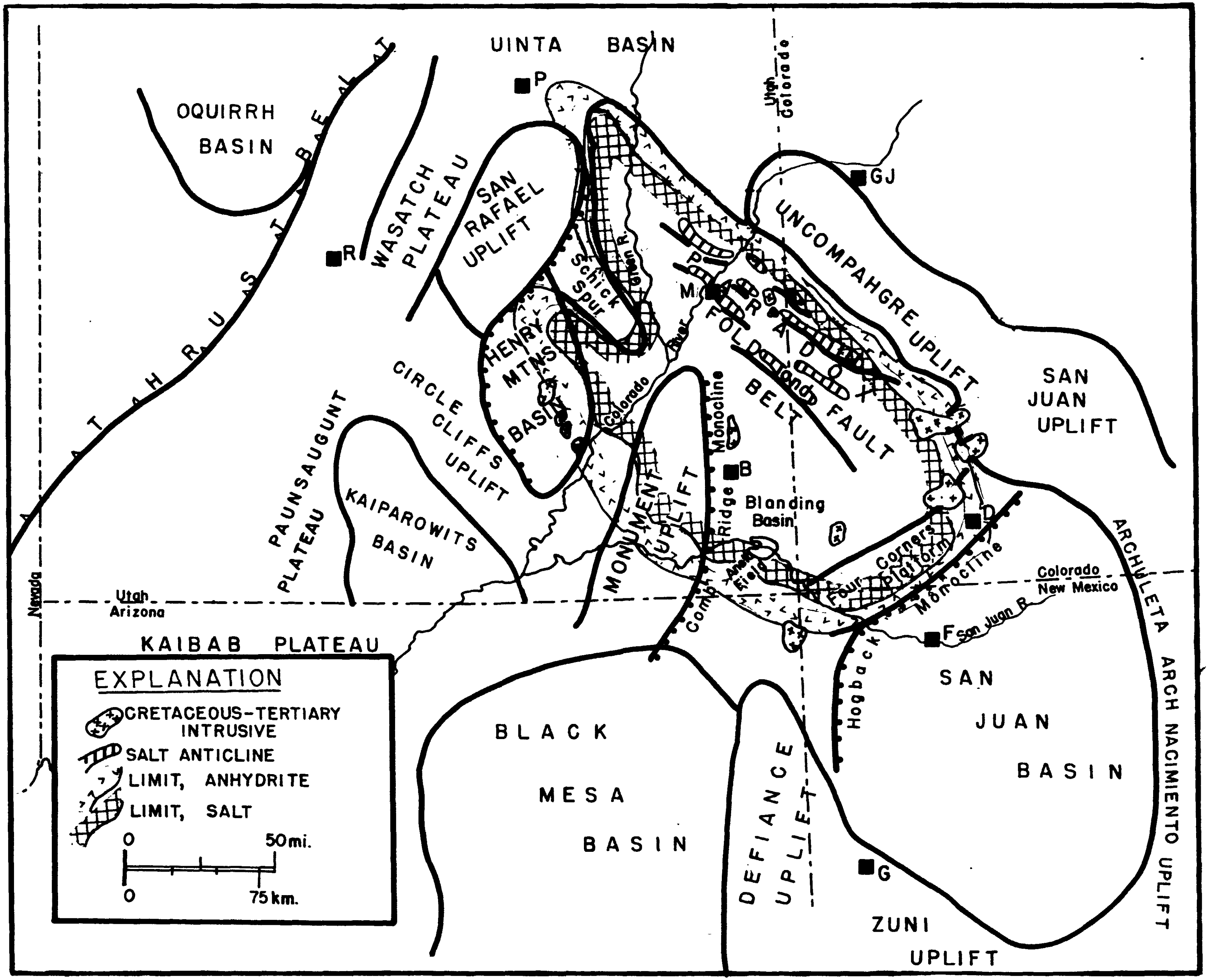


Figure 2.--Major structural features, Paradox basin region, showing location of Aneth Oil Field. Cities shown: UTAH: P-Price; M-Moab; R-Richfield; B-Blanding. COLORADO: GJ-Grand Junction; D-Durango. NEW MEXICO: F-Farmington; G-Gallup

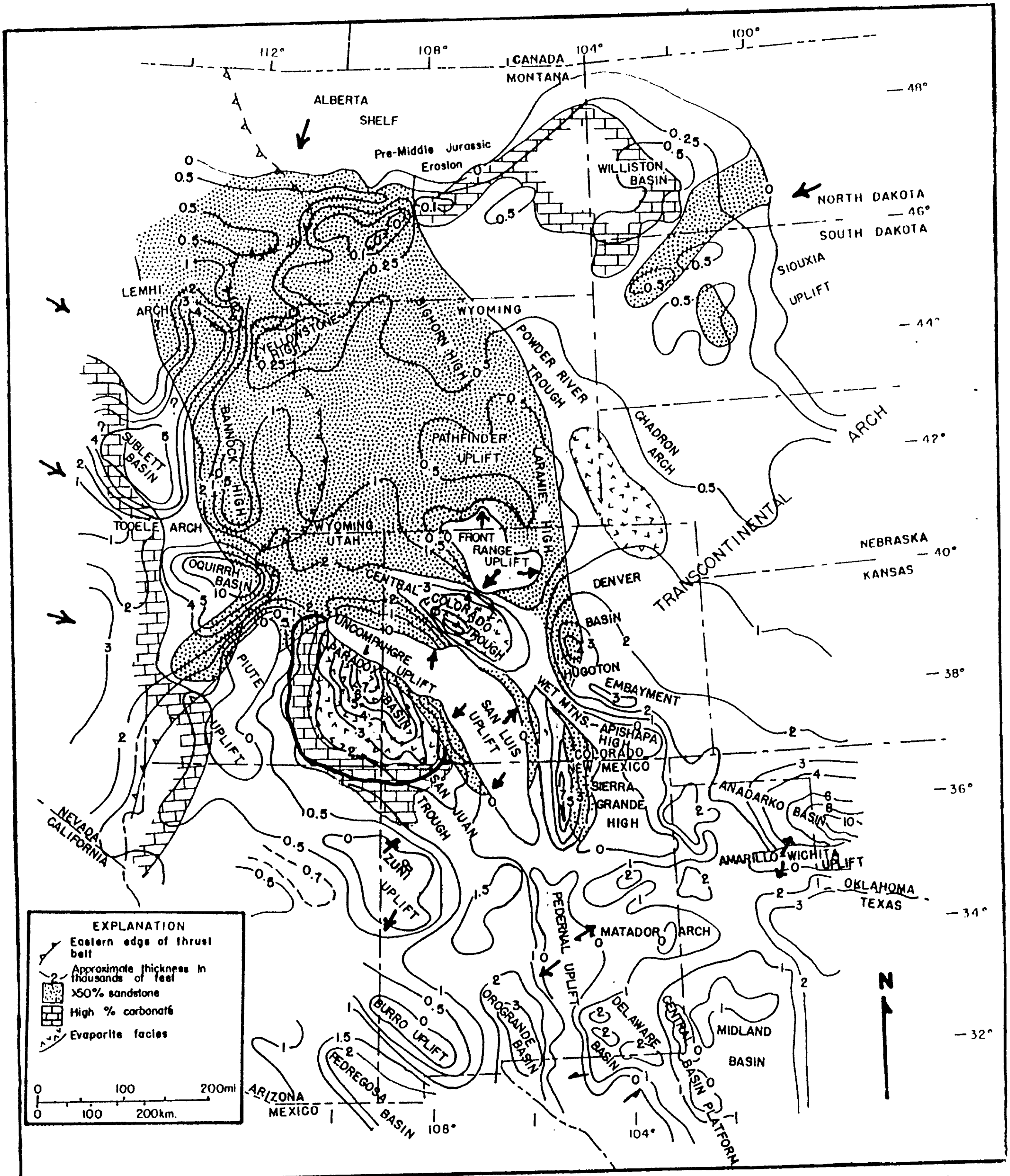


Figure 3.--Pennsylvanian System, Rocky Mountain area, showing approximate thickness, general sedimentary facies and main paleotectonic elements. Arrows indicate probable transport directions of terrigenous clastic sediments. Paradox evaporite basin shown by heavy line. Modified after Peterson and Smith (1986).

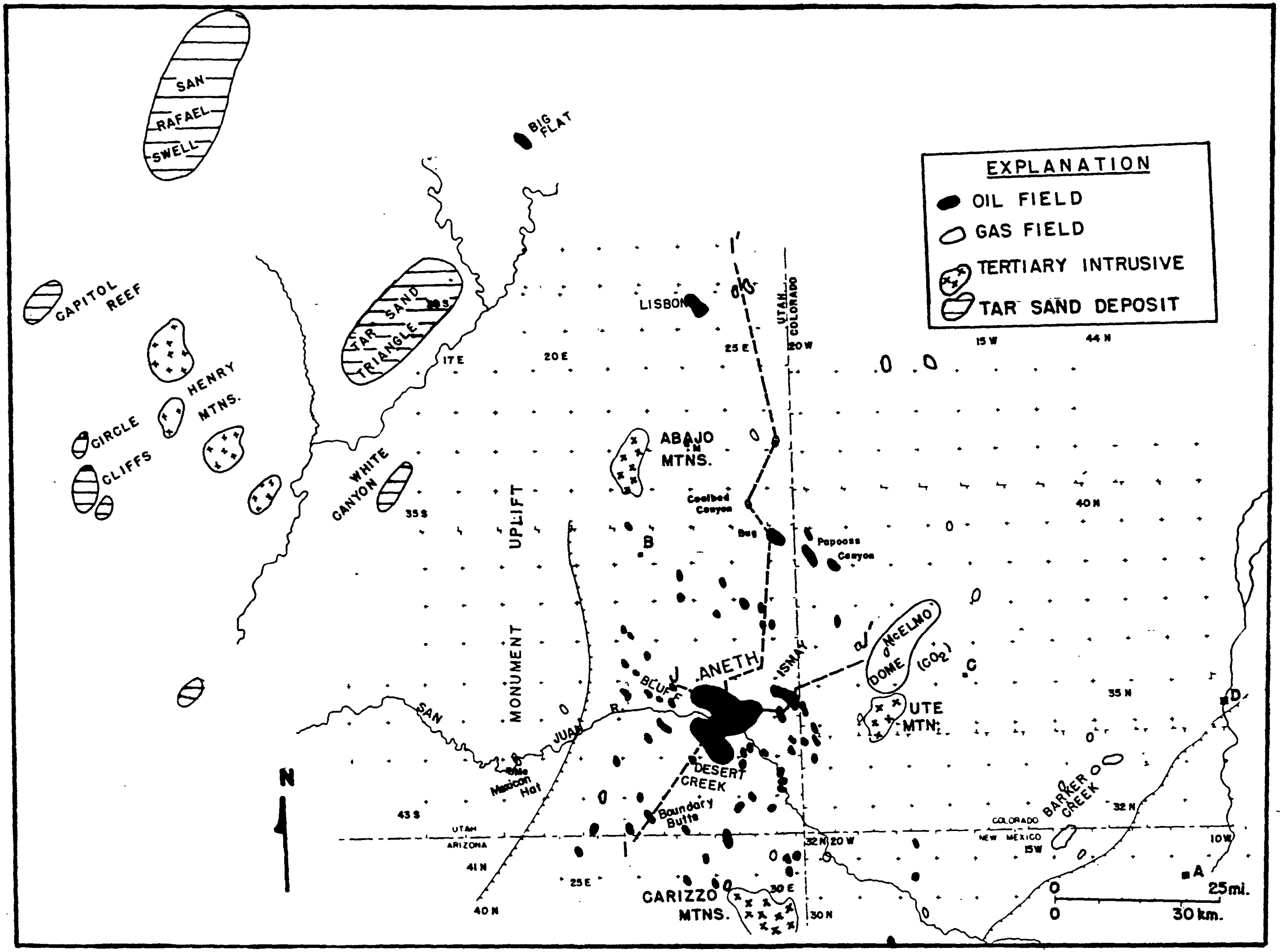


Figure 4.--Oil and gas fields, Four Corners area. Lines of cross-sections I-I' and J-J' of figures 34 and 35 are shown. Almost all producing fields are from Pennsylvanian carbonate reservoirs. Main areas of tar sands in Permian sandstone reservoirs are also shown.

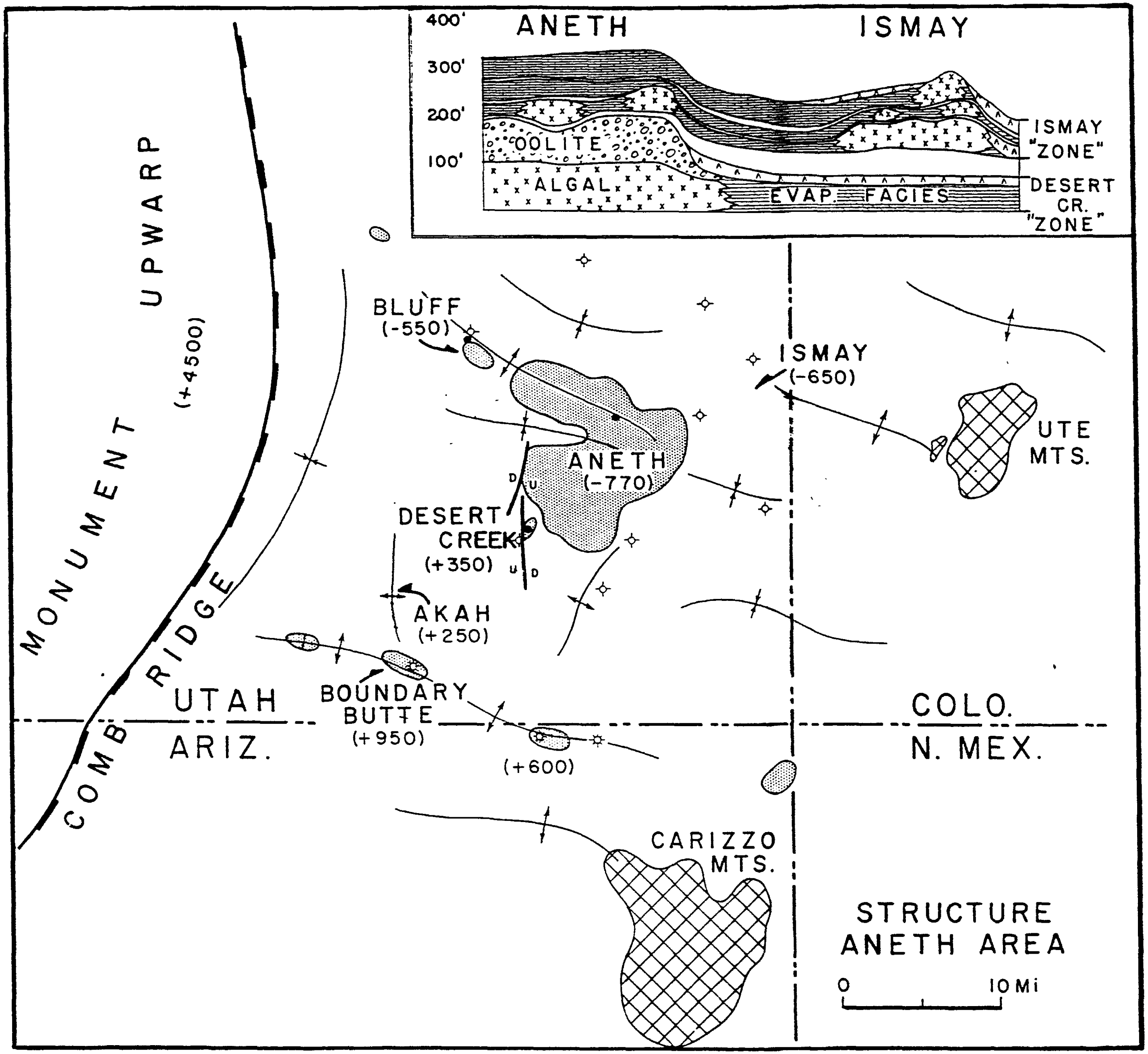


Figure 5.--Generalized map showing structural features and location of Aneth Oil Field and deep wells drilled prior to Aneth discovery. Structure is top of Desert Creek zone in ft above or below sea level. Modified after Peterson (1966b).

Aneth discovery was completed in carbonate reservoirs of the Pennsylvanian Hermosa Formation at 5828-5879 ft (1,780-1800 m) in February 1956, flowing 1,700 BOPD (barrels of oil per day). Three subsequent discoveries, the Shell No. 1 North Desert Creek (September 1956 - Ratherford Unit), Texaco No. 1 Navajo C (January, 1957 - McElmo Creek Unit), and Davis Oil No. 1 Navajo A (February, 1957 - White Mesa Unit) all proved to be in the massive carbonate buildup that makes up the greater Aneth field. The Davis discovery was drilled on a farmout from Carter Oil Co., whose White Mesa No. 1 well in 1955 was on a structural closure just a short distance southeast of the edge of the main Aneth buildup.

Early exploration drilling in the southern Paradox basin was based on identification of seismic structures on mappable horizons near the top of the Paradox Formation. Stratigraphic isolation of the Aneth mound complex and other carbonate buildups was a major factor in the disappointing early exploration efforts in the basin. Prior to the Aneth discovery, nine abandoned exploratory wells, in addition to the discovery wells of four nearby marginally-commercial fields, had been drilled on seismic highs (fig. 5). The giant Aneth field was literally surrounded by these exploratory failures before drilling of the discovery well. The discovery was located at a relatively low structural position on the axis of the Bluff-Aneth subsurface structural nose. It was drilled as a joint venture by two major companies in order to evaluate expiring leases on Navajo Indian lands. The discovery was made only after most of the more significant structural closures of the area had been drilled with relatively minor success.

Petroleum exploration in the northern part of the Paradox basin dates from 1891, when the first exploratory well in Utah was drilled near the town of Green River (Hansen, 1956). Sporadic drilling continued for some time in this area, and by the early 1960's most of the significant structures had been tested, resulting in discovery of several small oil and gas fields from Cretaceous and Jurassic reservoirs a short distance north of the assessment boundary. Interest in Pennsylvanian and Mississippian possibilities was accompanied by drilling of salt structures west of Moab during the 1950's. Oil and gas shows were encountered in several wells, but only one marginal discovery was made at the Big Flat field. In 1959, the Pure Oil Co. discovery of oil in Mississippian carbonate reservoirs at the Lisbon field on the southwest flank of the Lisbon salt anticline resulted in a major exploration effort for pre-salt structural traps. Several small oil and gas accumulations in Mississippian and Devonian reservoirs were found at this time.

Gas was discovered in 1951 in Upper Cretaceous sandstone reservoirs at the Clear Creek field on the Wasatch Plateau (Walton, 1968). This discovery was followed by the drilling of several structural closures in the area during the 1950's, most of which were non-productive or marginally commercial.

Exploration in the Kaiparowits basin area began in 1921 with drilling of the Ohio Co. Circle Cliffs No. 1 Precambrian test of the Circle Cliffs anticline on the eastern margin of the Kaiparowits basin. In 1948, oil staining and non-commercial production of oil from Mississippian carbonate reservoirs were obtained in the Last Chance area about 50 mi. north of the Circle Cliffs well. At about the same time, non-commercial oil production was obtained from Permian and Mississippian carbonate reservoirs at the John's

Valley and Upper Valley areas of the Kaiparowits basin, approximately 50 mi west of Circle Cliffs (Campbell, 1969; Goolsby and others, 1988). During the 1960's and 1970's, several deep tests were drilled in the Kaiparowits basin without success.

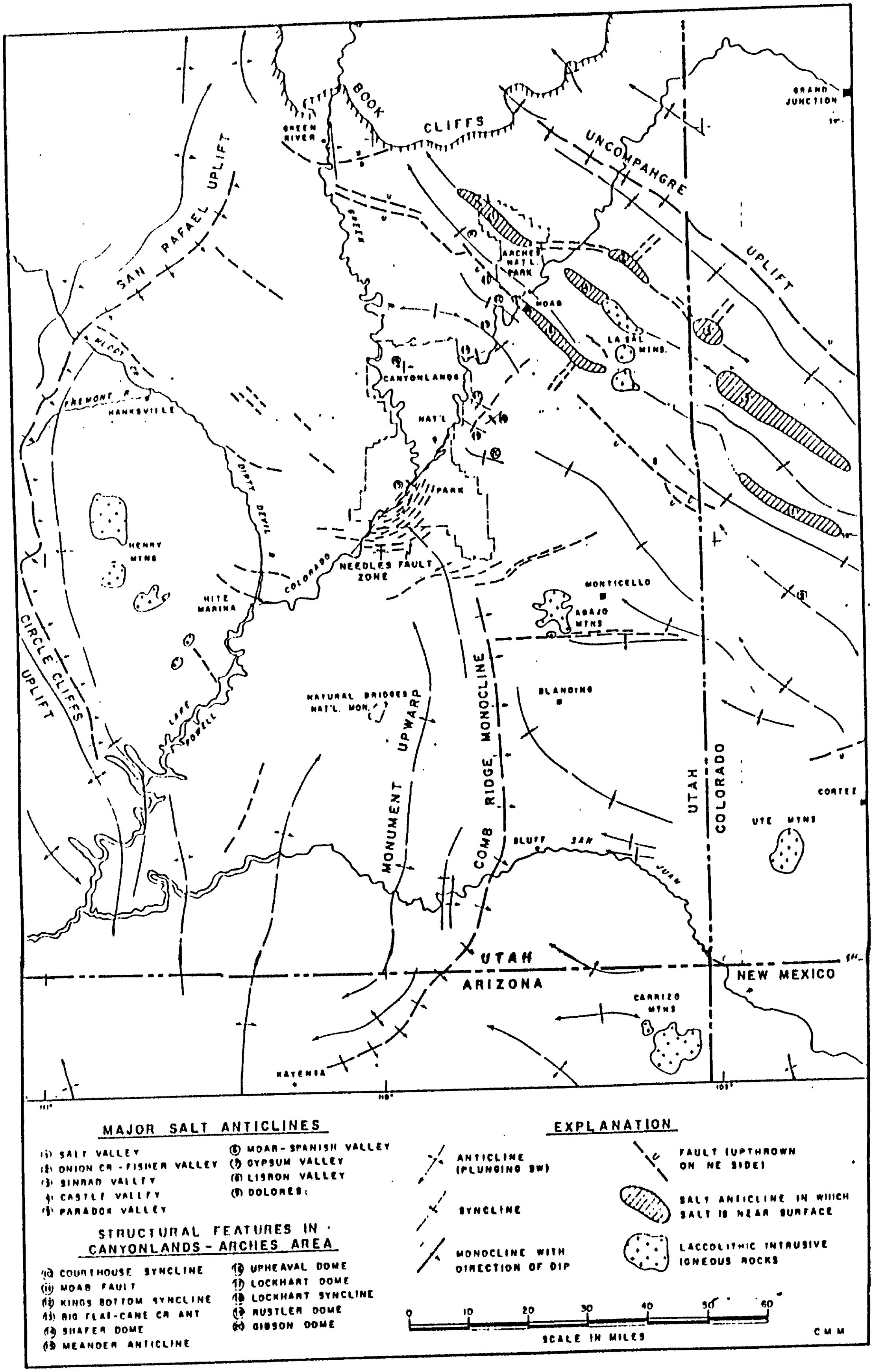
STRUCTURE AND PALEOSTRUCTURE

Detailed reports on the structure of the Paradox basin and adjacent areas are published by several authors, including Gregory (1951), Hunt and others (1953), Kelley (1955), Shoemaker and others (1958), Jones (1959), Elston and Shoemaker (1960), Fetzner (1960), Joesting and Case (1960), Szabo and Wengerd (1975), Witkind (1975), Gorham (1975), Stone (1977), Suguira and Kitchco (1981), White and Jacobson (1983), Frahme and Vaughan (1983), Chapin and Cather (1983), Kluth (1986), and Stevenson and Baars (1986).

The Paradox basin province is within the central and western part of the Colorado Plateau physiographic province. The Paradox basin proper, located in the eastern part of the physiographic province, is bounded on the south by the Four Corners platform and the Defiance uplift, on the west by the Monument and San Rafael uplifts, on the north by the juncture of the north plunge of the San Rafael uplift and the northwest extension of the Uncompahgre uplift, and on the east by the Uncompahgre and San Luis uplifts (figs. 1, 6-10). All these major features underwent stages of tectonic growth as early as Pennsylvanian time, with probable minor earlier growth of some of the features. Evidence of basement faulting as old as Cambrian or late Precambrian has been documented (Baars and See, 1968).

