Chapter 9

Geologic Assessment of the Phosphoria Total Petroleum System, Uinta-Piceance Province, Utah and Colorado

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By Edward A. Johnson

Chapter 9 *of*

Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado

By USGS Uinta-Piceance Assessment Team

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Abstract

The Phosphoria Formation was deposited during Early to Late Permian time in the central part of an epicontinental marine embayment on the western margin of the North American craton. This embayment, known as the Sublett Basin, covered an area of about 100,000 square miles, and the Phosphoria sea occupied its central part. The Phosphoria is now present in parts of six States in the north-central Rocky Mountains.

The Meade Peak Phosphatic Shale and Retort Phosphatic Shale Members of the Phosphoria contain organic claystone, muddy siltstone, phosphorite, and dolomitic calclithite. Total organic carbon in these members averages 10 percent (locally as high as 30 percent), which in conjunction with their broad areal extent and level of thermal maturity qualifies them as major source rocks for hydrocarbons. The Retort is absent in northeastern Utah and northwestern Colorado, and although the Meade Peak is present in northeastern Utah, its relatively low total organic carbon content excludes it from being a major source of hydrocarbons for that area. North of the Uinta-Piceance Basins, in the primary domain of the former Phosphoria sea, the Meade Peak and Retort were buried deeply enough to generate hydrocarbons. This process might have started as early as the Late Triassic and continued until the close of the Cretaceous. Phosphoria-sourced oil, estimated to be as much as 225 billion barrels, began migrating up dip through carrier beds in the Late Jurassic and probably reached the area of the future Uinta-Piceance Basins in Early Cretaceous time. Migration ceased in the Late Cretaceous as the Laramide orogeny caused local uplifts that disrupted the continuity of the carrier beds.

Oil from the northern Piceance Basin that is chemically consistent with oil in western Wyoming known to be sourced from the Phosphoria is contained in several lithostratigraphic units. Most prominent is the Weber Sandstone at the Rangely oil field, but Phosphoria-type oil has also been identified at oil fields in the greater Danforth Hills area in the Shinarump Member of the Chinle Formation, Entrada Sandstone, Sundance Formation, and Morrison Formation. In addition, Phosphoria-type oil mixed with Cretaceous-type oil has been identified in the Morrison Formation and Dakota Sandstone. Phosphoria-sourced oil is present in what is interpreted to be a stratigraphic-structural trap at the Rangely oil field, and in structural traps such as the thrusted anticlines in the greater Danforth Hills area and the nonthrusted anticlines in the greater Cisco area and the Douglas Creek area.

The contribution of Phosphoria-sourced oil to the hydrocarbon resources of the Uinta-Piceance Province (roughly coincident with the combined Uinta and Piceance Basins) is evaluated in two assessments units. The Hanging Wall Assessment Unit includes all conventional hydrocarbon accumulations contained in stratigraphic-structural traps and in structural traps associated with thrusted anticlines within a belt of such structures marginal to the northern and northeastern boundary of the province. Although three possible source rocks are considered in the assessment unit, Minturn Formation, Phosphoria Formation, and undivided Mancos and Mowry Shales, hydrocarbons sourced from the Phosphoria are volumetrically the most significant. Hydrocarbons have been reported from 18 individual lithostratigraphic units variously distributed in 20 oil or gas fields. Of the 18 units, 11 were included in the 10 fields (7 oil fields and 3 gas fields) that exceed the minimum field size established for the petroleum resource assessment (0.5 million barrels of oil equivalent). This assessment unit contains estimated mean values of 4.47 million barrels of undiscovered oil, 28.15 billion cubic feet of undiscovered gas, and 0.94 million barrels of undiscovered natural gas liquids as potential additions to reserves in a 30-year forecast span.

The Paleozoic/Mesozoic Assessment Unit includes all conventional hydrocarbon accumulations sourced from Paleozoic rocks, or a combination of Paleozoic and Mesozoic rocks, south of the Hanging Wall Assessment Unit. Although various units are source-rock candidates, hydrocarbons derived from the Phosphoria are probably volumetrically the most significant. The accumulations are present in anticlinal structures associated with either the Douglas Creek arch or the Uncompahgre uplift. Hydrocarbons included in this assessment unit have been reported from 6 individual lithostratigraphic units variously distributed in 14 oil or gas fields. Of the six units, four were included in the four fields (two oil fields and two gas fields) that exceeded the minimum field size chosen for the assessment. This assessment unit contains estimated mean values of 6.29 million barrels of undiscovered oil, 49.93 billion cubic feet of undiscovered gas, and 1.65 million barrels

of undiscovered natural gas liquids as potential additions to reserves in a 30-year forecast span.