The Pennsylvanian Paradox evaporite basin formed the northwestern part of an elongate, rifted, northwest-trending structural-sedimentary trough, which developed as part of the crustal disturbance that created the ancestral Rocky Mountains. Rapid subsidence and restricted marine circulation between the distal northwest part of the trough and the open marine accessway to the southeast, resulted in deposition of thick evaporites in the Paradox basin during Desmoinesian time (fig. 9). Complementary uplifts on the east side of the basin (Uncompahgre and San Luis) (figs. 1, 9-11) rose rapidly at this time and shed large volumes of clastic debris along their borders. The central, deeper basin areas, however, were essentially starved of significant clastic material during evaporite deposition.

Deformation of the Paradox basin area began in the Middle Pennsylvanian, associated with the development of the ancestral Rocky Mountains. Differential subsidence and probable rifting parallel to the rising Uncompahgre uplift affected the basin interior and influenced the thickness patterns of salt deposits in the central basin, as well as the thick arkosic deposits on the east side derived from the rapidly rising highland. Salt flowage, influenced by rejuvenation of pre-salt fault patterns, probably began in middle to late Desmoinesian time and culminated during Early Permian time (Cater, 1955; Cater and Elston, 1963; Elston and others, 1962) to form the prominent northwest-trending salt anticlines and pillows characteristic of the Paradox fold and fault belt (fig. 2).



Tectonic map of southeastern Utah and adjacent areas.

Figure 6.--Tectonic map of southeastern Utah and adjacent areas. From Molenaar and Baars, 1985

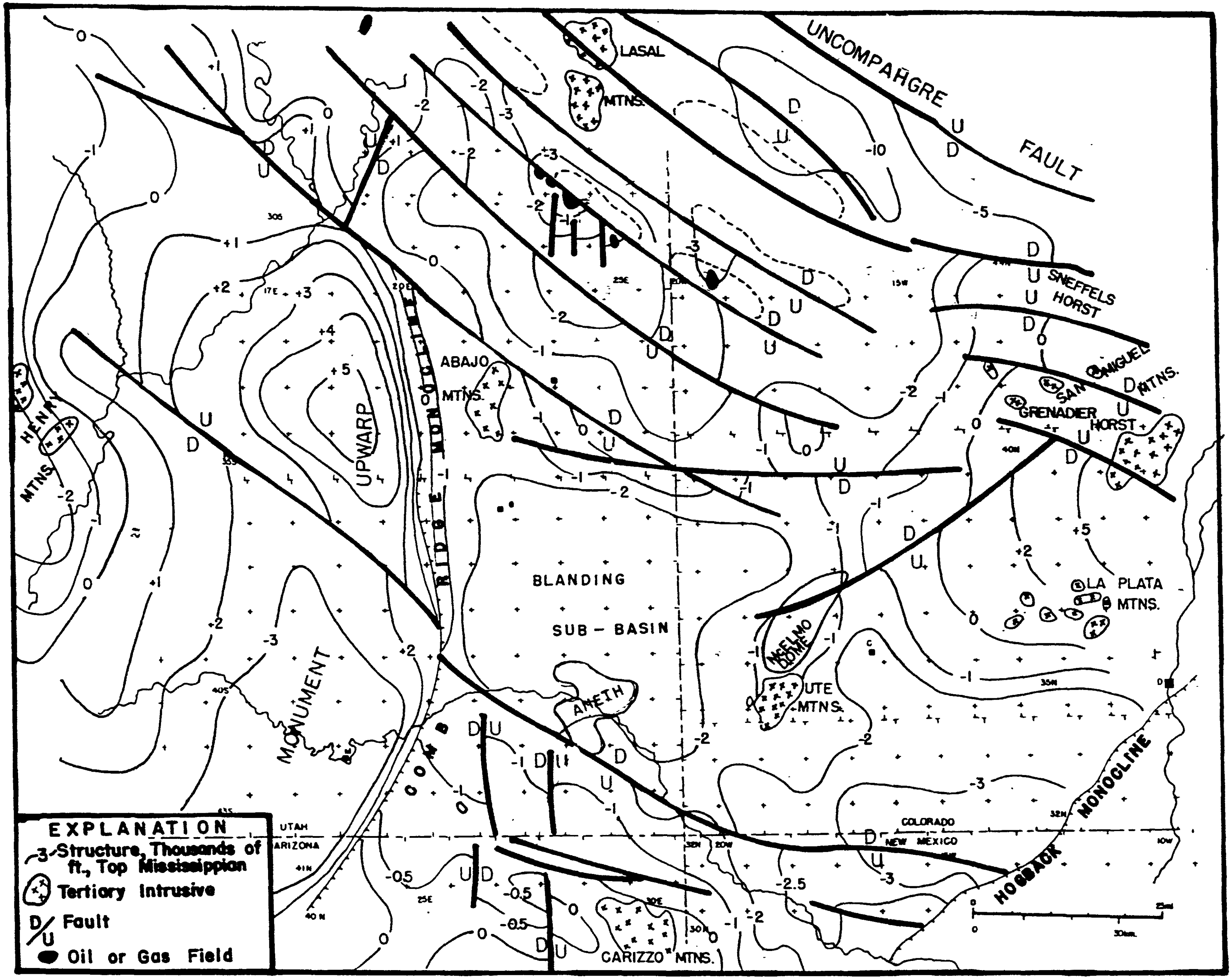


Figure 7.--Structure map, top of Mississippian Leadville Limestone. Modified after Szabo and Wengerd (1975). Oil or gas fields producing from Mississippian carbonate reservoirs are shown.

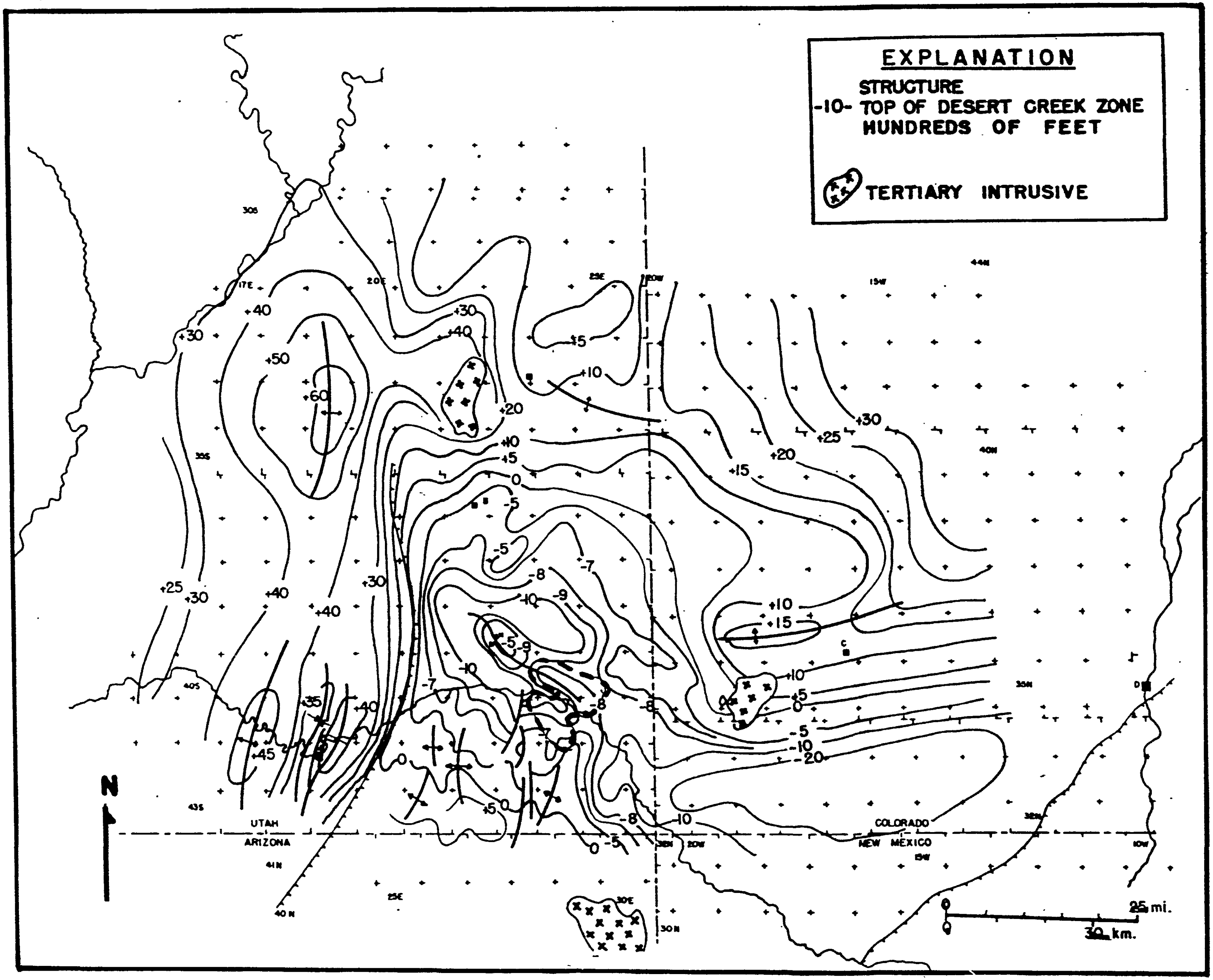


Figure 8.--Structure in hundreds of feet, top of Desert Creek zone. Outline of Aneth Field shown by heavy dashed line.

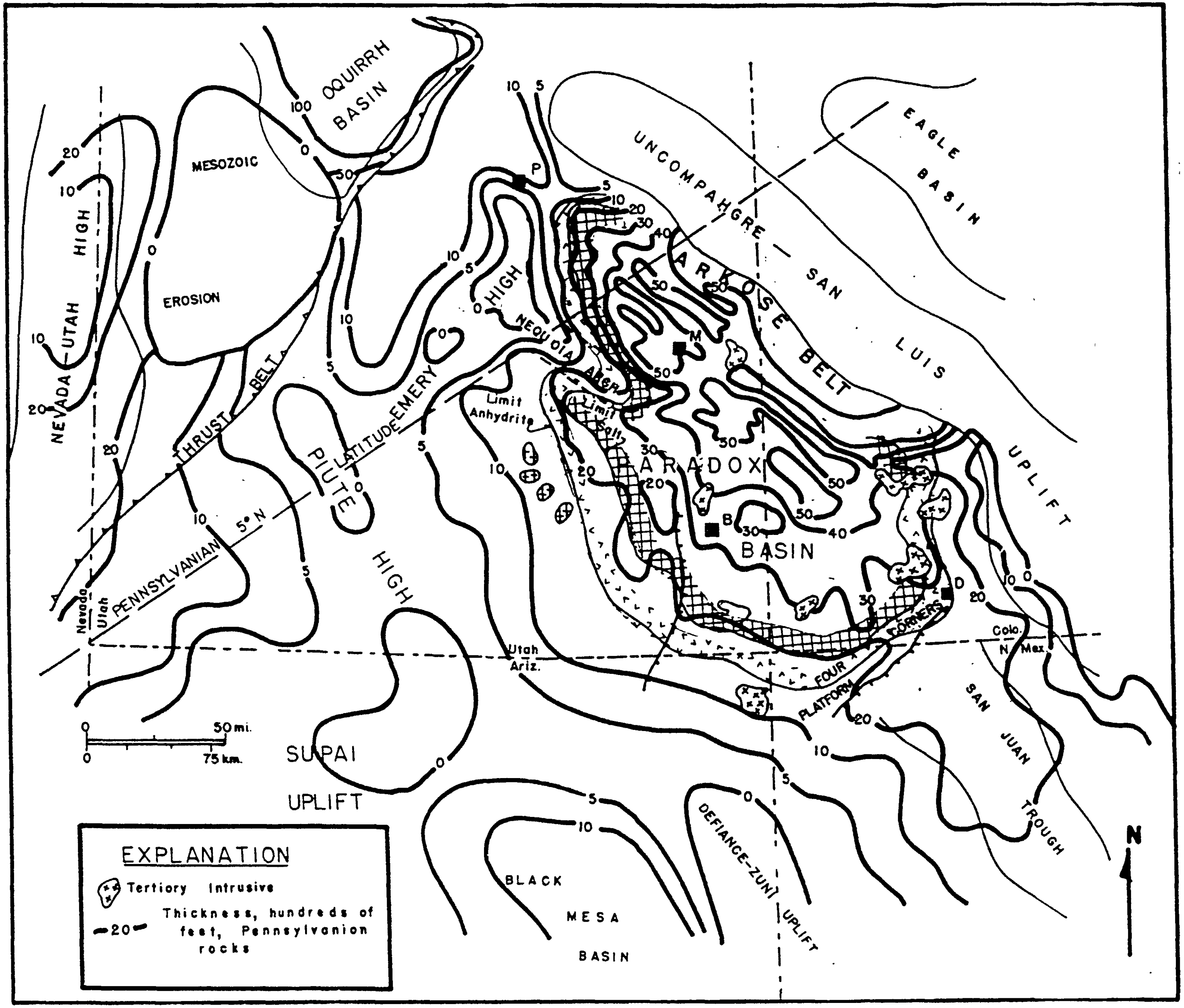


Figure 9.--Thickness map, Pennsylvanian System, Paradox basin region, showing edge of evaporites and main basins and uplifts of Pennsylvanian age. Arkose belt on east side of basin grades rapidly westward into salt and black, organic-rich shale facies. East edge of Mesozoic Sevier thrust belt, and position of Pennsylvanian 5° N latitude are shown.

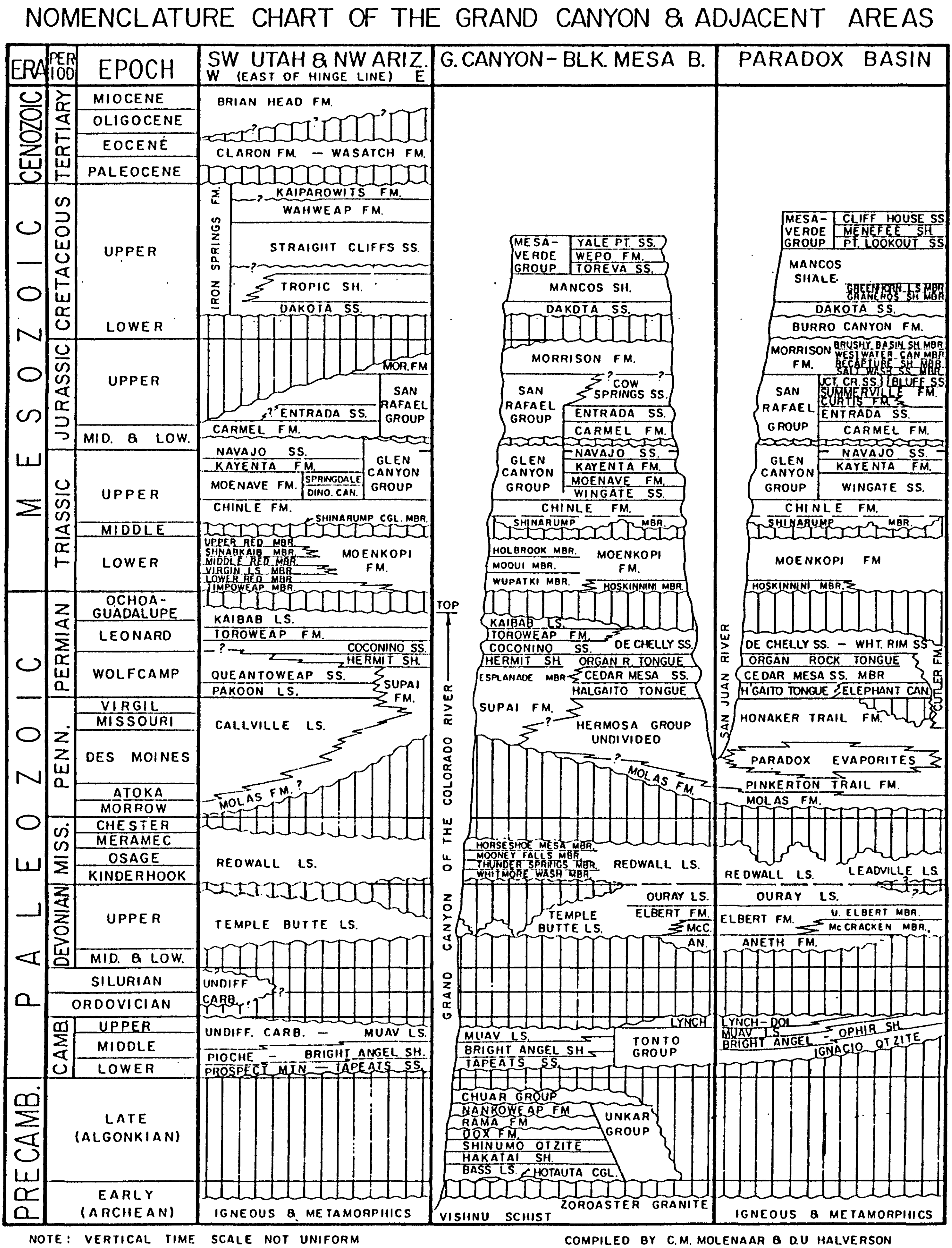


Figure 10.--Stratigraphic correlation chart, Four Corners area, northern Arizona, and Central Utah. From Molenaar and Halvorsen (1969).

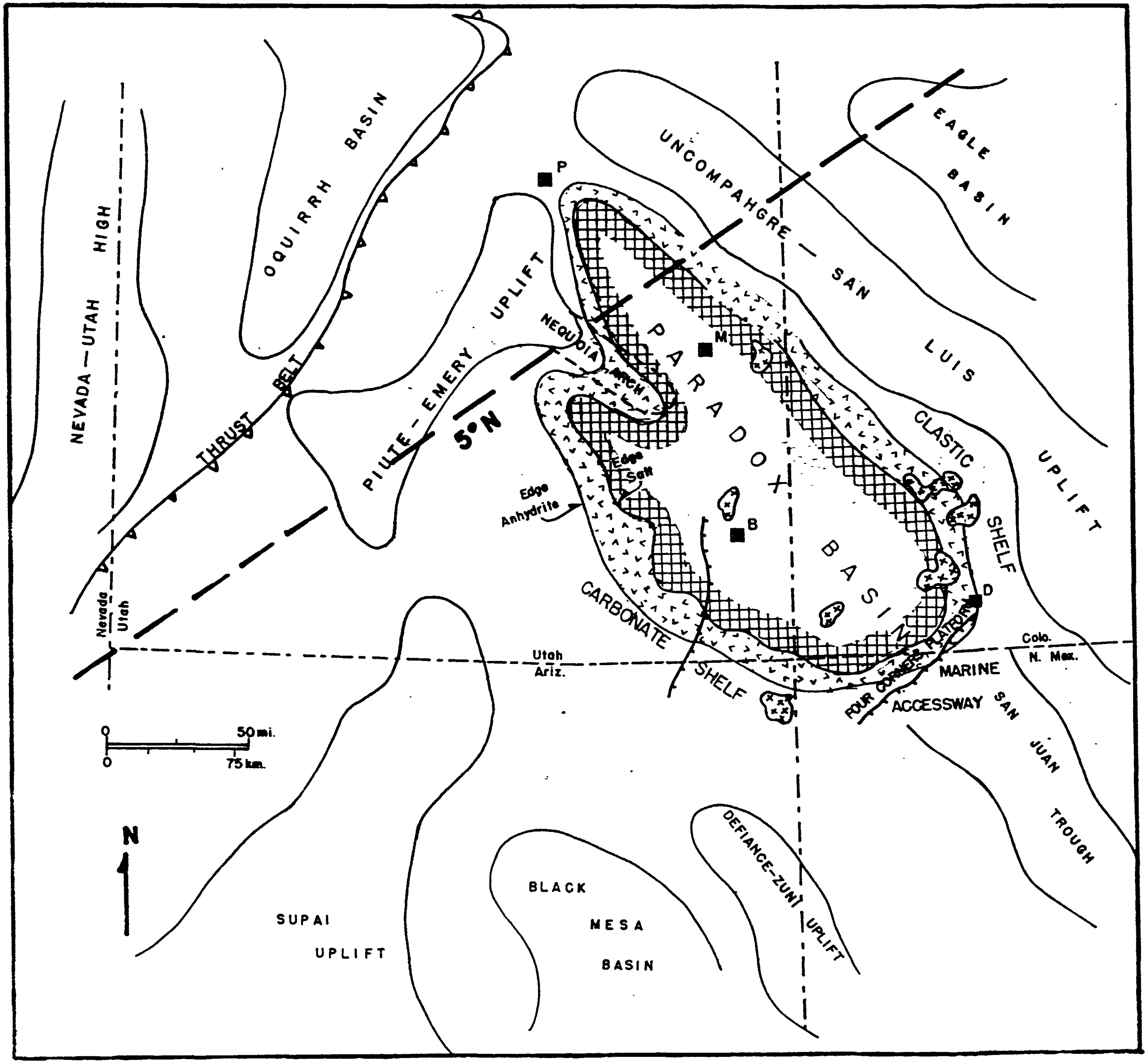


Figure 11.--Pennsylvanian paleotectonic features, Paradox basin and adjacent area.

By early or middle Mesozoic time, subsidence of the Paradox basin and accompanying rise of the Uncompahgre-San Luis highland diminished greatly when the region became part of the Mesozoic Rocky Mountain shelf. Much of the region became emergent and was relatively stable tectonically. During the latest Cretaceous and early to middle Tertiary, folding and faulting occurred, much of which tended to follow Paleozoic structural trends. Several igneous stocks or laccolith intrusions were emplaced at this time (fig. 2).

Kelley (1955) described three main tectonic elements of the present basin area (fig. 2): 1) the Paradox fold and fault belt, adjacent to the northwest-trending Uncompahgre uplift, dominated by northwest-trending folds and faults, many of which are associated with prominent piercement salt anticlines in the northeastern part of the belt. The southwestern part of the belt is more mildly deformed, but folds and faults generally maintain the northwesterly trend; some are associated with salt swells; 2) the Monument uplift, a north-south elongated regional fold bounded on the east by the steeply-dipping Comb Ridge monocline; and 3) the Blanding sub-basin, which occupies the southern part of the Paradox basin east of the Monument upwarp. Gentle folds within the Blanding sub-basin generally trend west to northwest. Several broad, open folds occupy the southern boundary of the basin.

The Four Corners platform on the southeastern margin of the Paradox basin is occupied by generally northeast-trending gentle folds and is bounded on the southeast by the steeply-dipping early Tertiary Hogback monocline.

Kelley (1955) interpreted the Paradox basin as a strong post-Mississippian sag, part of a broad belt of northwest-southeast tangential compression related to formation of the ancestral Rockies.

Szabo and Wengerd (1975) explained the Paradox basin as the result of a regional sag between the Zuni-Defiance uplift of New Mexico-Arizona and the Front Range uplift of Colorado, caused by withdrawal and lateral transfer of subcrustal material in a broad area of eastern Utah and western Colorado. Early in Pennsylvanian time, accelerated subsidence resulted in flexing and faulting in the fold and fault belt and mid-basin arching along the Uncompahgre uplift. These movements separated the initial broad basin into two half-basins, the Paradox and Eagle. Continued subsidence, basin expansion, rejuvenated flexing and faulting in a series of steps, along with radial folding, lasted through middle Desmoinesian time, when emergence and faulting of the Uncompahgre occurred. This activity shaped the final form of the Paradox basin.

Gorham (1975) and Baars (1976) interpreted the Paradox as part of an aulacogen system related to development of the ancestral Rockies. Later, Stevenson and Baars (1986) interpreted the Paradox as a complex "pull-apart" basin related to the intersection of conjugate lineaments of continental dimensions. Extensional tectonics related to growth of the ancestral Rocky Mountains in Pennsylvanian time caused rapid subsidence of the basin along rejuvenated basement structures, some of which may be as old as Proterozoic.

Kluth (1986) presented a plate tectonic model to explain the development of the ancestral Rocky Mountains and associated basins. The faults and foreland block uplifts characteristic of the ancestral Rocky Mountains resulted from transcurrent faulting, with accompanying wrenching and translation, along the North American craton margin during the collision of North America with South America-Africa in Pennsylvanian time during assembly of the supercontinent Pangea (fig. 12). The large fault-block mountains formed when the southwestern peninsular projection of the craton (Transcontinental arch and its extension) was pushed northward by the collision. In Early Pennsylvanian time, the collision began in the Ouachita Mountains region of southwestern Arkansas and Oklahoma and shifted westward with time. By the Middle Pennsylvanian, continental foreland deformation reached its greatest intensity resulting in growth of the ancestral Rocky Mountains and associated strongly downwarped basins. Positioning of the block uplifts and basins was probably governed in part by pre-existing zones of crustal weakness along the continental margin of the time. Deformation of the craton diminished during the Early Permian.

The Paradox is a hybrid basin, a type IIBa platform rift-sag followed by a type IIa foredeep and foreland basin, according to the Klemme basin classification (Klemme, 1980, personal communication, 1989; Halbouty and others, 1970). The concept of the "pull-apart" basin was applied by Burchfiel and Stewart (1966) to the Death Valley graben. Klemme (1980), however, applied the term to large, linear basins (Klemme type V) occupying the intermediate crustal zone between thick continental crust and thin oceanic crust along the major oceanic boundaries of spreading plates (divergent margins). The Klemme type II basin and Kluth's model appear to correspond well with the geology of the Paradox-Uncompahgre couple and its regional relationships.

STRATIGRAPHY AND SEDIMENTATION

Detailed reports on the stratigraphy of the Paradox basin and adjacent areas are published by several authors, including Wengerd and Strickland (1954), Wengerd (1955, 1958, 1962), Wengerd and Matheny (1958), Wengerd and Szabo (1968), Herman and Sharps (1956), Herman and Barkell (1957), Heylmun (1958), Welsh (1958), Katich (1958), Peterson (1959, 1966a, 1966b), Peterson and Ohlen (1963), Peterson and Hite (1969), Hite (1960, 1961, 1968, 1970), Hite and Buckner (1981), Fetzner (1960), Ohlen and McIntyre (1965), Parker and Roberts (1963), Lessentine (1965), Baars, (1966, 1975, 1976), Baars and See (1968), Walton (1968), Molenaar (1975, 1981), Spoelhof (1976), Szabo and Wengerd (1975), Craig and Shawe (1975), Craig (1981), Peterson and Ryder (1975), O'Sullivan and MacLachlan (1975), and Stevenson and Baars (1986).

Marine and continental sedimentary rocks of Cambrian through Tertiary age are present in south-central and southeastern Utah and southwestern Colorado (figs. 10, 14-23), although large parts of the stratigraphic section are eroded in the main uplift areas. Thickness of Phanerozoic sedimentary cover ranges from more than 15,000 ft (4,500 m) in the main basins to less than 5,000 ft (1,500 m) in uplift areas (fig. 12). Sedimentary rocks of Proterozoic age are probably present in the southwestern part of the region (Kaiparowits basin and adjacent area) as part of the northern extension of the Chuar and Unkar Groups of the Grand Canyon region (figs. 12, 17, 18) (Reynolds and others, 1988; Summons and others, 1988; Rauzi, 1990). The Paleozoic section is primarily marine carbonate and clastic rocks in the lower part grading to mixed marine and continental clastic rocks in the upper part.

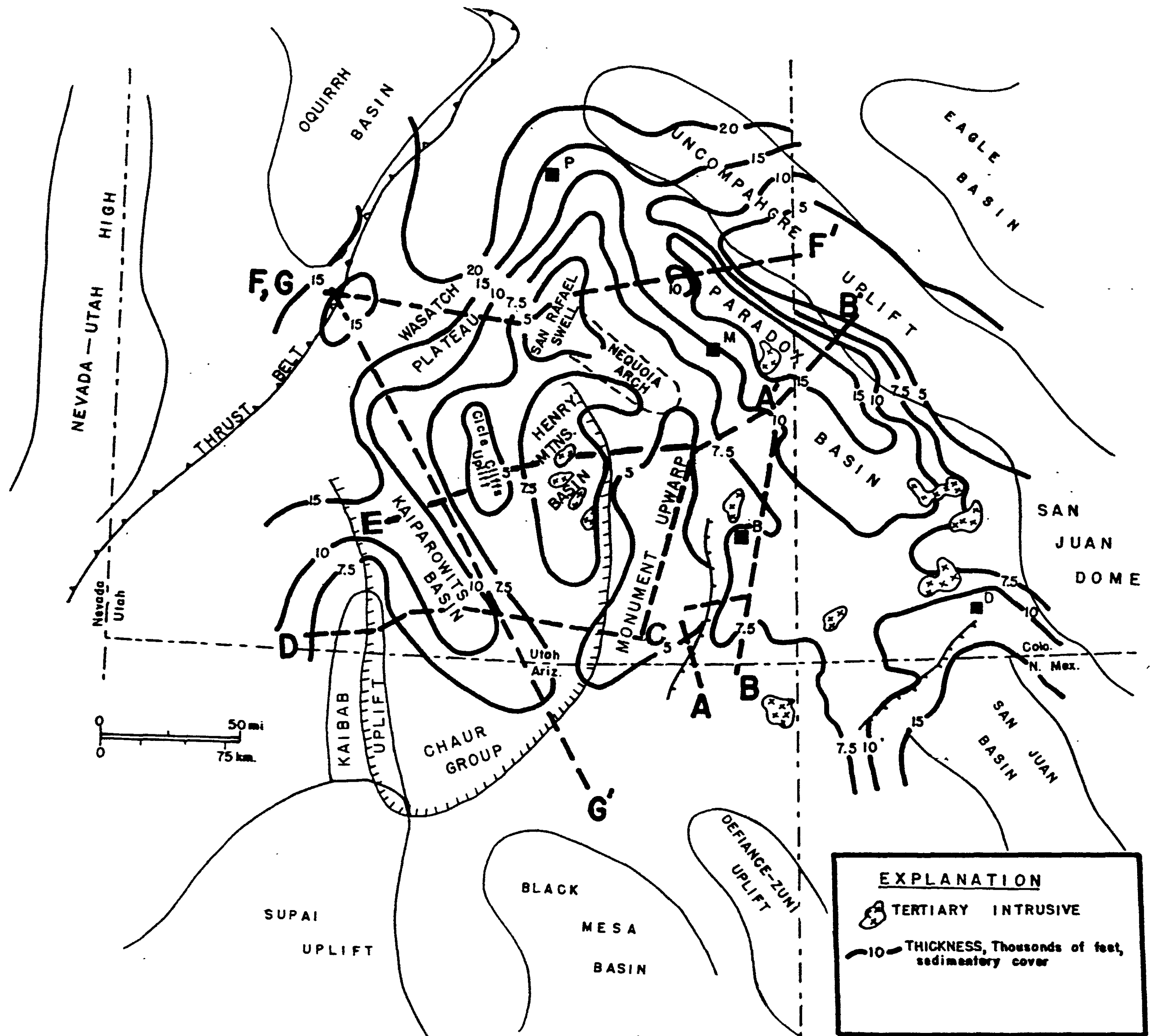


Figure 12.--Thickness, thousands of feet, sedimentary cover. Cross-section lines of figures 14-18 and 23, 24 are shown. Approximate distribution of Proterozoic Chuar Group shown by hachured line.

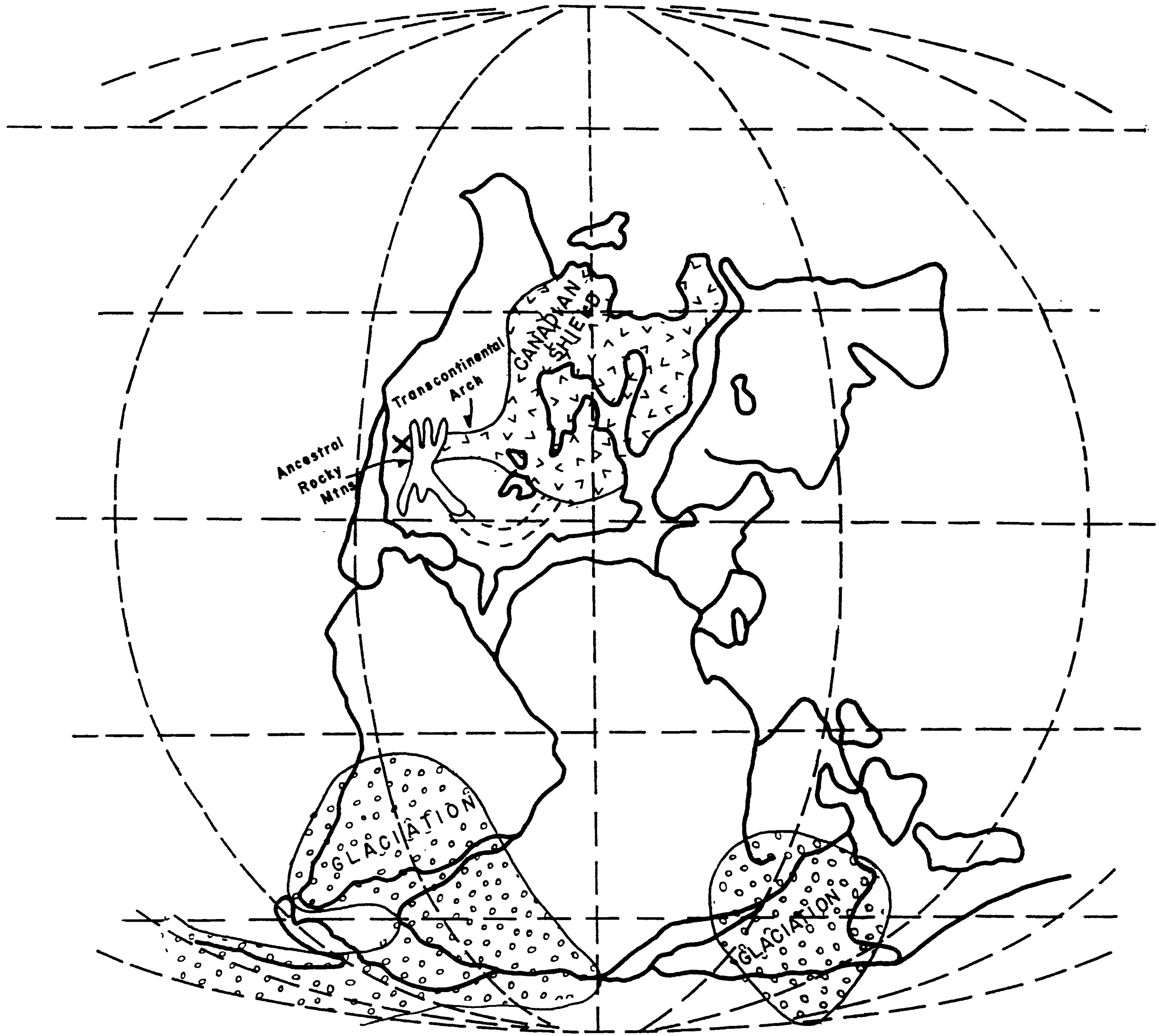


Figure 13.--Continental latitudinal positions, Middle Pennsylvanian time. Modified after Bambach and others (1980). X-indicates approximate position of Paradox basin.

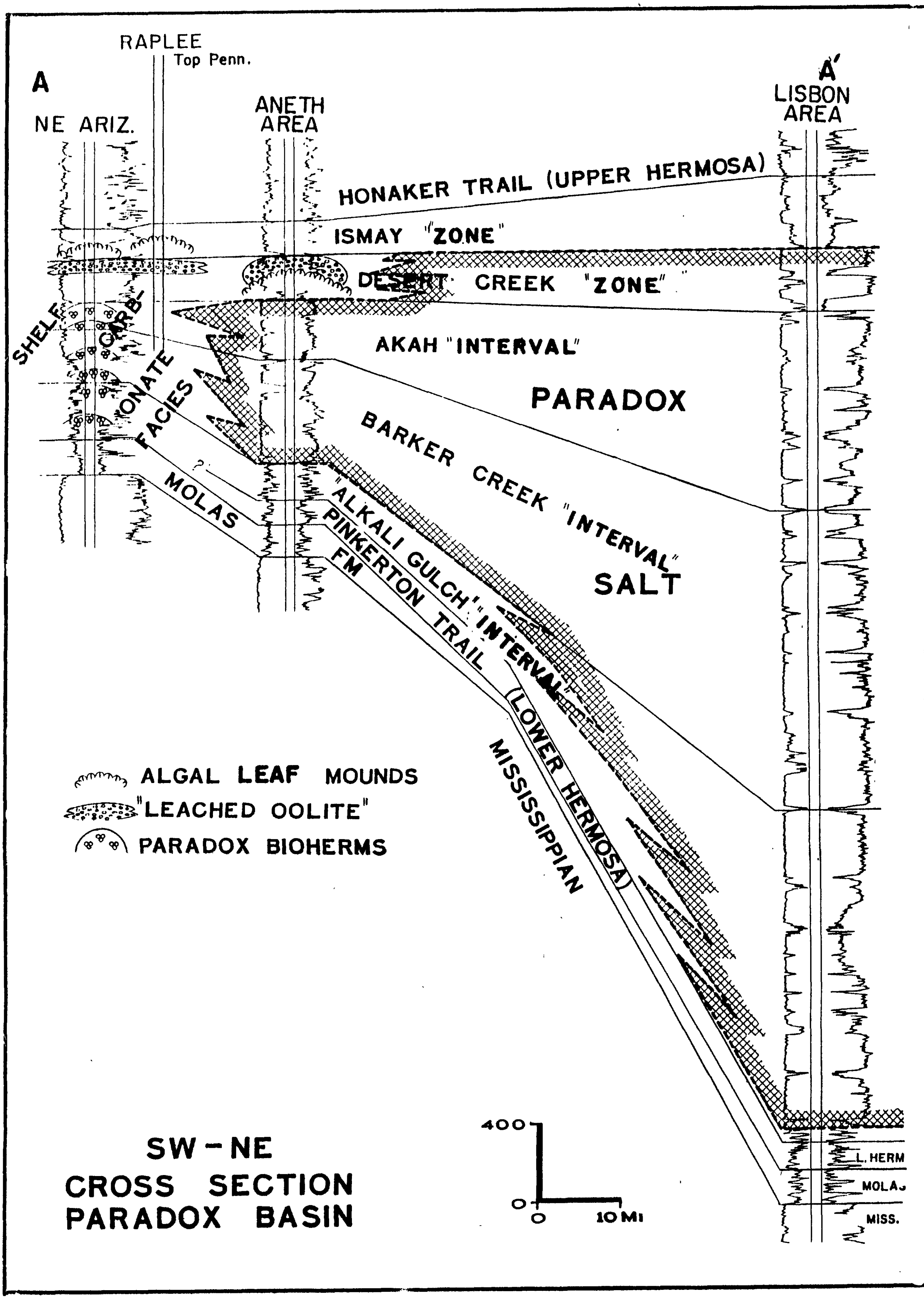


Figure 14.--South-north paleostructural-lithologic cross-section A-A', Paradox basin, showing relationship between shelf carbonate reservoir facies and Paradox evaporite black shale-bearing marker-bed facies. Modified after Peterson and Ohlen (1963). Datum is top of Pennsylvania System. Line of cross-section shown on fig. 12.

Symbols for stratigraphic units on figures 15-18 and 23

Symbol	Unit
PC	Precambrian
C	Cambrian
O	Ordovician
S	Silurian
D	Devonian
Dv	Victoria Sandstone
M	Mississippian
Mr	Redwall Limestone
M1	Leadville Limestone
Mf	Fitchville Formation
Mg	Gardner Formation
Md	Deseret Formation
Mh	Humbug Formation
1P	Pennsylvanian
1Pc	Callville Formation
1Pm	Molas Formation
1Ph	Hermosa Formation
1Phl	lower Hermosa
1Phu	upper Hermosa
P	Permian
Pc	Coconino Sandstone
Pq	Queantoweap Formation
Pt	Toroweap Formation
Pka	Kaibab Limestone
Por	Organ Rock shale
Pcm	Cedar Mesa sandstone
Pec	Elephant Canyon Formation
Pwr	White Rim Sandstone
Pcu	Cutler Formation
Pg	Gerster Formation
Ph	Hermit Formation
Tr	Triassic
Trm	Moenkopi Formation
Trmv	Virgin Limestone Member, Moenkopi Fm.
Trms	Sinbad Member, Moenkopi Fm.
Trs	Shinarump Conglomerate Member, Chinle Fm.
Trc	Chinle Formation
J	Jurassic
JTrgc	Glen Canyon Group
Jn	Navajo Sandstone
Jk	Kayenta Formation
Jw	Wingate Formation
Jca	Carmel Formation
Je	Entrada Sandstone
Jcu	Curtis Formation
Jsu	Summerville formation
Jm	Morrison formation
Jwi	Windsor Formation
K	Cretaceous
Kcm	Cedar Mountain Formation
Kd	Dakota Formation
Ktr	Tropic Shale
Kst	Straight Cliffs Formation
Km	Mancos Shale
Kwa	Wahweap Sandstone
T	Tertiary

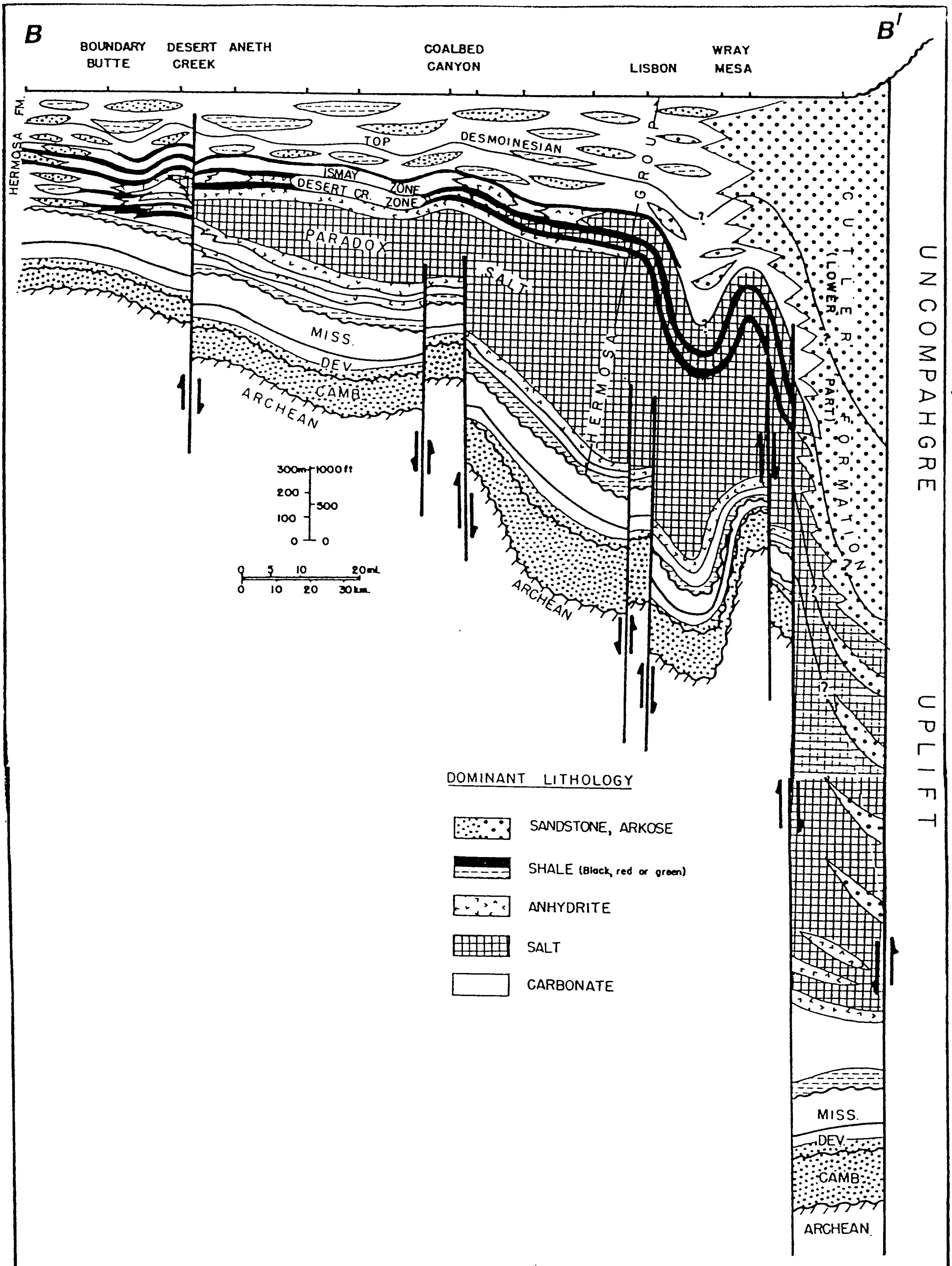


Figure 15.--Southwest-northeast stratigraphic-paleostructural cross-section B-B', northeastern Arizona to Uncompahgre uplift; Datum, top of Pennsylvanian System. Line of cross-section shown on fig. 12.

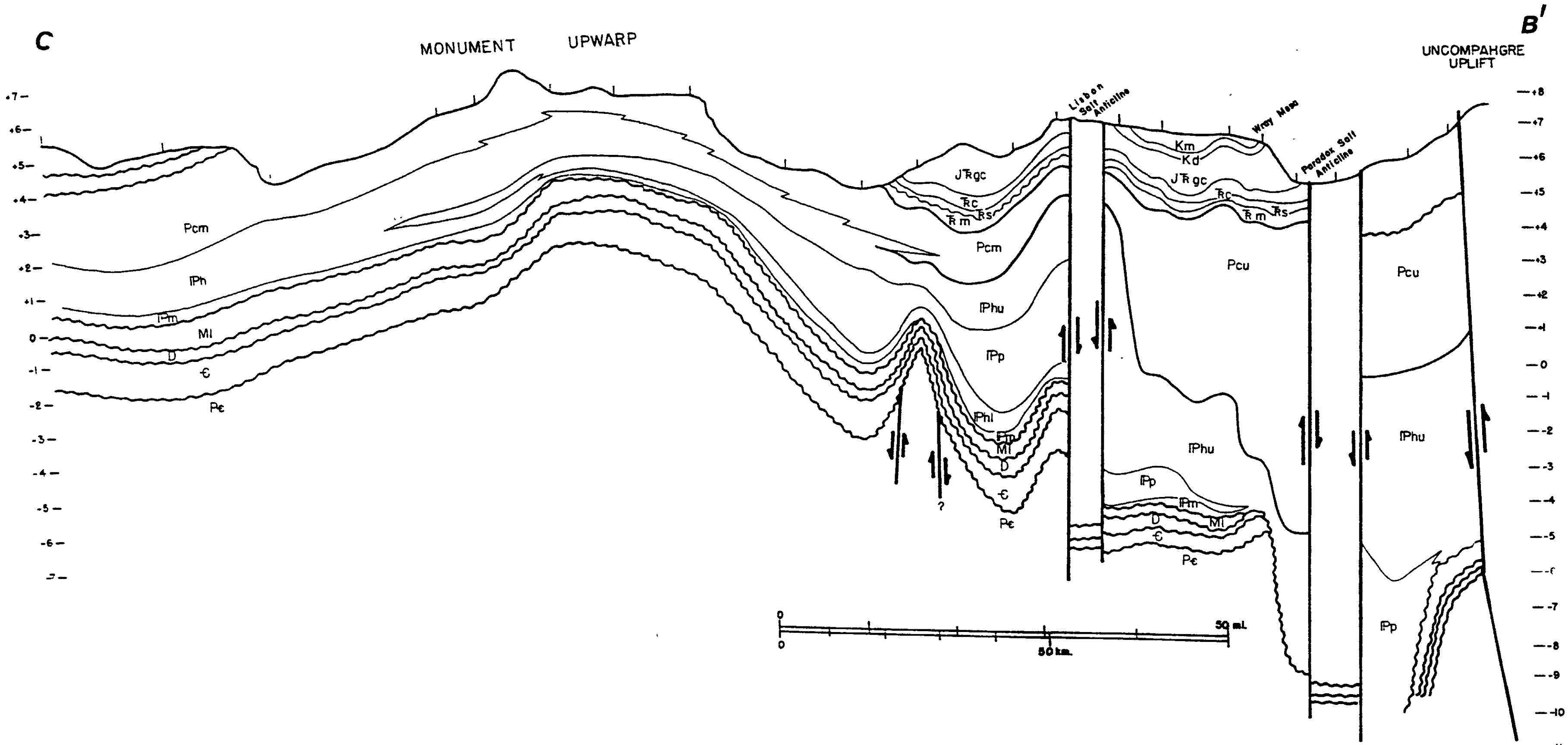


Figure 16.--Southwest-northeast structural-stratigraphic cross-section C-B', south end of Monument Upwarp to Uncompahgre uplift. Line of cross-section shown on fig. 12.