Introduction

During the middle part of the Mesozoic Era, the Lower to Upper Permian Phosphoria Formation was a significant contributor of hydrocarbons to the area that is now the Uinta-Piceance Basins (fig. 1). The basin straddles the State line that separates northwestern Colorado from northeastern Utah. As the name implies, the basin has two parts—the Uinta Basin on the west and the Piceance Basin on the east. The two parts are separated by the north-trending Douglas Creek arch, which parallels the State line along the Colorado side, and are commonly discussed together because of similar depositional and structural histories. Clockwise, the Uinta-Piceance Basins are bounded on the north by the Uinta Mountain uplift, on the northeast by the Axial Basin uplift, on the east by the White River uplift, on the southeast by the Gunnison uplift, on the south by the Uncompahgre uplift, on the southwest by the San Rafael Swell, and on the west and northwest by the Wasatch Plateau. The Uinta Basin extends east-west for about 120 mi along its northern edge and is as much as 100 mi wide in the north-south direction along the west side of the Colorado-Utah State line. Vernal, Utah, is located in the northern part of the basin and is the largest town in the basin. The Piceance Basin trends north-south in its northern one-third and southeast in its southern two-thirds. Overall, the basin is about 100 mi long and 40–50 mi wide. Grand Junction, Colo., is located in the southern part of the basin and is the largest town in the basin. For the purpose of petroleum resource assessment, the Uinta-Piceance Province was established by the U.S. Geological Survey (USGS) (fig. 1), and this assessment area, covering approximately 28,700 mi^2, roughly coincides with the geologically defined Uinta-Piceance Basins.

It has long been established that the Phosphoria generated a considerable amount of hydrocarbons that are now contained in a wide variety of lithostratigraphic units in the north-central Rocky Mountains (Cheney and Sheldon, 1959; Sheldon, 1967; Claypool and others, 1978; and Maughan, 1984). Because of the contribution of the Phosphoria to the petroleum potential of the region, the formation's source rocks and their maturation history, along with the resulting fluid migration and eventual accumulation in various reservoir rocks, are combined here into a single total petroleum system for the purpose of resource assessment.

Numerous workers have postulated that Phosphoria-sourced oil is present in the northern part of the Uinta-Piceance Basins (Stone, 1967; Barbat, 1967; Whitaker, 1975; Fryberger, 1979; Maughan, 1984, 1975; Koelmel, 1986; Fryberger and Koelmel, 1986; Stone, 1986; and Hefner and Barrow, 1992). Of particular significance is the voluminous amount of Phosphoria-type oil contained in the Middle Pennsylvanian to Lower Permian Weber Sandstone at the Rangely oil field in northwestern Colorado. In addition, chemical analyses of certain oils collected from the Weber and other formations at widely spaced oil fields throughout the basins show a strong correlation with the oil contained in the Weber at Rangely (Lillis and others, Chapter 3, this CD-ROM). In some cases, the oil is identical to that at Rangely, and in other cases the oil appears to be a mixture of Rangely-like oil and oil from another source. Because the presence of Phosphoria-sourced oil in the basin is established, and because, at least at Rangely, it is present in significant quantity, the Phosphoria Total Petroleum System (TPS) was established as one of five total petroleum systems considered in the USGS petroleum resource assessment of the Uinta-Piceance Province.