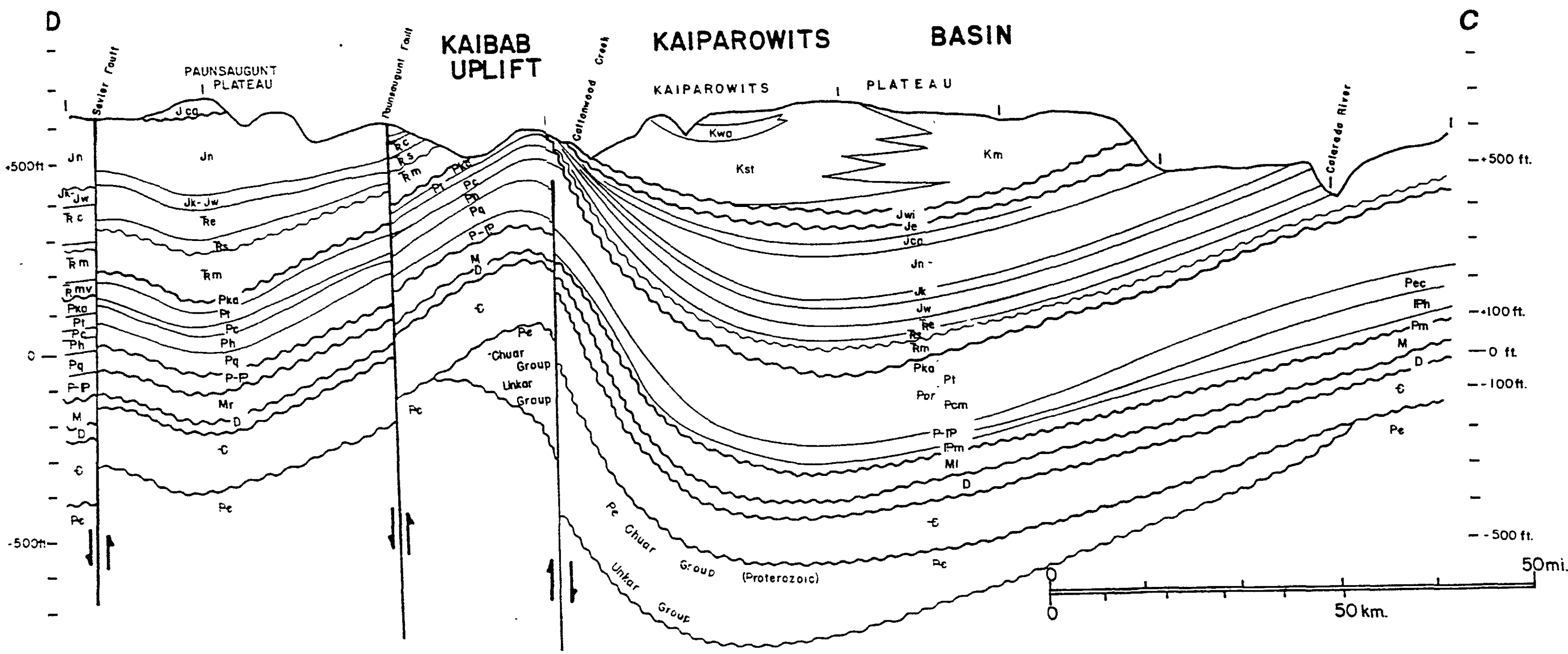


Figure 17.--West-east structural-stratigraphic cross-section D-C', across Paunsaugunt Plateau and Kaiparowits basin. Line of cross-section shown on fig. 12.

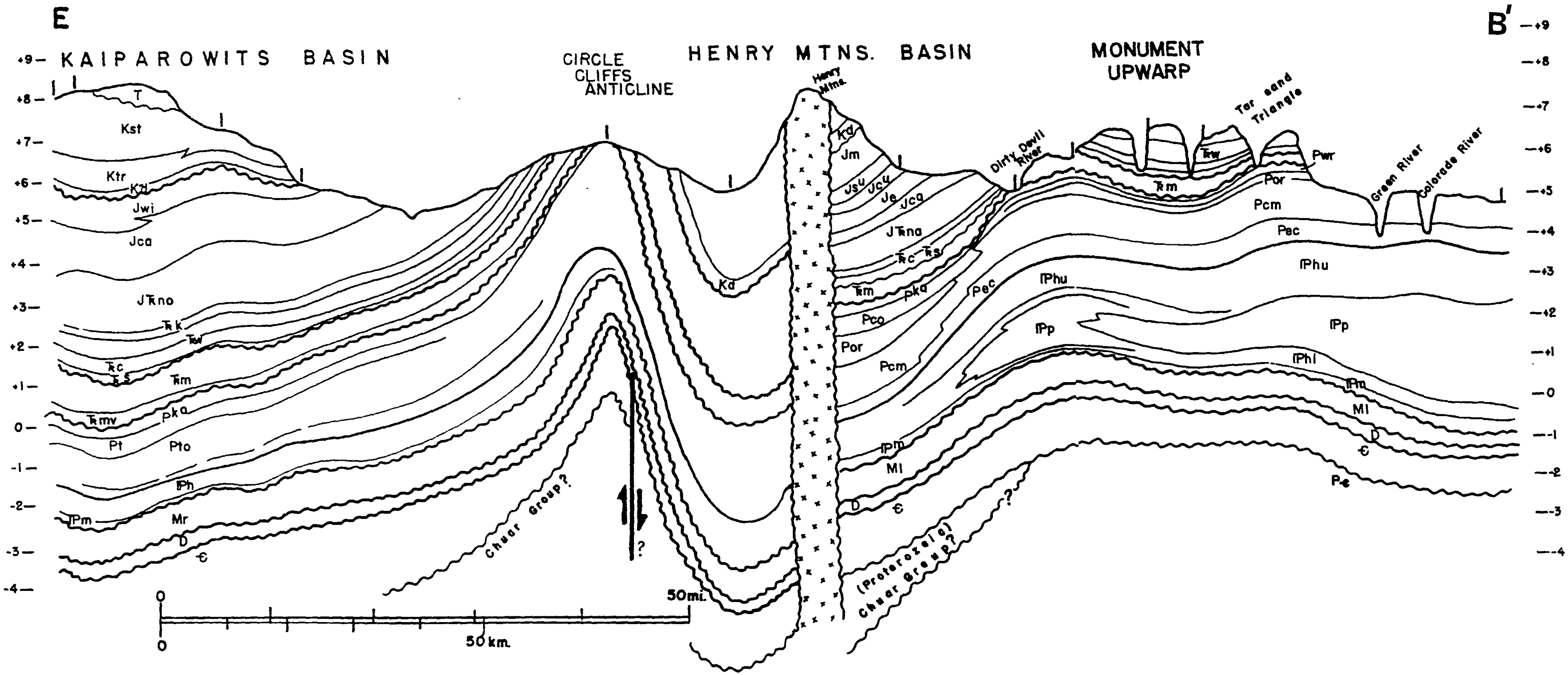


Figure 18.--West-east structural-stratigraphic cross-section E-B', Kaiparowits basin to north end of Monument Upwarp. Line of cross-section shown on fig. 12.

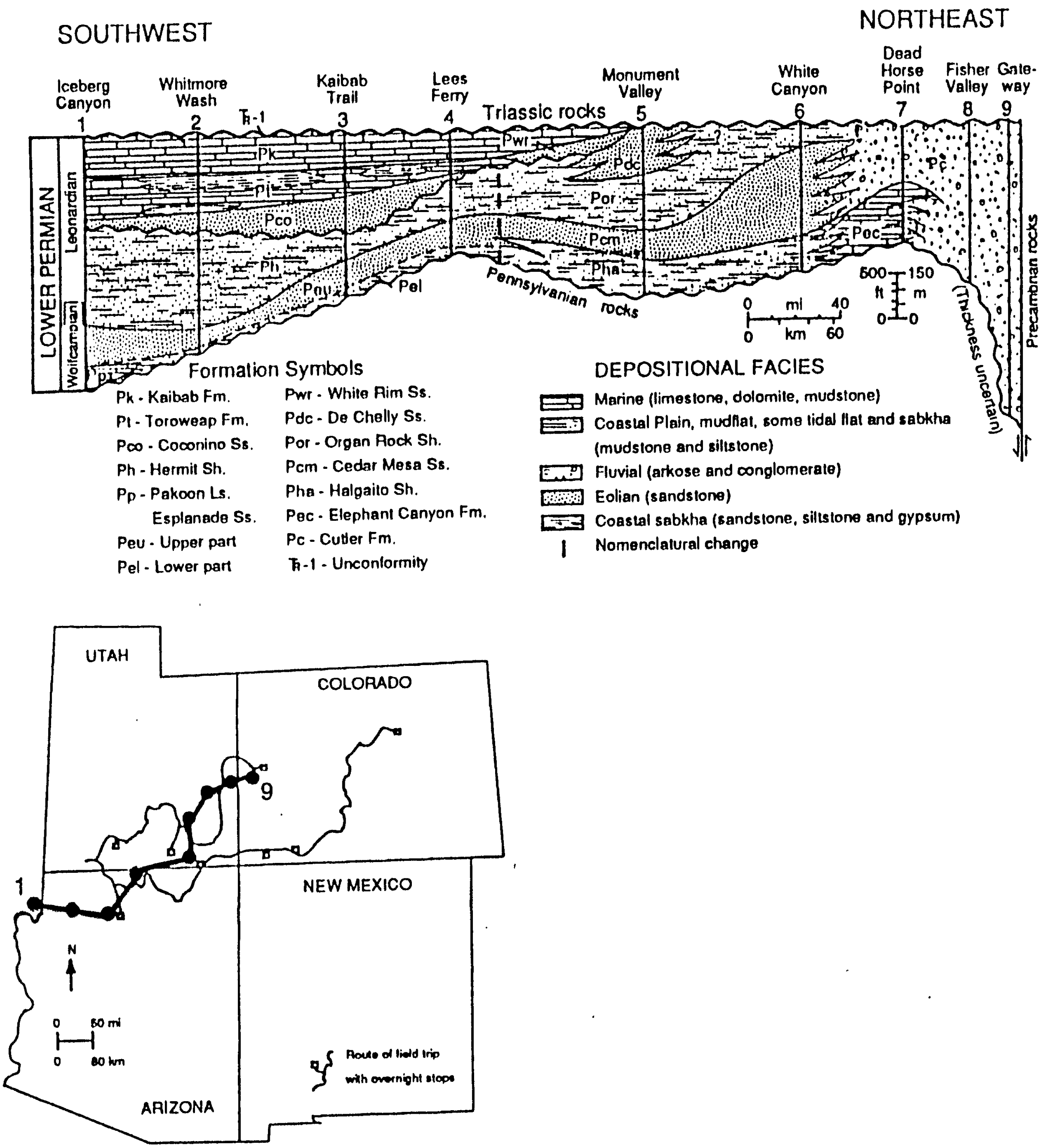


Figure 19.--Detailed stratigraphic cross-section of Lower Permian rocks partly along approximate line E-B' of fig. 18. From F. Peterson and Turner-Peterson, 1989.

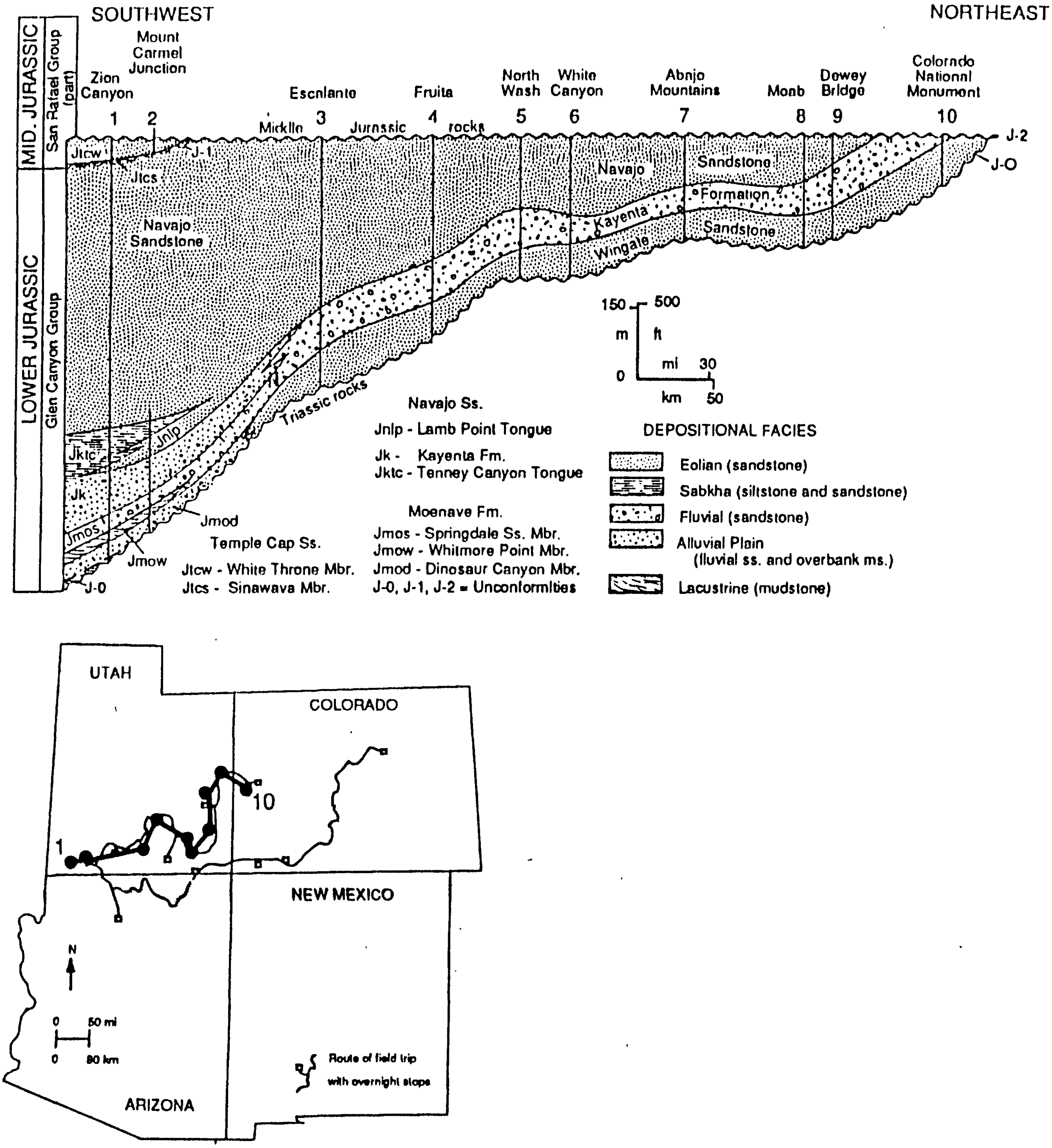


Figure 20.--Detailed stratigraphic cross-section of Lower Jurassic and lower Middle Jurassic rocks partly along approximate line E-B' of fig. 18. From F. Peterson and Turner-Peterson, 1989.

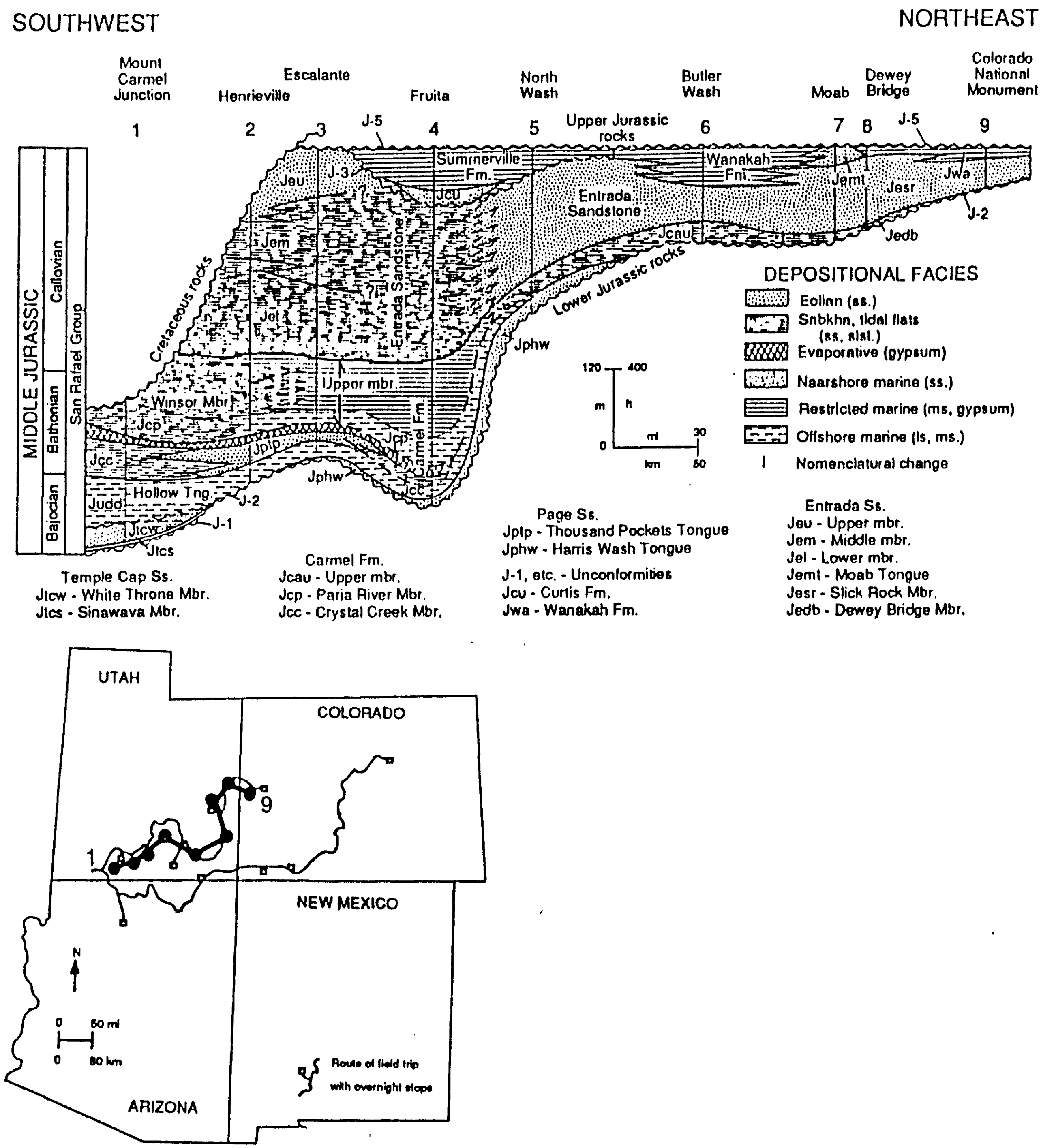


Figure 21.--Detailed stratigraphic cross-section of Middle Jurassic rocks partly along approximate line E-B' of figure 18. From F. Peterson and Turner-Peterson, 1989.

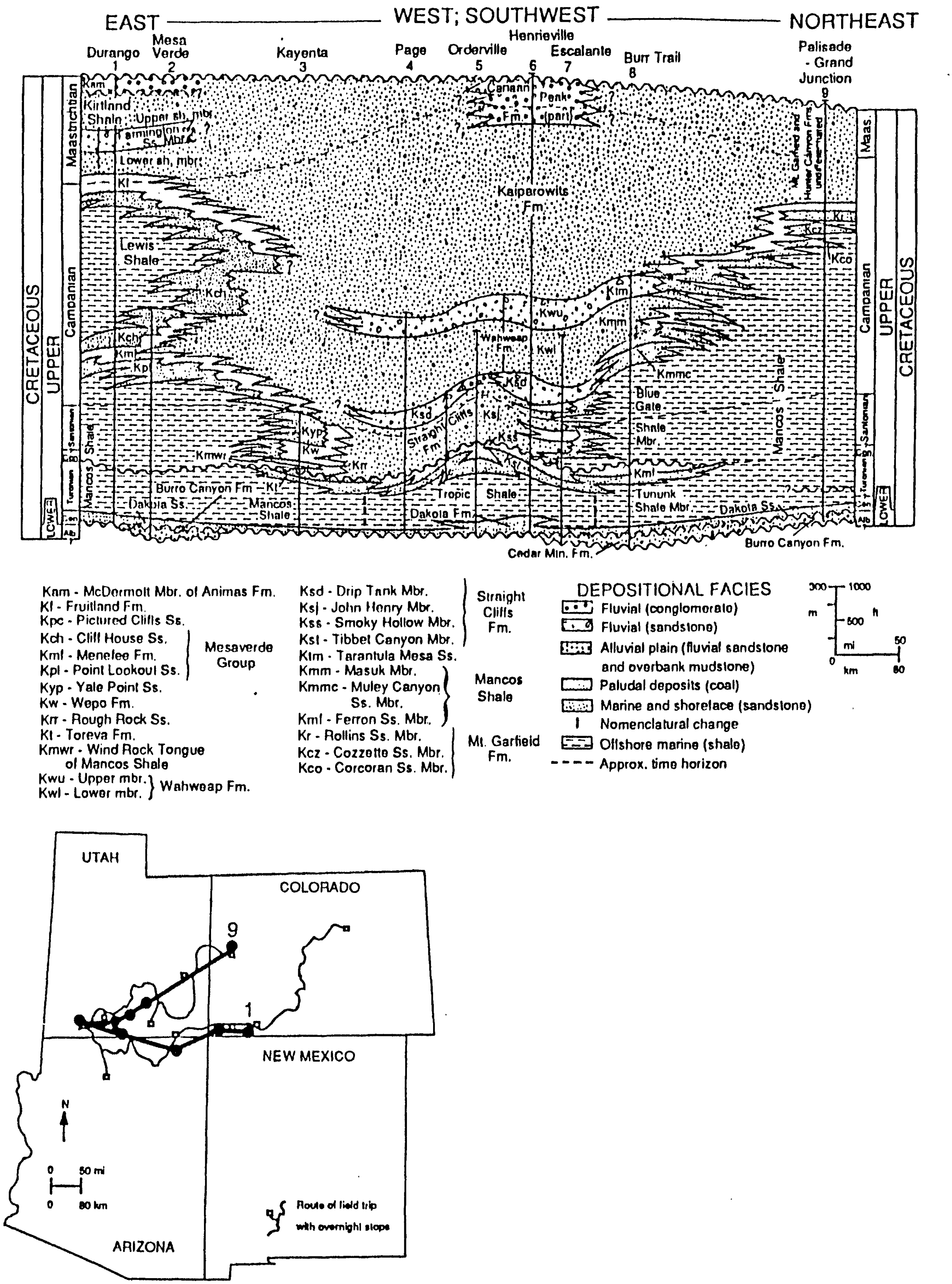


Figure 22.--Detailed stratigraphic cross-section of Cretaceous rocks partly along lines D-D' and E-B' of figures 17 and 18.

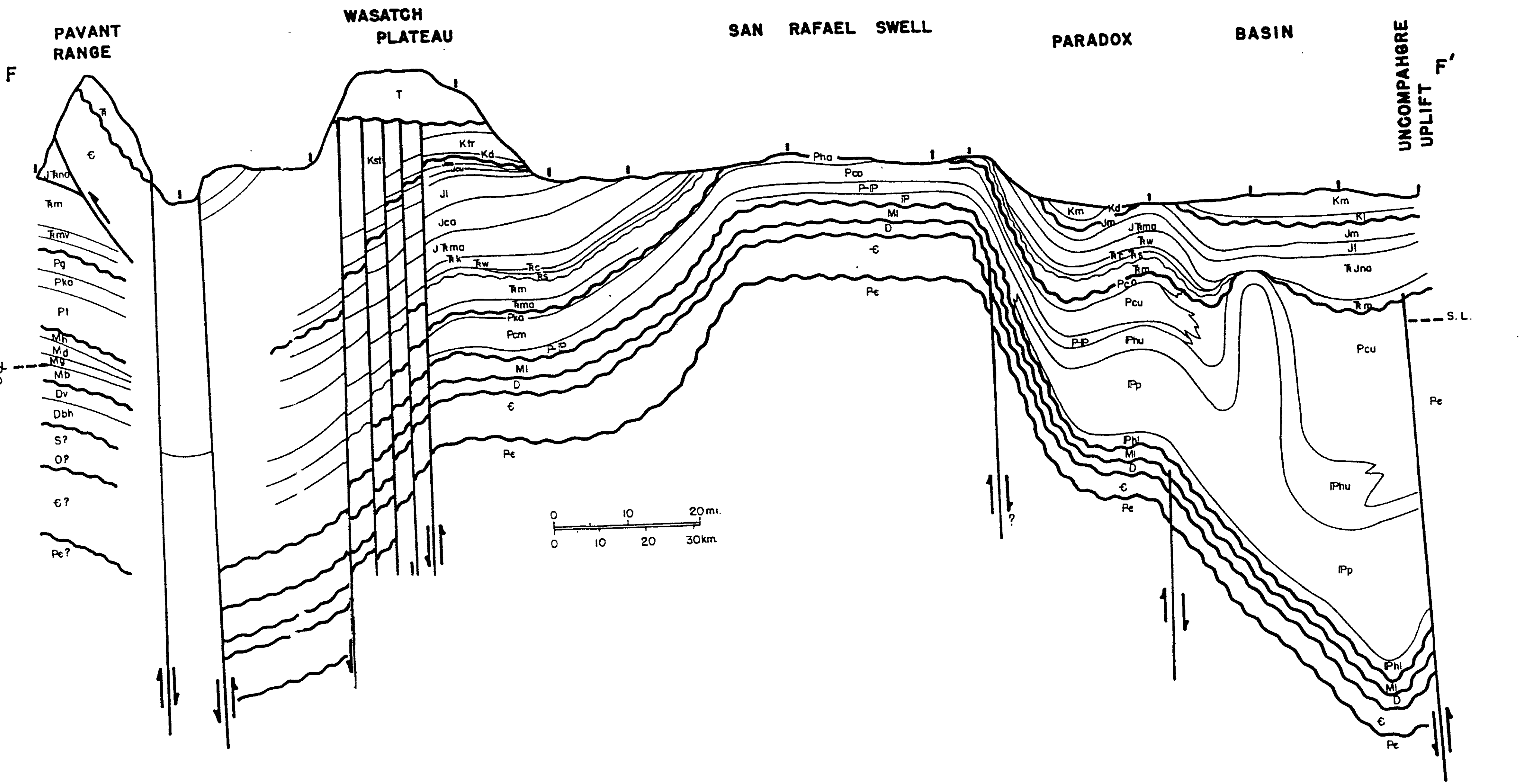


Figure 23.--West-east structural-stratigraphic cross-section F-F', Pavant Range across Wasatch Plateau, San Rafael Swell, and north end of Paradox basin, to Uncompahgre uplift. Line of cross-section shown on fig. 12.

Regional unconformities are present in several parts of the section, particularly the Lower Cambrian, Upper Cambrian through Upper Devonian, Mississippian and Lower Pennsylvanian, Upper Permian, and Jurassic. Most of the surface area in the region is characterized by exposures of Mesozoic sandstones and shales. Precambrian rocks are exposed in the Uncompahgre uplift and the San Juan Mountains on the east side of the Paradox basin. Paleozoic rocks are exposed in the San Juan Mountains, the Monument, Circle Cliffs, and San Rafael uplifts, and in salt anticlines of the central basin.

During most of Paleozoic time, the North American continent was located in the tropical to subtropical latitude belt (figs. 9, 10), where optimal conditions existed for marine carbonate deposition. The approximate position of the Pennsylvanian equator was a short distance south of the Paradox basin, approximately across present-day central New Mexico and Arizona. Prevailing wind direction was approximately from a present-day north-northeast direction (F. Peterson, 1988; Parrish and F. Peterson, 1988).

The pre-Pennsylvanian sedimentary pattern of most of the Rocky Mountain region was that of relatively stable and widespread shelf deposition of shallow-water marine carbonate and clastic sediments. Sedimentary facies were associated with regional transgressions of the early Paleozoic seas across the broad Rocky Mountain shelf lying west of the Transcontinental arch, a feature that extended from Minnesota southwest to central Colorado, northern New Mexico and northern Arizona (fig. 3).

Cambrian rocks are more than 1,500 ft (450 m) thick in the western part of the Paradox basin assessment area and thin uniformly eastward to less than 500 ft (150 m) in northeastern Arizona (figs. 24, 25). These rocks include a time-transgressive basal sandstone or quartzite (Tapeats or Ignacio Sandstone) (fig. 24), of Early Cambrian age to the west, becoming Late Cambrian near its pinchout edge in southwestern Colorado and northwestern New Mexico. On the west, the basal sandstone grades upward into marine green shale, siltstone, and limestone, which is overlain by massive dolomite with minor shale beds. Both the middle shale and upper carbonate are time-transgressive units that thin eastward and in part grade into sandstone and siltstone beds of the Ignacio Sandstone.

Ordovician, Silurian, and Lower and Middle Devonian rocks are absent throughout the assessment region. Rocks of Late Devonian age rest disconformably on Upper Cambrian sandstone or quartzite in the eastern part of the area and on Upper Cambrian dolomite in the west (figs. 10, 16-23). Upper Devonian rocks, consisting of marine glauconitic sandstone and sandy dolomite in the lower part and marine dolomite or limestone in the upper part, are more than 500 ft (150 m) thick in the central and northwestern part of the assessment area and generally less than 300 ft (90 m) in the southeastern area (fig. 26).

During Mississippian time, shallow water marine carbonate deposits (Leadville or Redwall Limestone and equivalents) blanketed the entire Rocky Mountain shelf. These rocks are 0 - 500 ft (0-150 m) thick in the Four Corners area (fig. 27) and thicken to more than 1,000 ft (300 m) in the Kaiparowits - Wasatch Plateau region. The Leadville is composed mainly of

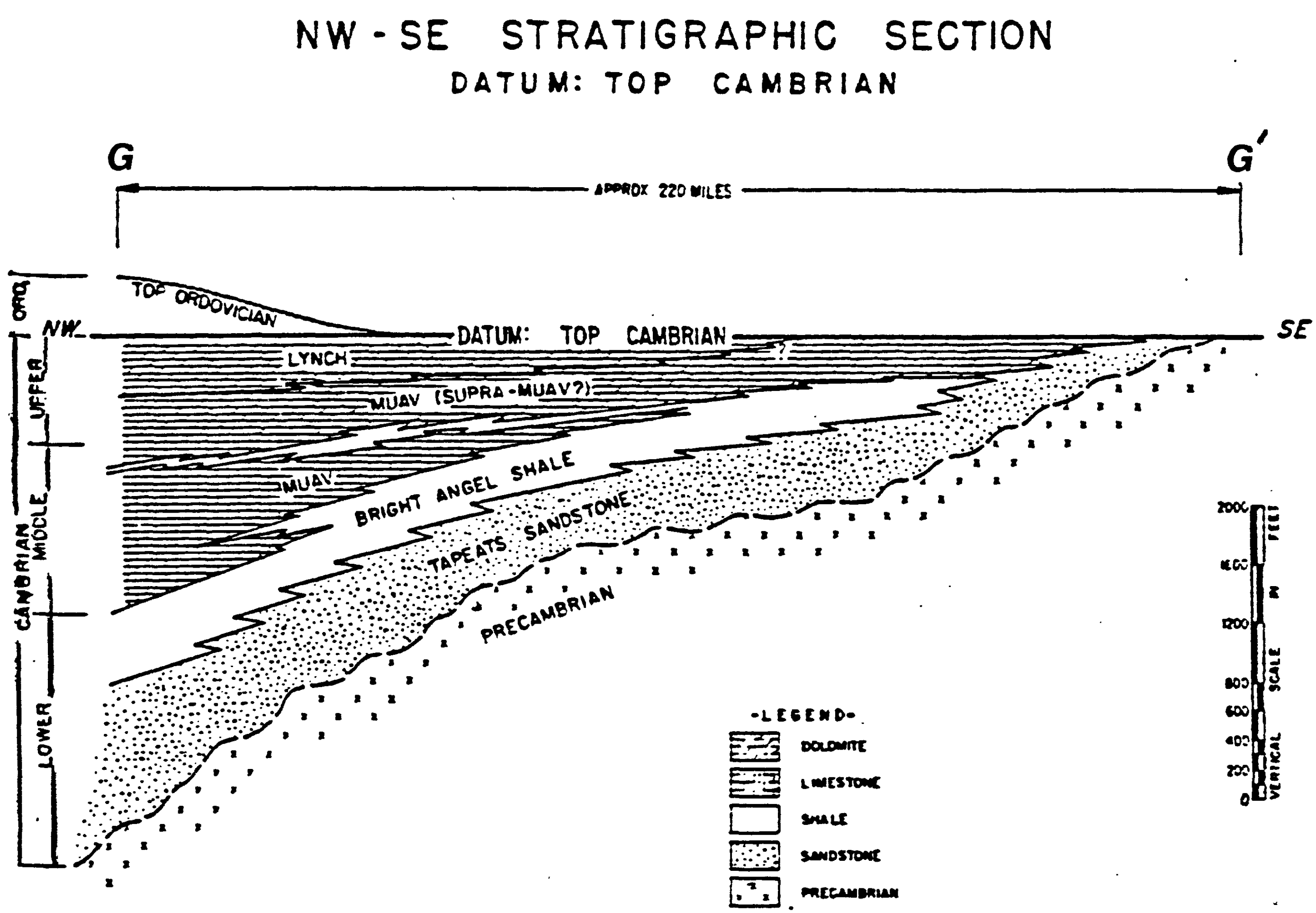


Figure 24.--Northwest-southeast stratigraphic section G-G' for Cambrian, Ordovician, and Silurian Systems. Figure 12 shows line of section. After Lessentine (1965).

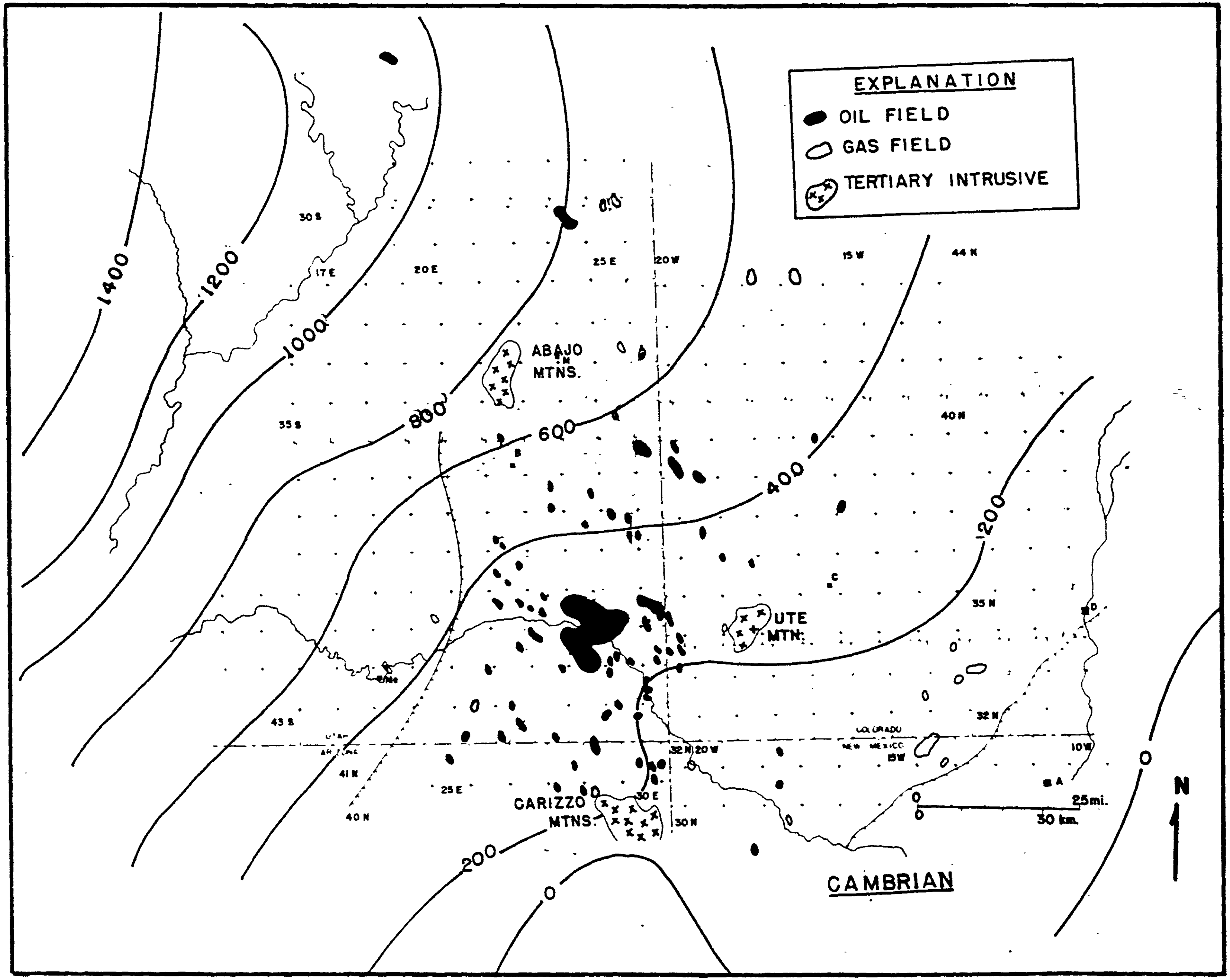


Figure 25.--Thickness in ft, Cambrian System, southern Paradox basin. Paradox basin oil and gas fields are shown.

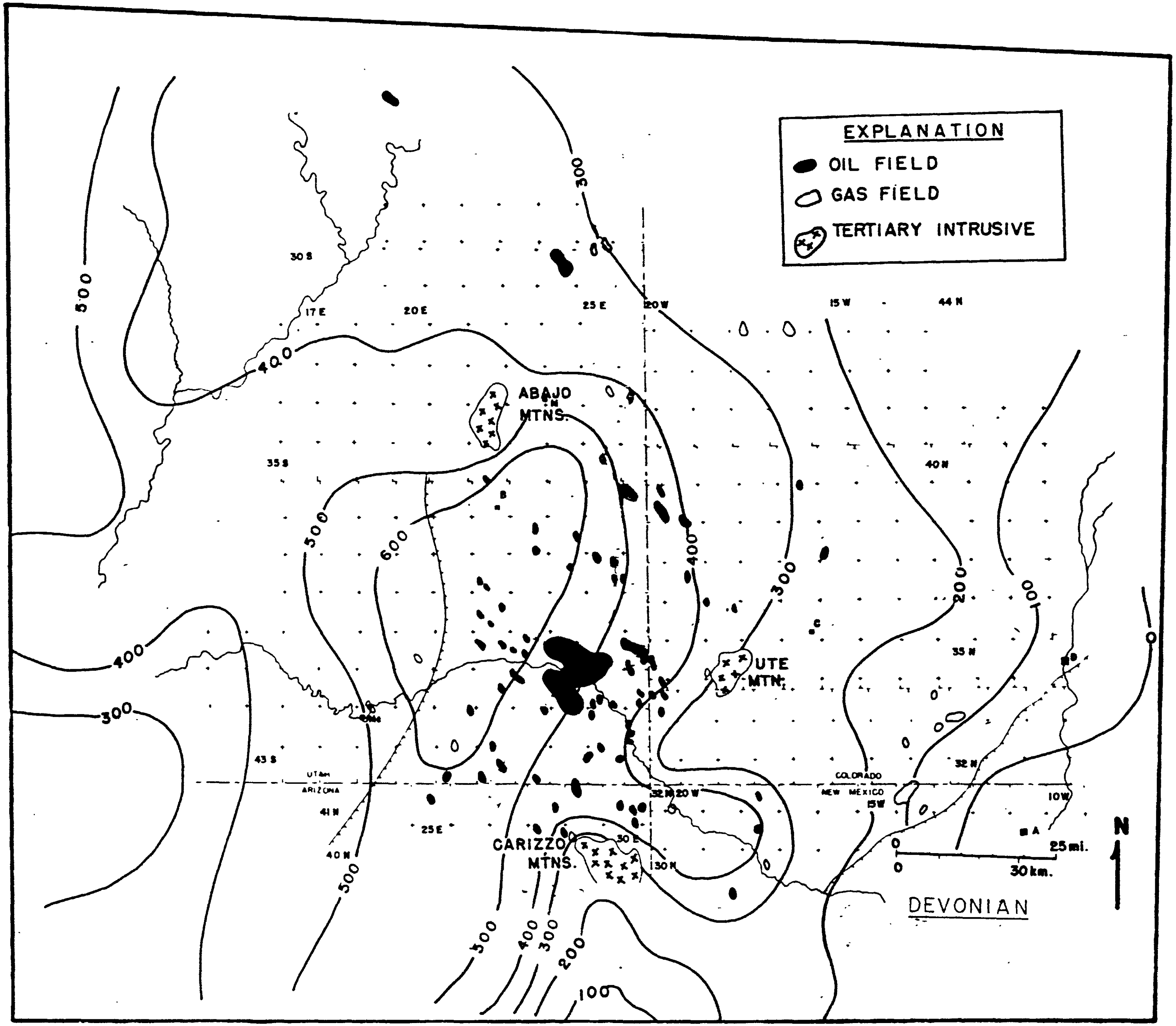


Figure 26.--Thickness in ft, Devonian System, southern Paradox basin. Paradox basin oil and gas fields are shown.

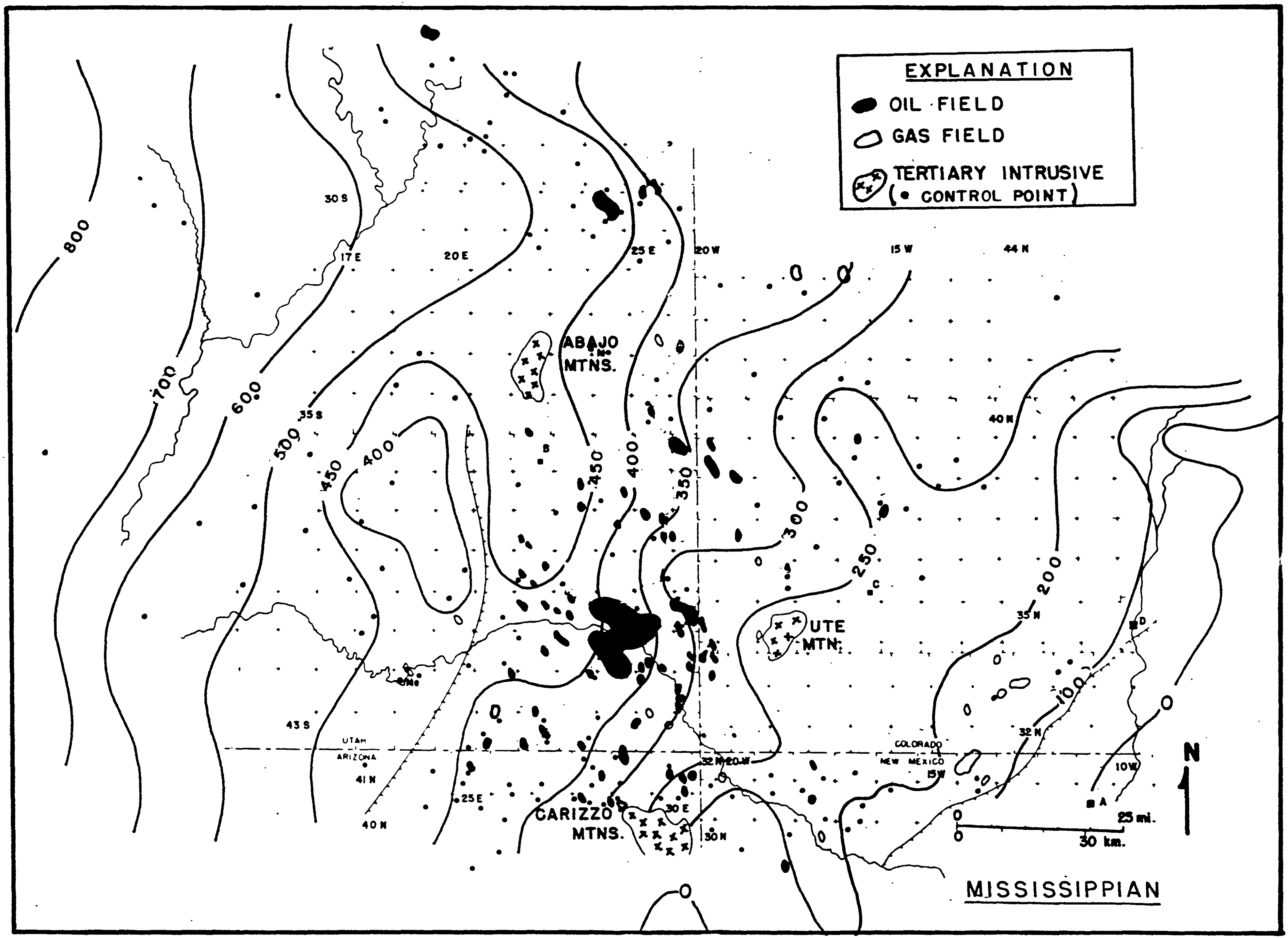


Fig. 27.--Thickness in ft, Mississippian System, southern Paradox basin. Paradox basin oil and gas fields are shown.

massive marine oolitic and crinoidal limestone and crystalline dolomite with variable amounts of chert. Oil production is obtained from the Leadville at the Lisbon oil field and at several smaller fields in the Paradox basin. The Leadville also contains major resources of carbon dioxide at several localities in the Four Corners area, particularly at McElmo dome in Colorado (fig. 7).

Prolonged emergence of the Rocky Mountain shelf during Late Mississippian and Early Pennsylvanian time resulted in regional development of a karst topography with associated red regolith, weathered carbonate rubble, and extensive solution features at the top of the Mississippian carbonate section that extended from New Mexico and Arizona north into Canada (Peterson and Smith, 1986).

Early in Pennsylvanian time, the broad emergent Rocky Mountain continental shelf underwent the initial stages of tectonism that intensified during Middle Pennsylvanian to Permian time with the rapid growth of the ancestral Rocky Mountains. Active subsidence of the Paradox basin began in the early Desmoinesian and continued at an accelerated pace until approximately the Middle Permian.

Rocks of Pennsylvanian age are more than 5,000 ft (1,500 m) thick in the Paradox basin and thin to 500 ft (150 m) or less on the Emery and Piute highs in south-central Utah (fig. 9). Pennsylvanian deposition in the Paradox evaporite basin was strongly cyclic and is represented by as much as 35-40 complete or partially complete cycles (fig. 14). Development of the cycles is probably related to a combination of factors, including: 1) eustatic sea level changes caused by cycles of Carboniferous glaciation in the southern hemisphere, probably in combination with ocean basin events related to sea floor spreading; 2) more localized changes in rate and type of clastic influx and its relation to submarine topography and turbidity of waters; 3) climatic effects, and 4) minor changes in rates of basin subsidence and tectonic movements.

During the Pennsylvanian and Permian, peripheral uplifts furnished clastic debris that was carried into the rapidly subsiding Paradox basin. The major source of clastic material was the Uncompahgre-San Luis uplift, which supplied more than 15,000 ft (4,600 m) of coarse arkosic clastic debris along the northeast border of the basin. Minor sources of finer clastics were present on the southwest and west (figs. 9, 10). Pennsylvanian-Permian tectonism accompanied by cyclic eustatic sea-level changes and the relative isolation of the Paradox basin from the main marine realm to the southeast and west resulted in complicated and diverse facies patterns within the basin. During Desmoinesian time, three main intertonguing sedimentary facies were deposited: 1) a coarse clastic facies, that becomes increasingly arkosic beginning in middle Desmoinesian time and reaches a maximum thickness in a narrow belt along the northeastern border of the basin adjacent to the Uncompahgre-San Luis uplift; 2) an evaporite facies, mainly of early Desmoinesian age, thickest near the basin axis, including halite and potash, anhydrite, finely crystalline dolomite, and black organic-rich shale or shaly dolomite; and 3) a shelf carbonate facies, along the southern and southwestern shelf of the basin. The carbonate facies locally contains mound-like buildups of biogenic carbonates. A narrow belt of mound-bearing sandy to silty carbonate also is present between the clastic and evaporite facies along the western border of the San Luis uplift near the main marine accessway. The evaporite-dominated facies of the inner basin changes relatively abruptly to carbonate facies across the shelf area to the southwest and west, where the Hermosa Group becomes predominantly cyclically deposited carbonate rocks with minor fine-grained clastics. Time equivalents of the various facies can be correlated from the inner basin to the shelf province on the basis of basinwide black and gray shaly marker units (fig. 14), the most prominent of which are organic-rich. The lower Hermosa (Pinkerton Trail Formation of Wengerd, 1958) demonstrates the initial development of cyclic sedimentation that resulted in repetitive deposition of clastic and carbonate units. Vertically, the cyclic section below the salt shows a progressive increase in carbonate content, but ultimately grades through dolomite and black shale into the overlying Paradox evaporite facies in the basin interior. Cyclic deposition is best demonstrated in the Paradox evaporite facies. Above the Paradox, the cycles increase in carbonate content in the lower part of the upper Hermosa (Honaker Trail Formation). The upper part of the Honaker Trail is increasingly dominated by coarser clastics with minor limestone beds. Permian rocks are dominantly clastic, including the major part of the arkosic facies on the northeastern side of the basin, grading westward to finer clastics with minor carbonate and anhydrite beds. Eolian sandstone and overlying marine carbonate (Kaibab Limestone) make up a significant amount of the Permian section along the western flank of the Paradox basin and westward into the Kaiparowits basin and Wasatch Plateau areas (figs. 10, 17-19, 23).