As a first step in studying the Phosphoria TPS, a regional polygon was established enclosing the area within the Uinta-Piceance Basins where Phosphoria-sourced oil might have migrated (fig. 2). The west, north, and east edges of the polygon mostly coincide with the province boundary but the southern edge is more difficult to define. By overlaying the Pennsylvanian and Permian paleogeographic maps of Mallory (1972), a map was compiled to show the maximum extent of the Pennsylvanian-Permian Quadrant-Tensleep-Weber erg in the north-central Rocky Mountains (fig. 3). The southern extent of the erg, now represented by the Weber, a major carrier bed for Phosphoria-sourced oil, lies within the Uinta-Piceance Province and the southeastern extent of the Weber was used as the southeast edge of the Phosphoria TPS polygon (fig. 4). The southern edge of the polygon coincides with the southernmost extent of Phosphoria-type oils contained in the USGS collection from the Uinta-Piceance Basins (Lillis and others, Chapter 3, this CD-ROM). Based on a map showing the regional extent of the Phosphoria and its stratigraphic equivalents originally constructed by McKelvey (1949) and reproduced by Swanson and others (1953), marine carbonates of the Lower to Upper Permian Park City Formation that are coeval with the Phosphoria are present in the northern part of the Uinta-Piceance Province (fig. 5). Because the Phosphoria (or, more probably, the Park City) is reported to produce oil (most likely Phosphoria sourced) in northern Utah (Stowe, 1979), the southwest edge of the Phosphoria TPS polygon coincides with the southern extent of the Park City in the province.

Throughout the Paleozoic Era and first half of the Mesozoic Era, the area that is now the Uinta-Piceance Basins was located between the North American craton on the east and the open Cordilleran sea on the west. During this lengthy time interval, various eustatic changes in sea level resulted in a variety of depositional settings, and the resulting sedimentary deposits represent such diverse environments as marine carbonate shelves (for example, the Mississippian Madison Limestone), broad alluvial plains (for example, the Upper Triassic Chinle Formation), and regional dune fields (for example, the Middle Jurassic Entrada Sandstone). A major uplift of the region during the Cretaceous Period caused the