Through most of the early and middle Mesozoic, the region became emergent and was relatively stable. Triassic deposition was dominated by continental redbeds (shale, siltstone and sandstone) on the east with intertonguing marine deposits in the western area. The uppermost Triassic and Lower Jurassic are characterized by massive eolian sandstones. Middle and Upper Jurassic deposits are continental and marine sandstone, shale, and siltstone with minor interbeds of limestone and gypsum or anhydrite, overlain by varicolored continental alluvial and lacustrine shale, siltstone, and sandstone of Late Jurassic and Early Cretaceous age. Continental deposition prevailed during much of this time. During the Late Cretaceous, marine and intertonguing continental clastics at or near the western margin of the Cretaceous seaway were deposited across most of the region. Much of this section has been removed by Cenozoic erosion, except for the Kaiparowits and Wasatch Plateau areas (figs. 10, 17-23).

PETROLEUM GEOLOGY

As of 1988, the Paradox basin proper contained approximately 125 oil and gas fields, mainly producing from Pennsylvanian carbonate reservoirs (fig. 4). Fields range in size from a few thousand barrels to the giant Aneth field with original reserves of approximately 400 MMBO (million barrels of oil), more than two-thirds of the total original reserves of the Paradox basin (fig. 28). The reasons for the location and giant size of the Aneth field are discussed elsewhere (Peterson, 1989, 1990). Most of the reserves of the basin are in Pennsylvanian carbonate reservoirs with a relatively small percent of the total from carbonate reservoirs of Mississippian age. Some production also is obtained from sandstone reservoirs of Permian age. Large volumes of mature, organic-rich petroleum source rocks, cyclically interbedded with carbonate and

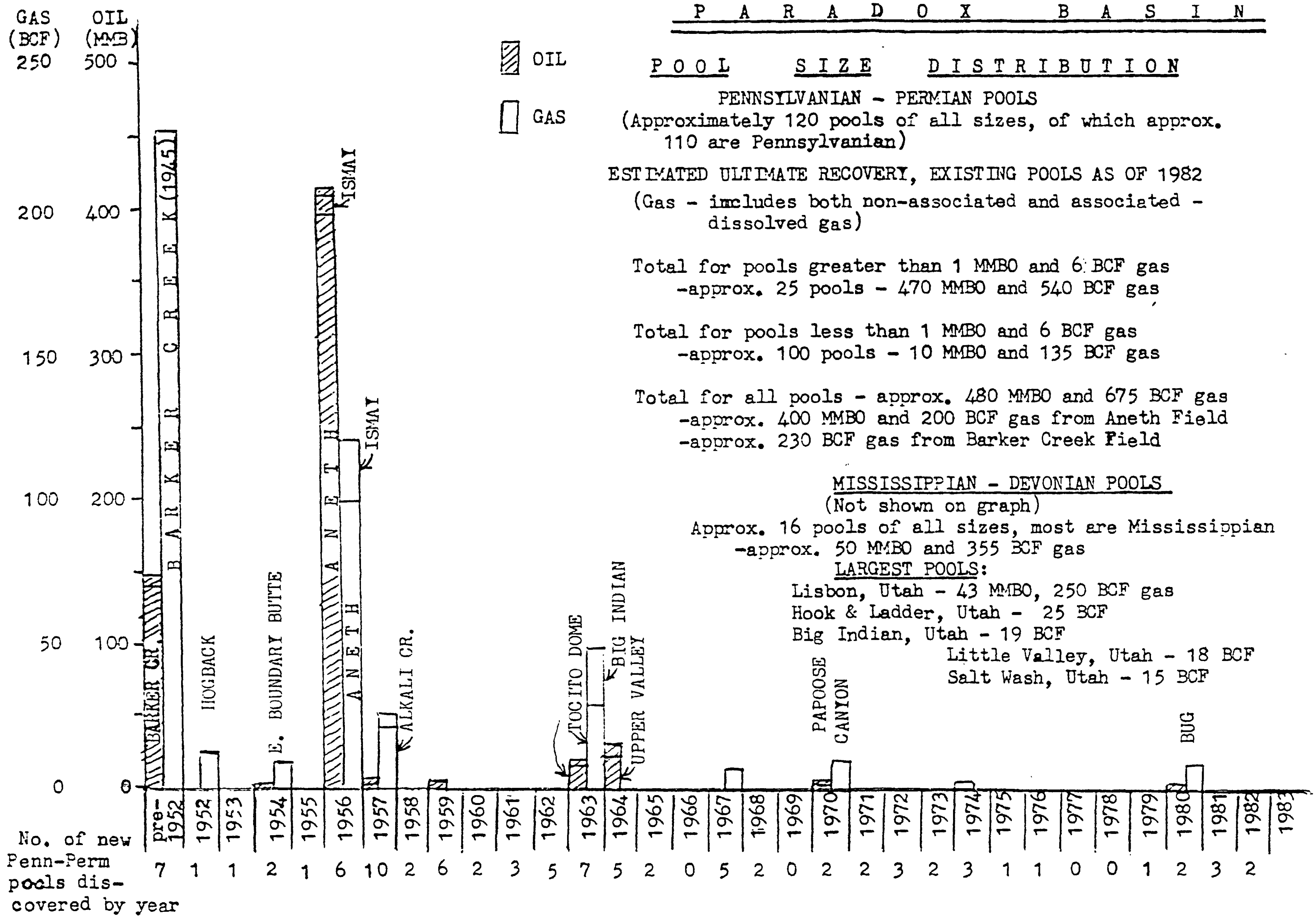


Figure 28.--Pool size distribution, Pennsylvanian and Permian oil and gas pools, Paradox basin, showing size distribution of existing pools greater than 1 MMBO or 6 BCF gas, pre-1952 to 1983. Total number of pools of all sizes discovered by year is shown at bottom of graph. Some fields shown are outside the assessment province boundary, but are within the geologically-defined Paradox basin proper.

evaporite beds, are present in much of the Pennsylvanian section in the Paradox basin (figs. 14, 15, 29). Possible source rocks also are present in the Upper Permian Kaibab and the Sinbad Member and equivalents of the Lower Triassic Moenkopi Formation along the western flank of the Paradox basin and the Kaiparowits basin (figs. 17, 18, 19). Cretaceous marine shales and coaly beds are probable source rocks for gas in the Wasatch Plateau-Kaiparowits basin region. Thermal gradients in the Paradox basin are approximately 2.2-3.3°C/100 m (1.2-2.0°F/100 ft) (Hite and others, 1984). Thick deposits of gray to black organic-rich shale and siltstone are present in the Upper Proterozoic Chuar Group in the Grand Canyon region of Arizona and probably are present over a large part of south central Utah (figs. 13, 15, 16) (Summons and others, 1988; Rauzi, 1990; Palacas and Reynolds, 1989).

Important deposits of tar are present in the Middle Permian White Rim Sandstone and Lower Triassic Moenkopi Formation in the Tar Sand Triangle, Circle Cliffs and San Rafael uplifts, Capitol Reef, and other areas on the western flank of the Paradox basin (figs. 4, 7, 18).

Production at Aneth is primarily from the Desert Creek zone, which consists of the following sequence, from the base upward (figs. 30, 31, 33):

1. Black, laminated, organic-rich, dolomitic, silty shale or shaly dolomite and siltstone (Chimney Rock shale), the basal unit of the cycle. The Chimney Rock is underlain by a 10-15 ft (3-5 m) anhydrite bed, which lies above approximately 150 ft (45 m) of halite.
2. Dark brown to gray finely-crystalline or chalky dolomite or dolomitic, fossiliferous limestone.
3. Porous algal limestone or slightly dolomitic limestone, locally pelletal.
4. Thin anhydrite bed, present only on the fringes of the mound buildup.
5. Foraminiferal pellet limestone.
6. Porous "leached oolite", slightly dolomitic, limestone, commonly fossiliferous.
7. Thin anhydrite bed, present only on the fringes of the buildup. This is the top of the cycle, overlain by black, organic-rich shale (Gothic shale) similar to the basal unit of the Desert Creek cycle (Chimney Rock shale). The Gothic is the basal unit of the overlying Ismay zone.

Porosity in the Desert Creek zone at the Aneth field is in two main reservoir rock types, a calcareous phylloid (leaf-like) algal limestone in the lower part, and a "leached oolite" limestone and dolomite interval in the upper part (figs. 33-35). The algal reservoir is slightly over 100 ft (30 m) thick in the central part of the mound, and the leached oolite averages approximately 100 ft (30 m) in most of the mound complex, giving a maximum mound thickness of somewhat over 200 ft (60 m). In plan view, the overall porous mound buildup is somewhat horseshoe-shaped with the major breadth and thickness in the greater Aneth field area, thinning to the northwest along two relatively narrow and irregular arms (figs. 31, 32). The middle Desert Creek anhydrite unit covers the thinner part of the mound belt to the northwest. This anhydrite also covers other small individual Desert Creek mound buildups away from the Aneth field, but does not cover the mound rocks in the field proper. The main porous rock in the lower Desert Creek mounds is composed largely of calcified remains of the green alga Ivanovia (Khvorova, 1946; Parks, 1958; Wray and Konishi, 1960), intermixed with pelleted mud lenses, which probably represent pockets of fine lime mud trapped during mound growth.

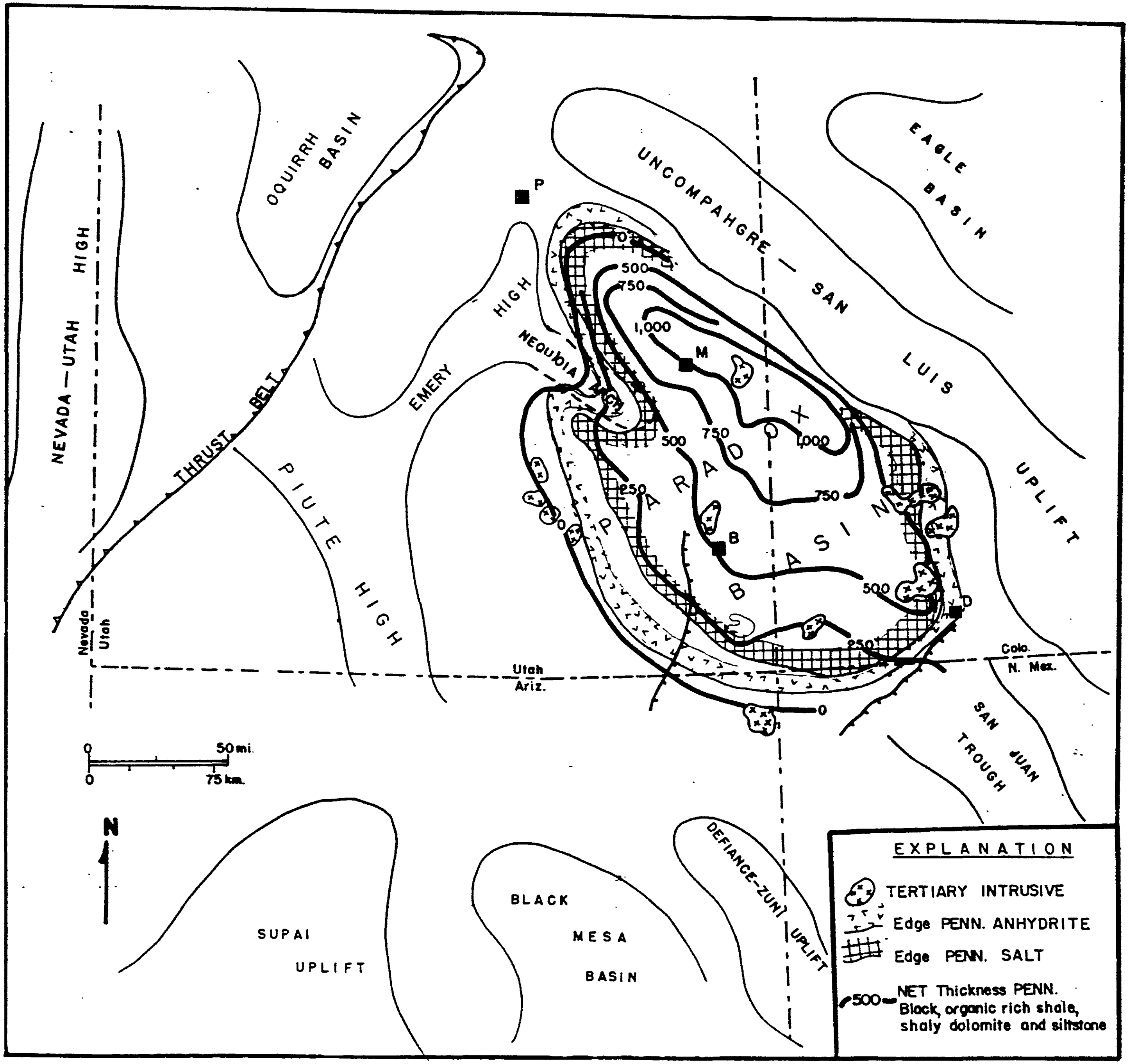


Figure 29.--Composite net thickness in ft of Pennsylvanian black, organic-rich shale, shaly dolomite, and siltstone, Hermosa Group, Paradox basin.

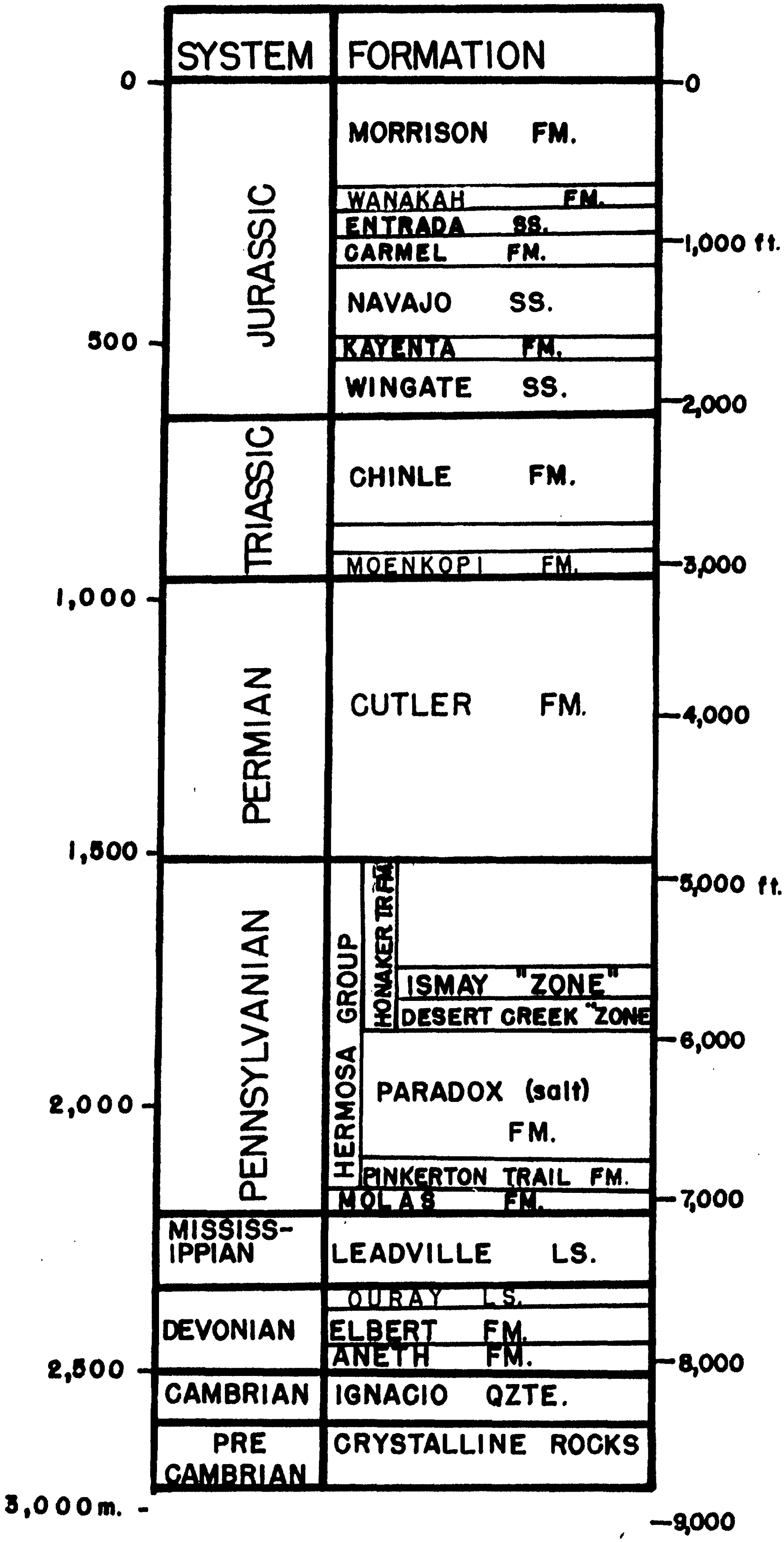


Figure 30.--Stratigraphic column and average depths in feet and meters, Aneth area.

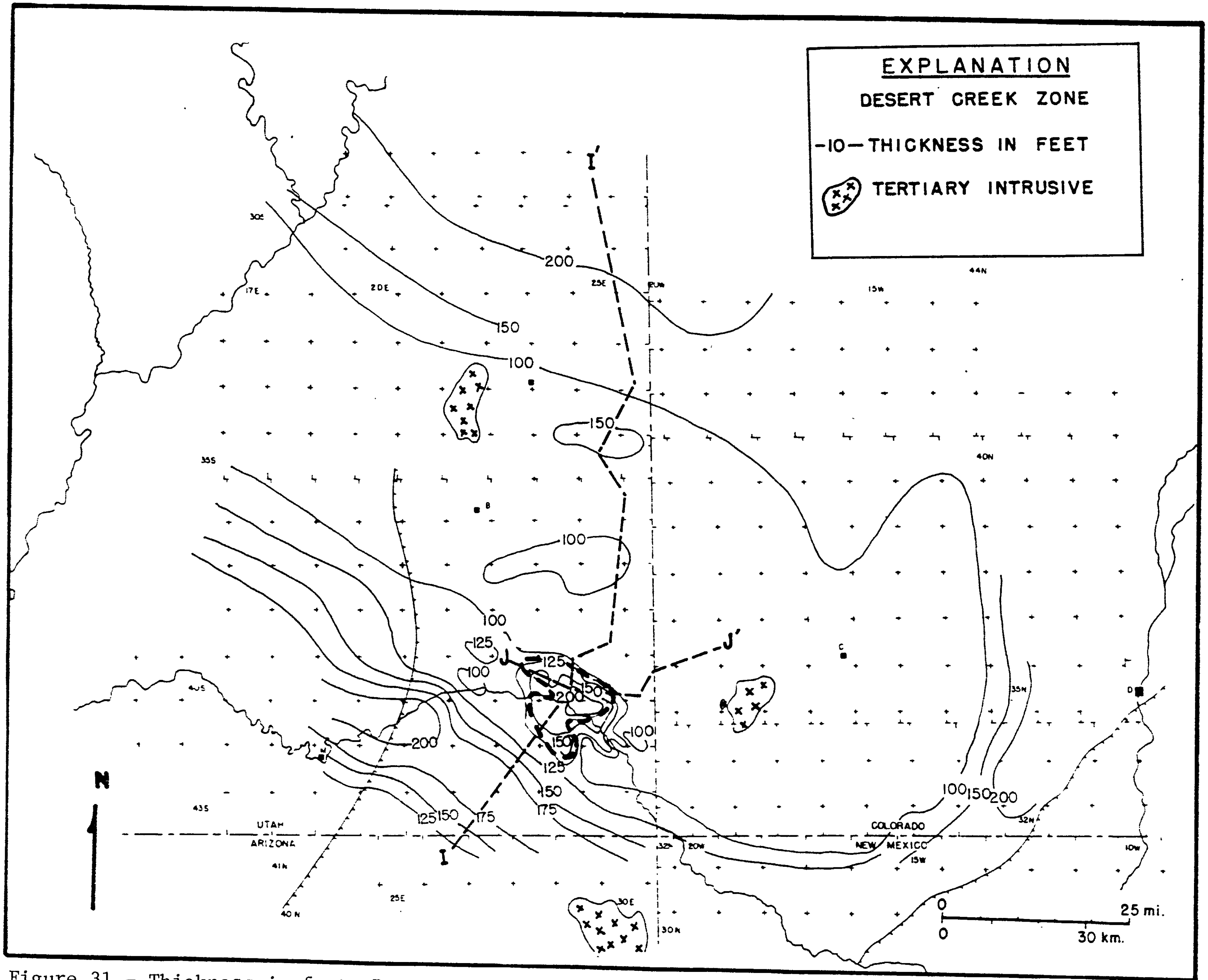


Figure 31.--Thickness in feet, Desert Creek zone, southern Paradox basin. Lines of cross-sections I-I' and J-J' of figures 34 and 35 are shown.

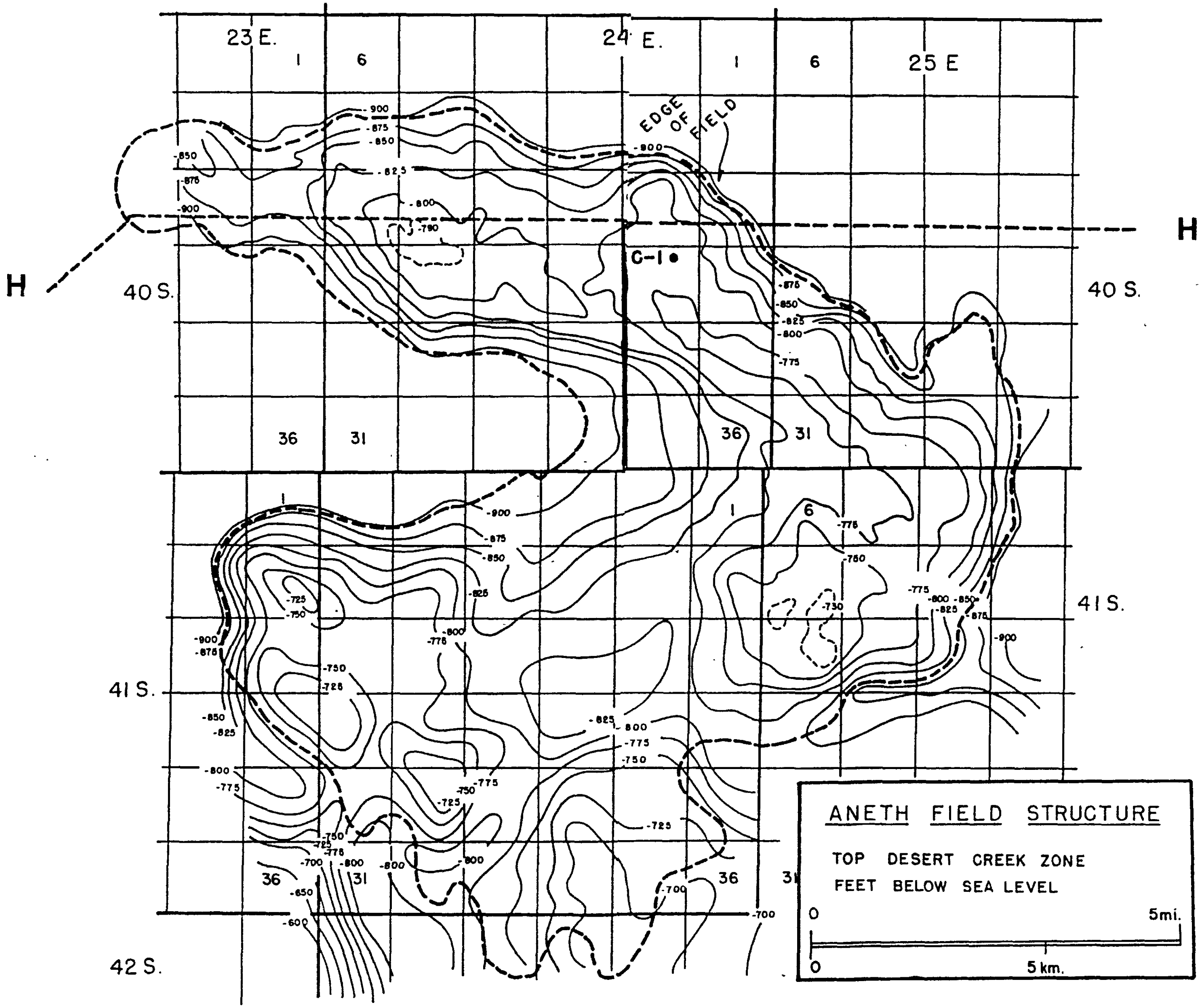


Figure 32.--Structure, top of Desert Creek zone, Aneth field. Cross-section line H-H' of figure 33 and C-1 discovery well are shown. Contour interval 25 ft.

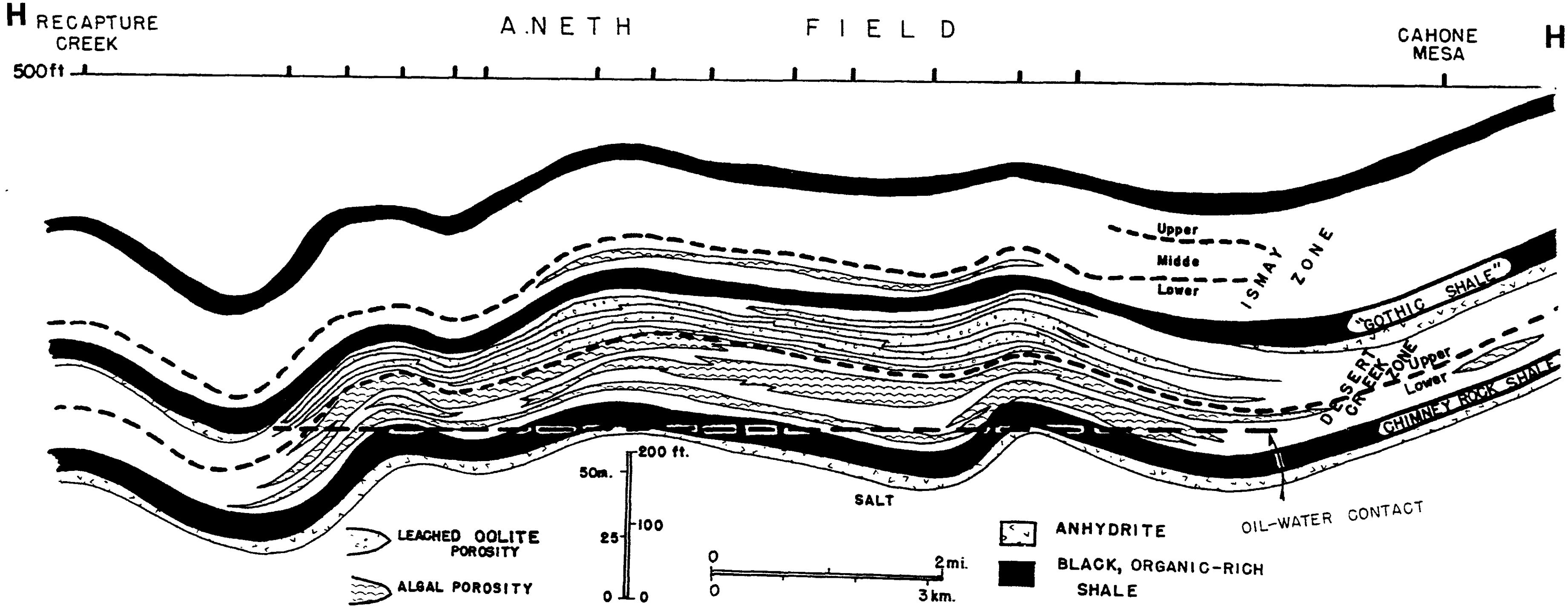


Figure 33.--West-east structural-stratigraphic cross-section, H-H', Aneth oil Field, showing reservoir porosity layers in lower and upper Desert Creek zone, oil-water contact, and organic-rich Chimney Rock and Gothic shales. Datum is -500 ft sea level. Line of cross-section shown on figure 32.

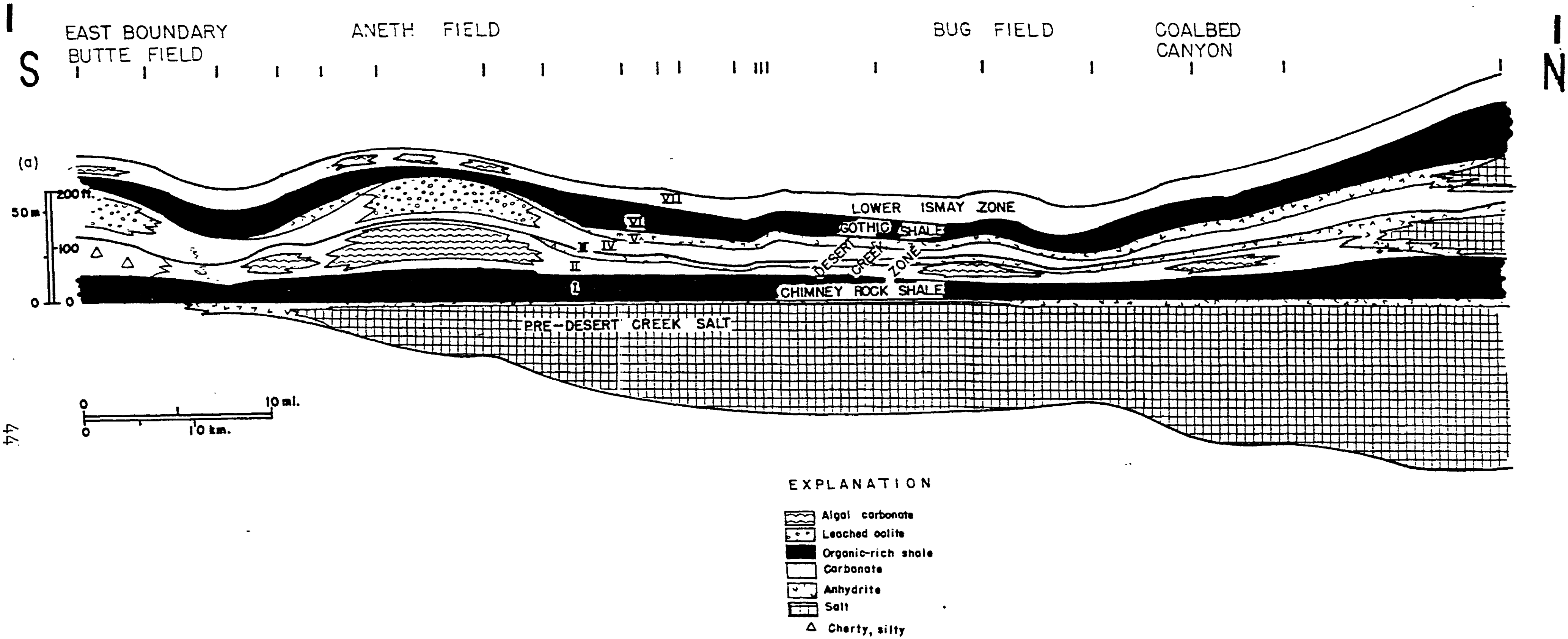


Figure 34.--South-north lithologic cross-section I-I', northeastern Arizona to central Paradox basin, showing algal and leached oolite carbonate reservoir buildups of Desert Creek and lower Ismay zones in Aneth field area and related facies to north. Line of cross-section shown on figure 4.

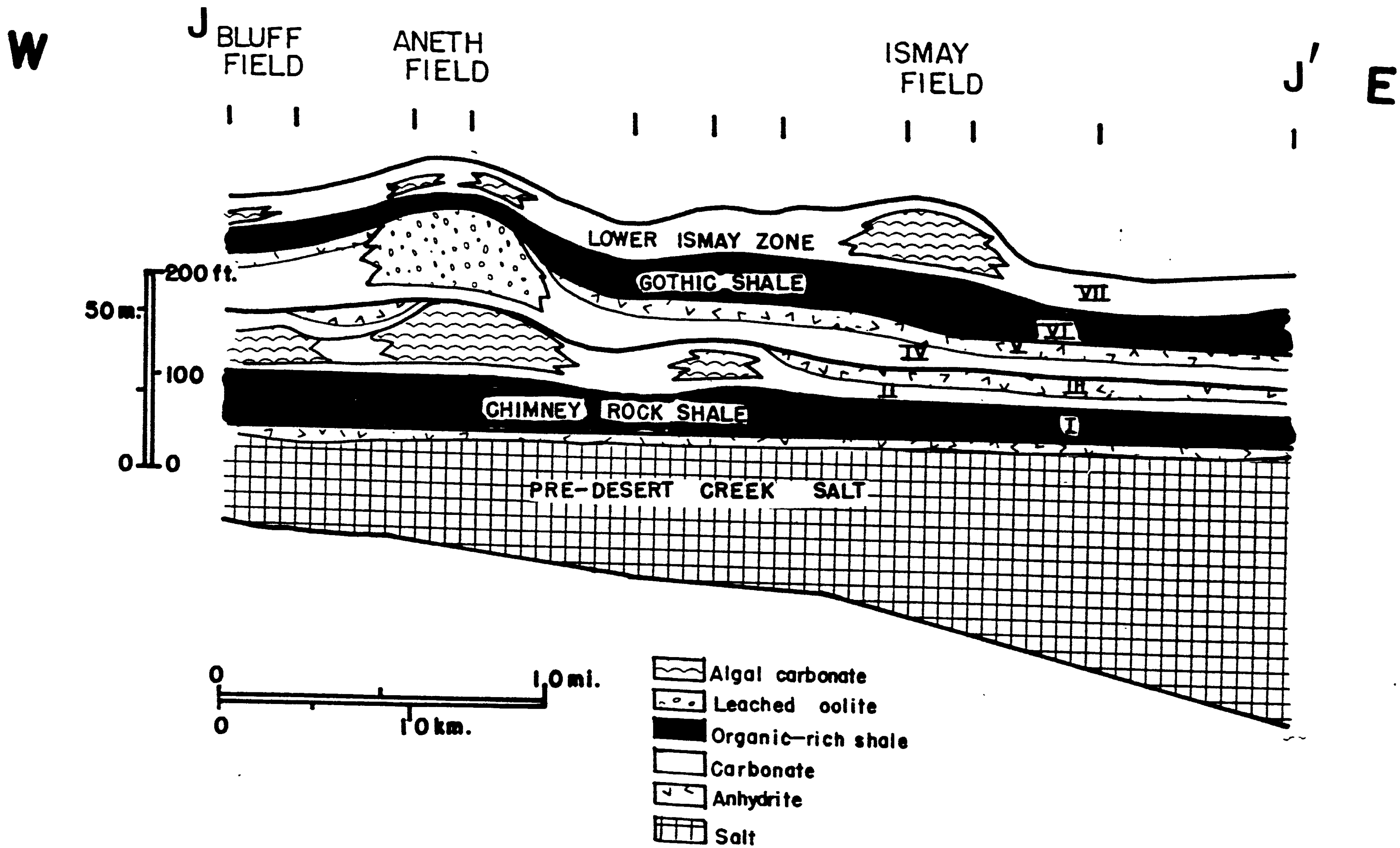


Figure 35.--West-east lithologic cross-section J-J', Aneth Oil Field to Ismay Oil Field east of Aneth, showing algal and leached oolite carbonate reservoirs. Line of cross-section shown on figure 4.

Fusulinids, other small foraminifers, some brachiopods, mollusks, and *Chaetetes* corals are present but not abundant in the algal rock unit. The better porosity is associated with pockets of maximum accumulation of leaf-like *Ivanovia* algal skeletal material, although the fine details of algal structure commonly are obscured by recrystallization, leaching, and cementation. Salinity, submarine topography, and basinal position in a non-turbid, well-circulated marine environment were important factors in positioning of the algal buildups.

The upper Desert Creek "leached oolite" facies consists largely of oolites, pellets, and coated fossil fragments that have been irregularly leached, recrystallized, and partly dolomitized (fig. 30). Oolitic and pelletal rocks generally are thicker on the borders of the main mound buildup. The inner part of the upper Desert Creek contains beds of bioclastic and recrystallized limestone mud, along with porous oolite-pelletal beds that are discontinuous in a channel-like pattern. Porosity is generally associated with leaching and partial dolomitization of the "oolite" and pellet-rock facies and is, on the average, higher than in the underlying algal facies. However, permeability of the "leached oolite" reservoir rock averages considerably lower than that of the algal reservoir (table 1). The upper oolite unit attains maximum thickness in the main mound area of the Aneth field, where it represents more than half of the porous section. Laterally, away from the Aneth mound complex, the oolite interval changes rapidly to chalky dolomite and anhydrite facies and is absent in the smaller Desert Creek mound buildups of the Blanding sub-basin (figs. 34, 35). The "leached oolite" facies also is present in the upper Desert Creek in a broad belt along the southwest basin shelf (fig. 31), where it commonly contains as much as 50 ft (15 m) or more of porous oil-stained limestone. However, along this extensive belt the Desert Creek has not been found with sufficient permeability for economic petroleum production.

Limestone mound porosity in the Ismay zone in the Aneth area is present largely in the lower Ismay, with more localized buildups in the middle and upper Ismay. Porous bodies are generally elongated northwesterly and are formed of somewhat discontinuous, irregular-shaped, narrow belts of algal limestone. This reservoir rock is similar to that of the algal and pelleted-mud reservoir rock of the lower Desert Creek zone. The lower Ismay mound reservoir is exposed in the San Juan River canyon east of Mexican Hat, Utah. The outcropping beds illustrate the discontinuous nature of individual algal buildups within the southwestern-most belt of Ismay mounds. A well drilled in the mound belt may penetrate a thickened mound of reservoir rock, whereas one drilled a short distance away may enounter a thin mound section with small recovery of hydrocarbons.

In the Ismay field area east of Aneth, the lower Ismay mound buildup is at maximum thickness along the eastern margins of the Ismay zone buildup trend passing through the Aneth area (fig. 35). Reservoir rock facies here is dominated by recrystallized algal and pelleted mud rocks similar to that of the lower Desert Creek mounds.

The sequence of depositional processes and related facies relationships of the Desert Creek cycle are visualized as follows (modified after Peterson, 1966a, Peterson and Hite, 1969):

Table 1. Reservoir Parameters, Aneth Oil Field (after McComas, 1963)

	Porosity (%)		Permeability (millidarcies) %		Residual Oil Saturation %		Total Water Saturation %		Connate Water Saturation %		Barrels of Oil in Place (range)	Estimated Recovery (% of oil in place)
	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.		
Algal reservoir	3.5–26.2	9.5	0.1–932	24	4.0–26.2	9.5	13.4–54.4	31.0	10–54	28	205–766 Barrels/acre ft	19–23
Oomoldic (leached oolite)	7.3–23.6	11.3	0.1–31	3.4	7–35	17.0	7.2–53.4	30.0	7.0–53	30		
Dolomite (inter-crystalline porosity)	8.2–32.4	13.0	0.1–83	3.0	8.5–38.8	17.0	23.5–55.8	35.0		33.0		
Leached fossil hash	0.3–18.9	6.3	0.1–1165	5.1	0.0–43.7	9.3	18–51.6	31.0		30.0		

Pre-Desert Creek evaporite phase.--Stratigraphically beneath the Aneth complex, pre-Desert Creek salt beds 100-150 ft (30-45 m) thick are overlain by a regional bed of anhydrite (figs. 34, 35). During deposition of the main pre-Desert Creek (Akah) salt facies, most of the basin area was semi-starved of clastic material, and salt deposition reached its maximum areal extent in the Paradox basin during this time.

Phase I, Chimney Rock shale.--Beginning with the Desert Creek cycle, clastic influx to the basin increased, mainly because of two factors: 1) progressive transgression of the marine shoreline toward the basin borders and consequent reworking and redeposition of clastic material accumulated on the previously exposed basin shelf, and 2) probable increase in uplift of the main clastic source areas, the Piute-Emery lowland to the west, Zuni-Defiance lowland to the south, and the Uncompahgre-San Luis highland to the northeast, on the west of which the Silverton delta began to form at this time. During rising sea-level phases of the post-salt cycles, tongues of clastic sediment extended into the basin, partly built by longshore drift related to wind and wave action and partly by extension of alluvial-deltaic distributary patterns. These clastic tongues caused variations in sea bottom topography prior to deposition of the overlying marine carbonate phase of each cycle or subcycle.

The Chimney Rock shale, comprised of silt, sand and clay to the northwest and of mixed silt, clay, and organic-rich carbonate mud to the southeast, built southeastward as an offshore bank during the early rising sea level phase of the Desert Creek cycle (fig. 36).

Phase II. Lower Desert Creek algal mound buildup.--Deposition of the longshore Chimney Rock mudbank left a broad, flat subsea platform on which initial growth of the northwest trending lower Desert Creek algal bank occurred during the continuation of the rising sea level stage of the cycle. Maximum buildup of algal material occurred at the southeastern extremity of the Chimney Rock mudbank where the Aneth field is located. At this position, optimum conditions for algal growth occurred related to moderately shallow-water depth and incoming circulation of non-turbid relatively normal marine waters. Belts of smaller mounds with northwest orientation also developed northeast of the Aneth belt where high salinity may have inhibited maximum algal growth.

Phase III. Middle Desert Creek anhydrite.--Falling sea level occurred after the lower Desert Creek algal mound buildup and resulted in exposure of the mound and widespread deposition of the middle Desert Creek anhydrite in low-lying areas of the southern basin. The middle Desert Creek anhydrite changes to halite in the basin center to the northeast (fig. 34). Early diagenesis, including leaching, partial dolomitization, and recrystallization of the algal framework probably occurred at this time. Smaller algal mounds in the Blanding sub-basin were not exposed at this time, resulting in deposition of the anhydrite unit over these mounds.

Phase IV. Upper Desert Creek "leached oolite" facies.--This unit was deposited during the second high sea-level stage of the Desert Creek cycle. These beds were deposited in shallow, non-turbid marine waters on the subsea topographic feature resulting from buildup of the underlying algal mound.

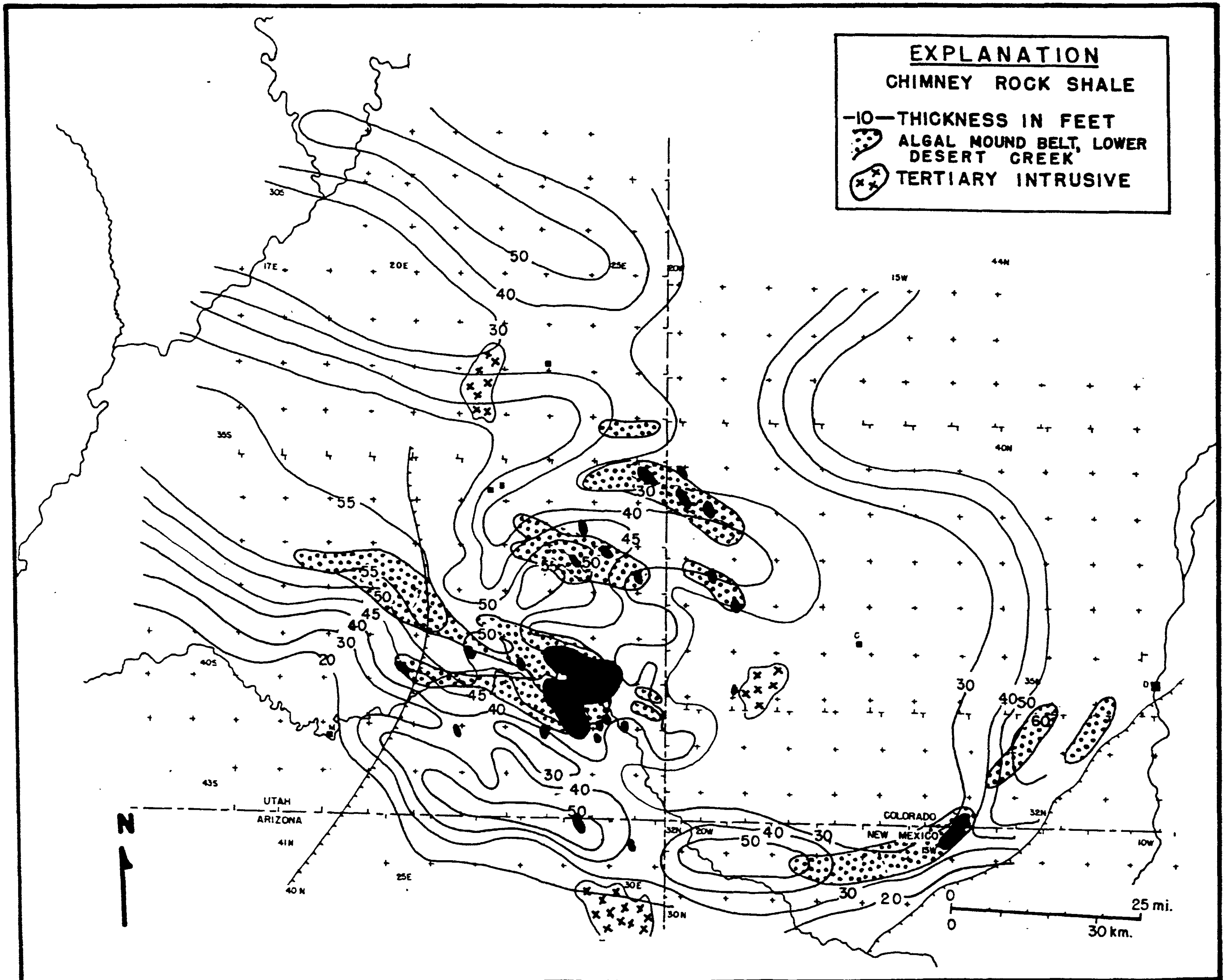


Figure 36.--Thickness in feet, Chimney Rock shale, southern Paradox basin, showing distribution of lower Desert Creek algal mound belts and oil or gas fields producing from lower Desert Creek algal carbonate reservoirs.

Phase V. Upper Desert Creek anhydrite.--The second low sea-level stage of the Desert Creek cycle resulted in a second exposure of the Aneth mound and widespread deposition of the anhydrite at the top of the Desert Creek zone. Anhydrite deposition completely surrounded the carbonate buildup and extended across the southern Paradox basin, changing to halite in the basin interior (fig. 34). Exposure of the Aneth mound at this time resulted in further leaching, partial dolomitization and recrystallization of the entire mound complex.

Ismay cycle.--Following deposition of the upper Desert Creek anhydrite, rising sea level resulted in deposition of the Gothic longshore mudbank at approximately the same position as that of the Chimney Rock (fig. 37). The Gothic mudbank covered the Aneth mound and extended to the southeast for approximately 15 miles (25 km) where the lower Ismay algal buildup occurred on the mudbank edge in the vicinity of the Ismay oil field (figs. 4, 35, 37). The Ismay cycle comprises three algal mound-bearing subcycles (lower, middle, and upper) which were deposited under conditions similar to that of the Desert Creek cycle.

Aneth Field.--The Aneth field is primarily a stratigraphic trap. The reservoir complex is an isolated carbonate mound buildup in which the oil accumulation has undergone only minor redistribution because of minor post-mound structural growth. Oil accumulation is controlled primarily by distribution patterns of individual carbonate reservoir mound buildup trends, together with porosity-permeability discontinuities within the buildup belt. Structural influence is limited to local redistribution of earlier oil accumulation within the isolated reservoir geometry during subsequent development of the structural framework of the area (Laramide). Minor local redistribution of the earlier accumulation may have occurred during Laramide and later structural growth. Judging from restored-thickness studies of the post-Ismay stratigraphic section, oil generation probably began by Early to Middle Cretaceous time. Maximum depth of burial of the Desert Creek and Ismay reservoir beds in the Blanding sub-basin area is estimated to have been approximately 10-12,000 ft (3,000-3,500 m) and probably occurred during early Tertiary time.

Production from the greater Aneth field is almost entirely from the Desert Creek zone with minor production from the lower Ismay. The Desert Creek zone is underlain by the Chimney Rock shale and overlain by the Gothic shale, (figs. 30, 33-35, 36, 37) both of which are organic-rich black sapropelic calcareous or dolomitic shale or shaly carbonate units. Both of these units, along with similar beds intertonguing with the reservoir rock, are the identified source rocks for the Desert Creek and Ismay oils.

The Aneth field includes two productive zones, Zone II, the lower Desert Creek algal reservoir, and Zone I, the upper Desert Creek "leached oolite" reservoir. Porous intervals in both zones tend to be lensing in nature with rapid lateral and vertical changes (fig. 33), although most are interconnected to varying degrees. Porosity in both zones has been enhanced by dissolution, recrystallization, and secondary dolomitization. On the flanks of the Aneth mound buildup, an 8-10 ft (2.5-3m) bed of anhydrite occurs at the top of each zone, but in each case the anhydrite pinches out around the edges of the mound (figs. 34, 35).

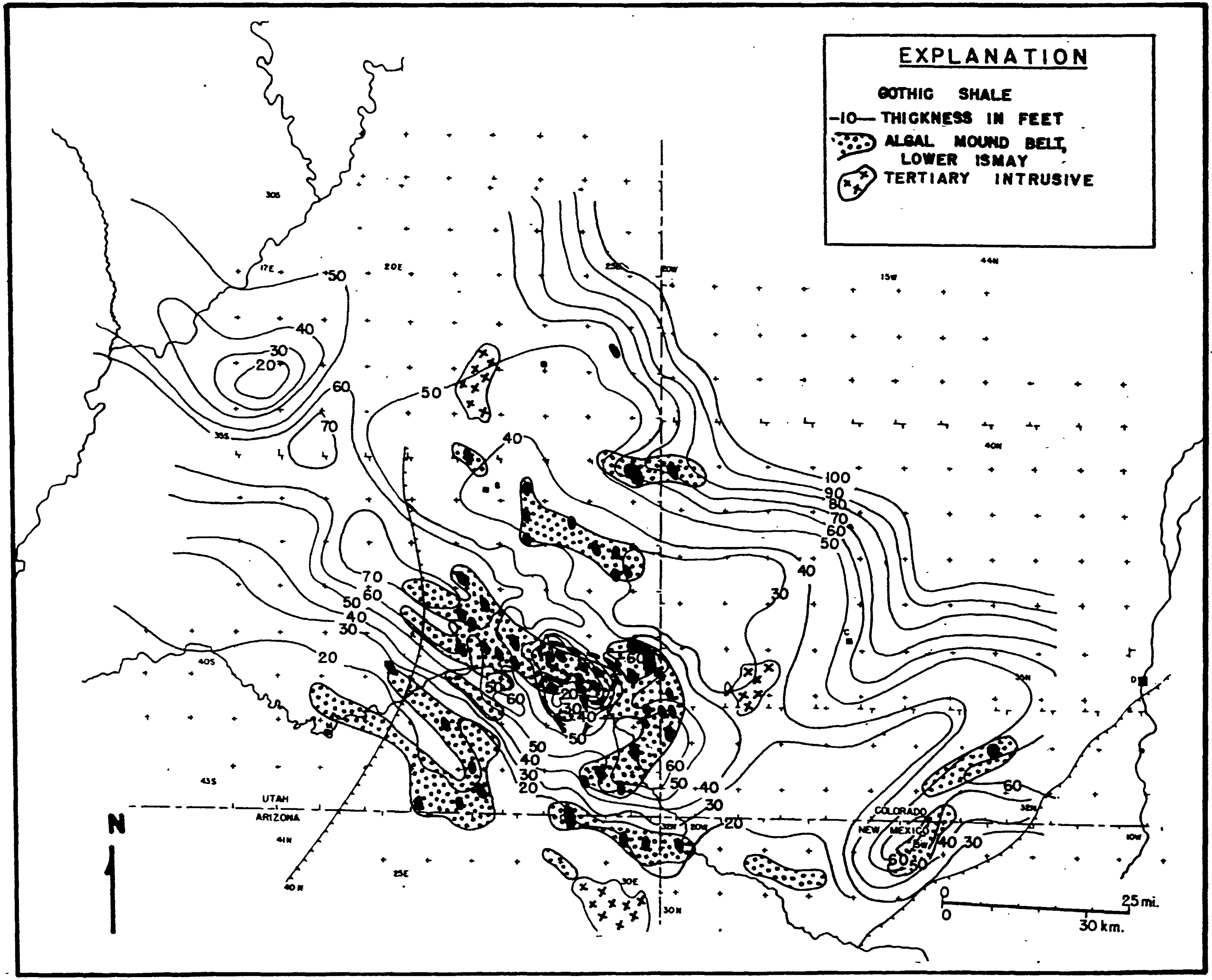


Figure 37.--Thickness in feet, Gothic shale, southern Paradox basin, showing distribution of lower Ismay algal mound belts and oil or gas fields producing from lower Ismay algal carbonate reservoirs.

Thickness of the Desert Creek zone in the greater Aneth area is as much as 200 ft (60 m) but decreases rapidly to 100 ft (30 m) or less away from the mound in the surrounding evaporitic facies (figs. 31, 34, 35). The eastern flank of the mound complex is steepest with relief of more than 100 ft (30 m) in less than one mile in places. The combined pay thickness of both zones averages about 50 ft (15 m) but reaches 100 ft (30 m) or more in some parts of the field. Productive limits of the field are generally determined by porosity and permeability changes related to carbonate facies changes, mound pinchouts, and anhydrite sealing near the periphery of the mound buildup. An unusual aspect of the Aneth mound reservoir complex is that it is almost completely filled with oil. A relatively small volume of porous, water-wet reservoir is present around the periphery of the mound (figs. 32, 33).

Many of the smaller mounds in the Blanding sub-basin area tend to show porosity filling by anhydrite and may have reasonably good porosity but low permeability.

PRINCIPAL PLAYS

Seven main plays are defined in the Paradox basin assessment province (fig. 1):

I. Porous carbonate buildups, Hermosa Group.
II. Buried fault blocks, Older Paleozoic.
III. Salt anticline flanks.
IV. Fractured interbeds, Paradox Formation.
V. Silverton delta.
VI. Wasatch Plateau.
VII. Kaiparowits basin anticlines.

Play I: Porous carbonate buildups, Hermosa Group.

Reservoirs.--The most important petroleum production in the Paradox basin province is from stratigraphically controlled carbonate reservoirs in the southern part of the Paradox salt basin. This play is predominantly oil-bearing with only moderate amounts of associated gas. Reservoirs occur in a series of depositional cycles in the carbonate facies of the Hermosa Group of Middle Pennsylvanian age. The cycles of the carbonate facies pass laterally into evaporite cycles of the Paradox Formation deeper in the basin.

Source Rocks.--Organic-rich black shales or shaly carbonates of the Chimney Rock and Gothic shales are the main source rocks in this play, along with intertonguing organic-rich and shaly carbonates adjacent to the mound buildups. In the Blanding sub-basin area, total organic carbon (TOC) values for the Chimney Rock shale range from approximately 1.0 to more than 3.0 percent, and values for the Gothic shale range from approximately 1.5 to near 4.0 percent (Hite and others, 1984; Shell Oil Co., personal communication, 1988). Organic-rich shales in the Paradox evaporite cycles below the Desert Creek may show as high as 13.0 percent TOC values (Hite and others, 1984). Data from core samples of the Gothic shale show that through a thickness of about 30 ft (9 m) this shale averages 2.5 percent TOC (Hite and others, 1984). Extractable organic matter (EOM) from this shale gave a calculated genetic potential of nearly 5,000 barrels of oil per acre-ft. Vitrinite reflectance (R_o) values in limited available core samples near the Aneth field are approximately 1.5; mean vitrinite reflectance (R_o mean) values may range between 1.3 and 2.0 for the Chimney Rock shale and 0.8 and 1.2 for the Gothic shale (Shell Oil Co., personal communication, 1988).

Crude oil from the Hermosa play is low sulfur and 40° to 43° API gravity. The associated gas has Btu values of over 1,000. Depths to production average about 5,500-6,000 ft (1,700-2,000 m). The Aneth field, by far the largest in this play, has produced approximately 400 MMBO and 350 BCF of gas.

Traps and Seals.--Accumulations occur primarily in isolated carbonate buildup belts that may or may not be associated with mapped structures. Structural closure is commonly influenced to varying degrees by draping over mound buildups. Lateral facies changes from porous biogenic reservoir rock to non-porous argillaceous or anhydritic carbonate and shale aid in trapping. Seals are commonly black, organic-rich high-carbonate shales or shaly carbonates and anhydrites. Basinal mound buildups, much smaller than those in the Aneth area, are usually sealed by overlying anhydrite beds.

Generation, Timing, and Migration.--Oil generation probably began in Late Cretaceous time and probably has continued to the present. In most cases, migration was probably coincident with generation with some adjustment related to late structural growth. Present-day thermal gradients in the basin are near normal, approximately 2.2 - 3.3°/100m (1.2 - 2.0°F/100 ft).

Exploration Status.--This play is moderately to well explored, but use of high resolution seismic techniques and detailed stratigraphic studies probably will result in discovery of small- to medium-sized new field or new pool accumulations, primarily in stratigraphic traps.

Estimated Ultimate Recovery from Existing Fields.--Approximately 500 MMBO.

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--14.0 MMBO in fields greater than 1 MMB, 13.3 BCF gas and 1.1 MMB NGL in fields greater than 6 BCF.

Total Area of Play.--Approximately 2,800 mi^2 (7,800 km^2).

Play II: Buried Fault Blocks, older Paleozoic, Leadville Limestone (Mississippian) and McCracken Sandstone (Devonian)

The 1960 discovery of the Lisbon Oil Field, largest in the play, stimulated intensive seismic exploration throughout the salt anticline region. This seismic work outlined most of the larger fault blocks and most of these were subsequently drilled. However, because some of the fault systems are complex and the seismic coverage is widely spaced, there are many small scale structures yet to be identified. The Lisbon field is the largest in the play with estimated ultimate recoverable reserves of approximately 43 MMBO and 250 BCF gas. In addition to Lisbon, there are five other small fields in this play, of which only the Salt Wash field has had significant production, approximately 1.3 MMBO and 12 BCF gas.

Reservoirs.--The principal productive formations in this play are the Leadville Limestone of Mississippian age and the McCracken Sandstone of Late Devonian age. The Leadville is the most important reservoir because of widespread porosity and permeability in dolomitized beds interbedded with limestones. In general, the Leadville comprises an upper limestone facies, commonly oolitic or crinoidal, and a lower dolomite facies with minor evaporites. The most favorable reservoir development is in the dolomite facies where good porosity and permeability result from dolomitization, selective leaching of crinoidal debris, and vertical fracturing.

Source Rocks.--Probable source rocks for this play are the organic-rich black shales of the Paradox Formation. Migration into Leadville or McCracken reservoirs has occurred where the fault blocks are in structural and/or depositional contact with the black shales, which are commonly highly fractured.

Traps and Seals.--Known accumulations are on uplifted fault blocks adjacent to salt anticlines or swells. Seals are Paradox Formation evaporite beds, which overlie and are in fault contact with the Mississippian or Devonian reservoirs.

Generation, Timing, and Migration.--Hydrocarbon generation probably began as early as Permian time and has continued to the present in some areas. Migration into pre-salt reservoirs was probably contemporaneous with Pennsylvanian and later growth of salt structures and was enhanced by severe fracturing of interbedded organic-rich shales during salt movement.

Depth Range.--6,000 to 15,000 ft (1,900 to 4,500 m).

Exploration Status.--This play is only moderately explored, with respect to small fields, although it is unlikely that additional fields similar in size to Lisbon will be discovered. Previous production history indicates that many accumulations will probably have thin oil columns and the associated gas will have relatively low Btu values. Future exploration will be constrained by drilling costs, the necessity for high resolution and closely spaced seismic data, and the problems of connecting small fields with existing pipelines.

Estimated Ultimate Recovery from Existing Fields.--Approximately 50 MMBO and 300 BCF gas.

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--9.4 MMBO in fields greater than 1 MMB and 27.9 BCF gas and 1.5 MMB NGL in fields greater than 6 BCF.

Total Area of Play.--Approximately 7,500 mi^2 (20,000 km^2).

Play III: Salt Anticline Flanks - Cutler Formation (Permian) and Honaker Trail (upper Hermosa) Formation (Pennsylvanian)

This play is associated with the northwest-trending salt anticlines in the Paradox fold and fault belt. Each anticline consists of a long undulating welt or pillow of Paradox Formation salt over which younger rocks are arched in anticlinal form. The central or salt-bearing cores of the anticlines range in thickness from 2,500 to more than 14,000 ft (770 to more than 4,300 m). The anticlines are flanked by deep synclines, which are mainly filled with 10,000 ft (3,000 m) or more of Permian Cutler Formation arkosic clastics and a mixed sequence of upper Hermosa (Honaker Trail) Formation clastics and carbonates.

Reservoirs.--The main reservoirs in this play are pelletal and oolitic limestones and occasional sandstones in the Honaker Trail Formation and arkosic sandstones in the Cutler Formation. Vertical communication between these reservoirs is probably common because of strongly developed fracture systems resulting from strong subsidence in the synclines and related salt movement and flowage into the adjacent salt anticlines.

Source Rocks.--Several potential sources for hydrocarbons are involved with this play. The organic-rich Paradox black shales are commonly in contact with the reservoir rocks along margins of the salt structures and may also be sufficiently connected by fracture or fault systems to allow vertical migration under the synclines. Honaker Trail shales with TOC values as high as 2.5 percent also are potential source rocks. Some coaly carbonaceous shales are locally present at the Cutler-Honaker Trail contact and may be the source for some gas accumulations. No data are available on maturity of these source rocks; however, vitrinite reflectance values from outcrops of the Lower Cretaceous Dakota Sandstone in the play area range from 0.60 to 1.20. These values suggest that the source rocks, which are presently buried to depths of 4,000 to more than 10,000 ft (1,200 to more than 3,000 m) in the synclines, are mature to post-mature.

Traps and Seals.--Stratigraphic and stratigraphic-structural traps occur in these rocks as the result of thinning and permeability pinchouts along the steeply-dipping flanks of salt anticlines. Some traps may also be the result of updip termination against the salt diapirs.

Generation, Timing, and Migration.--Hydrocarbon generation in the deeper parts of the basin probably began by Late Pennsylvanian or Permian time. Migration was coincident with salt movement and anticlinal growth and probably continues today.

Depth Range.--Approximately 5,000 to more than 15,000 ft (1,500 to more than 4,500 m).

Exploration Status.--A large amount of acreage is involved in this play and it has only been lightly explored. Four gas fields are present, only one of which has had significant production (Andy's Mesa field - 6 producing wells) with cumulative production of 16 MCF gas and 11,000 barrels condensate. The other three fields are small one-well fields.

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--9.7 MMBO in fields greater than 1 MMB and 104.2 BCF gas in fields greater than 6 BCF.

Total Area of Play.--Approximately 7,500 mi^2 (20,000 km^2).

Play IV: Fractured Interbeds, Paradox Formation (Pennsylvanian)

This play covers the deep structural trough of the Paradox basin and includes the Paradox fold and fault belt. The central basin trough contains a thick fill of Middle Pennsylvanian evaporites, the Paradox Formation of the Hermosa Group. The structural trough is characterized by long belts of salt anticlines and faulting which for the most part are associated with salt dissolution or flowage.

The Paradox evaporite facies consists of evaporite cycles, which include thick units of halite and thinner interbeds of black organic-rich shale, dolomite, and anhydrite.

Reservoirs, Source Rocks, Traps, and Seals.--The reservoirs in this play are also the source rocks. These rocks consist of fine-grained very silty dolomite and dolomitic or calcareous black shale. They are characterized by very low matrix permeability and are sealed above and below by thick beds of halite. Generated hydrocarbons have tended to remain in place with minimal lateral migration. Analyses of some of the richer beds indicate that as much as approximately 5,000 barrels per acre-ft of in-place unmigrated oil is present. As a rule, oil and gas shows are almost always encountered in the interbeds, but economic accumulations depend heavily on the intensity of fracturing. Because of impermeable thick salt seals, overpressuring is common, and many spectacular "blowouts" have been encountered during drilling.

Exploration Status.--Exploration for these fractured reservoirs is difficult because the fracturing mechanism and the patterns of fracturing are not well understood. There seems to be a general correlation between northeast-trending structural lineaments and production (Hite, personal communication, 1989). Some of the lineaments are thought to represent basement shear zones that in some way have propagated stress through the thick evaporite sequence. Because the interbeds have different rheological characteristics (brittle failure) than do the halite layers (plastic failure), it is possible that the thickest interbeds are most likely to develop the most intense fracture patterns. This belief is supported by the fact that most production from these beds has been from the thickest interbed, the "Cane Creek" marker bed, locally more than 150 ft (45 m) thick.

This is a demonstrated play, although almost all petroleum discoveries were accidental and made while drilling for deeper objectives. All existing fields are single well fields with one well having produced about 1.2 MMBO. This play may rightfully be considered as unconventional because its success may be dependent on improved drilling, completion, and stimulation technology. Horizontal drilling techniques may be a significant factor in future exploration programs. However, considering the large volume of hydrocarbons that may be trapped in the fractured interbeds and the fact that direct exploration for this type of accumulation has not been attempted, the potential for significant resources may be great, although difficult to realize.

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--124.8 MMBO in fields greater than 1 MMB, 124.8 BCF gas in fields greater than 6 BCF.

Total Area of Play.--Approximately 7,500 mi^2 (20,000 km^2).

Play V: Silverton Delta, Northeast Paradox Basin - Honaker Trail Formation (Pennsylvanian)

Along the east flank of the Paradox Salt basin, the Honaker Trail Formation of Pennsylvanian age contains an easterly-derived clastic facies known as the Silverton fan delta (Spoelhoef, 1976). The delta is made up of numerous depositional cycles, each of which includes a prodelta facies of dark marine shale. The prodelta units are believed to be correlative with the black organic-rich shales of the carbonate-evaporite cycles farther out in the basin. Isopach maps of individual black shale units indicate that many of them thicken significantly in the vicinity of the delta complex.

Reservoirs.--Limited subsurface data are available on the potential sandstone reservoirs of this play. However, some of these rocks crop out east of the San Miguel Mountains where the delta-front sandstones have been described as well-sorted, fine- to medium-grained, and arkosic (Spoelhoef, 1976). The arkosic and calcareous nature of much of the clastic section may be detrimental to consistently good porosity and permeability, but the variable energy regime of the deltaic depositional environment should enhance reservoir characteristics in many sandstone units.

Source Rocks.--Dark gray or black marine shales of potential source rock quality intertongue with the marine and delta front sandstone facies along the western margin of the Uncompahgre-San Luis highland. These rocks are organic-rich in the central basin region and probably become more humic in character in the deltaic complex where land-derived organic matter is more prevalent. The presence of large igneous intrusions (San Miguel and La Plata Mountains) suggests that greater maturation levels may be expected in parts of the area. The probability of type III kerogen plus higher heat flow indicate that the Silverton delta area will be gas prone.

Exploration Status.--This play is speculative and drilling density in the area is very low. At least one well located on the northwest margin of the play had significant gas shows in sandstones of the Honaker Trail which are probably part of the Silverton fan delta complex. Negative aspects of this play include the fact that many of the potential reservoir rocks crop out updip from the play area, increasing the probability of trap leakage and flushing of reservoirs by ground water recharge.

Traps and Seals.--Traps should be combination structural-stratigraphic on folded and faulted structures of variable size. The presence of distributary, delta fringe, and longshore sand bodies within the deltaic complex offer potential stratigraphic trap possibilities.

Depth Range.--3,000 - 20,000 ft (900 - 6,000 m).

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--Accumulations in this play are expected to be less than 1 MMBO or 6 BCF gas in size.

Total Area of Play.--Approximately 1,500 mi^2 (4,000 km^2).

Play VI: Wasatch Plateau - Ferron Sandstone Member (Cretaceous).

The Wasatch Plateau is a 75-mile (120 km) long and a 25-mile (40 km)-wide structural terrace, which is bounded on the east by the San Rafael uplift, on the west by the Sanpete-Sevier Valley, and on the north by the Uinta Basin. The area is characterized by a series of long continuous anticlines or faulted structures which parallel the trend of the San Rafael uplift. The anticlines are broken in the western half of the area by a complex series of north-south trending grabens, which may be the result of flowage or dissolution of salt in the underlying Jurassic evaporites. The play is confined to that part of the Plateau underlain by the Cretaceous Ferron Sandstone Member of the Mancos Shale.

Reservoirs.--The Ferron Sandstone appears to be part of two coalescing westerly-derived delta complexes. Permeable zones are present in both the delta front and in distributary sand bodies. Locally, as many as seven separate sands are present in the Member.

Source Rocks.--The Mancos Shale beds, which enclose the Ferron Sandstone facies are potential source rocks for this play. However, because only gas has been produced from the Ferron, it seems likely that the coals and carbonaceous shales which intertongue with the sandstone bodies are the source of the gas. Data are not available on maturation of these rocks, but because the Ferron is overlain by coal-bearing units of the Mesaverde Group which are ranked as sub-bituminous, the Ferron beds should be mature or overmature.

Traps and Seals.--The entrapment of gas in this play is related to structural closure on simple anticlinal folds and complexly faulted anticlines. Up-dip pre-faulting migration toward the depositional edge of the Ferron may also have influenced accumulation. Discontinuous sandstone bodies in the deltaic complex also offer the possibility of stratigraphic trap accumulations.

Depth Range.--Less than 1,000 ft (350 m) along the edge of the San Rafael Swell to more than 7,000 ft (2,100 m) in the western part of the play.

Exploration Status.--This play can probably be considered as moderately explored. Most of the larger traps have been drilled, but many small structures are untested. To date, six fields have been discovered, although several of these have been abandoned.

Cumulative Production.--Approximately 200 BCF of dry gas which averages about 1,000 Btu per ft^3.

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--Accumulations in this play are expected to be less than 1 MMBO or 6 BCF gas in size.

Total Area of Play.--Approximately 3,200 mi^2 (8,300 km^2).

Play VII: Kaiparowits Basin Anticlines

The Kaiparowits basin, which forms the limits of this play, is a structural basin whose boundaries are loosely defined by the Circle Cliff's uplift on the east and the Paunsaugunt fault system on the west (fig. 2). The area is characterized by a series of gentle but continuous folds whose axial trend is more or less northwest-southeast. At the surface, some of the fold axes have been mapped for more than 30 miles (78 km). The limited amount of subsurface data in the region suggests that the axial planes of many folds are tilted so that surface closure may not correspond to closure at depth. In general, the age of the folding is considered to be Laramide.

Reservoirs.--The only commercial production from this play is from the Kaibab Limestone of Permian age and the Timpoweap Member of the Triassic Moenkopi Formation. Reservoir rock in the Kaibab consists of dolomitized skeletal limestone. Supratidal dolomites are the reservoirs in the Timpoweap. The Redwall Limestone of Mississippian age is a potential reservoir in this region but these beds have been water-wet where drilled.

Source Rocks.--Data on potential source rocks are sparse. However, oil and gas shows are common. Potential source rocks are present, the supratidal argillaceous limestone beds of the Kaibab Limestone, the silty and argillaceous dolomites or siltstones of the lower Moenkopi (Sinbad or Timpoweap members), and the organic-rich shales of the Proterozoic Chuar Group.

Exploration Status.--Drilling density is very low in this region. Several of the larger anticlines have been drilled on the highest point of surface closure, although surface structure in this region does not necessarily coincide with structure at depth. Furthermore, a strong hydrodynamic drive is identified at the Upper Valley field, resulting in a tilted oil-water contact. Similar hydrodynamic conditions may exist on other anticlines in the area. Thus, some of the drilled anticlines may not have been adequately tested. Considering the number and size of the anticlines involved in this play and the apparent inadequate testing of hydrodynamic aspects of the region, this play may be considered as lightly explored.

Traps and Seals.--Potential traps are elongate anticlines and faulted anticlines, several of which have been drilled. Seals are red and gray shales of the Moenkopi Formation (Triassic).

Cumulative Production.--The only commercial field in this play is the Upper Valley oil field with cumulative production of about 20 MMBO. The oil is low gravity (19.3° to 26.0° API) and contains only a small amount of gas which is primarily CO_2.

U.S.G.S. Mean Estimate of Undiscovered Petroleum Resources.--Accumulations in this play are expected to be less than 6 BCF gas in size.

Total Area of Play.--Approximately 3,000 mi^2 (7,800 km^2).

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