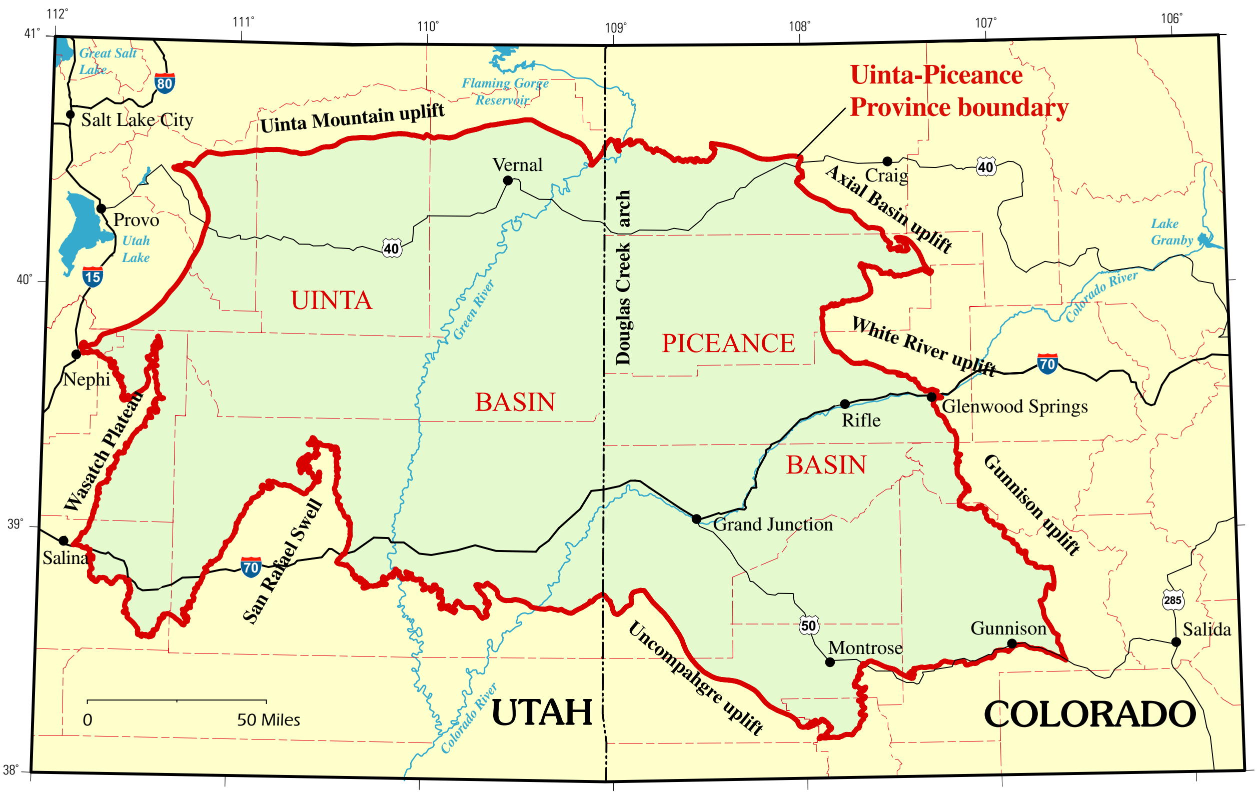


Figure 1. Index map of the Uinta-Piceance Province. Province boundary roughly coincides with the geologically defined Uinta-Piceance Basins.

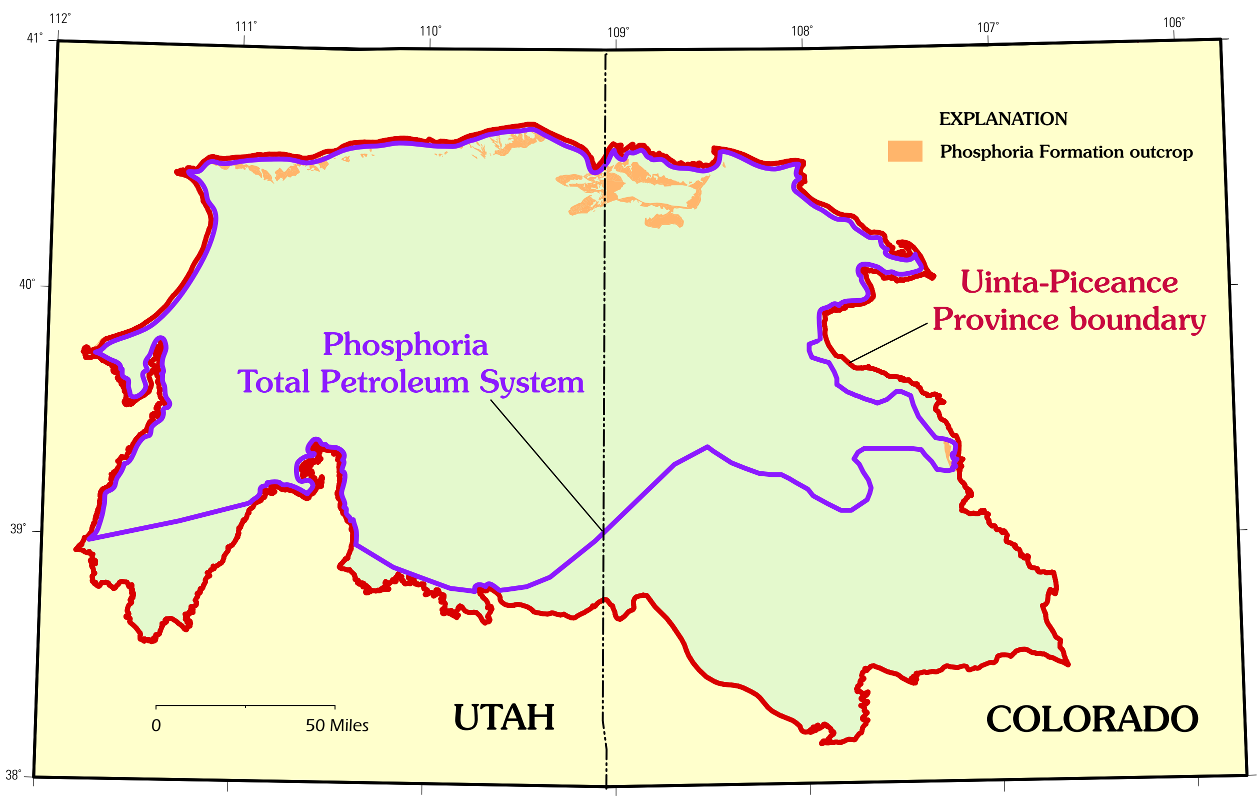


Figure 2. Extent of the Phosphoria Total Petroleum System in the Uinta-Piceance Province.

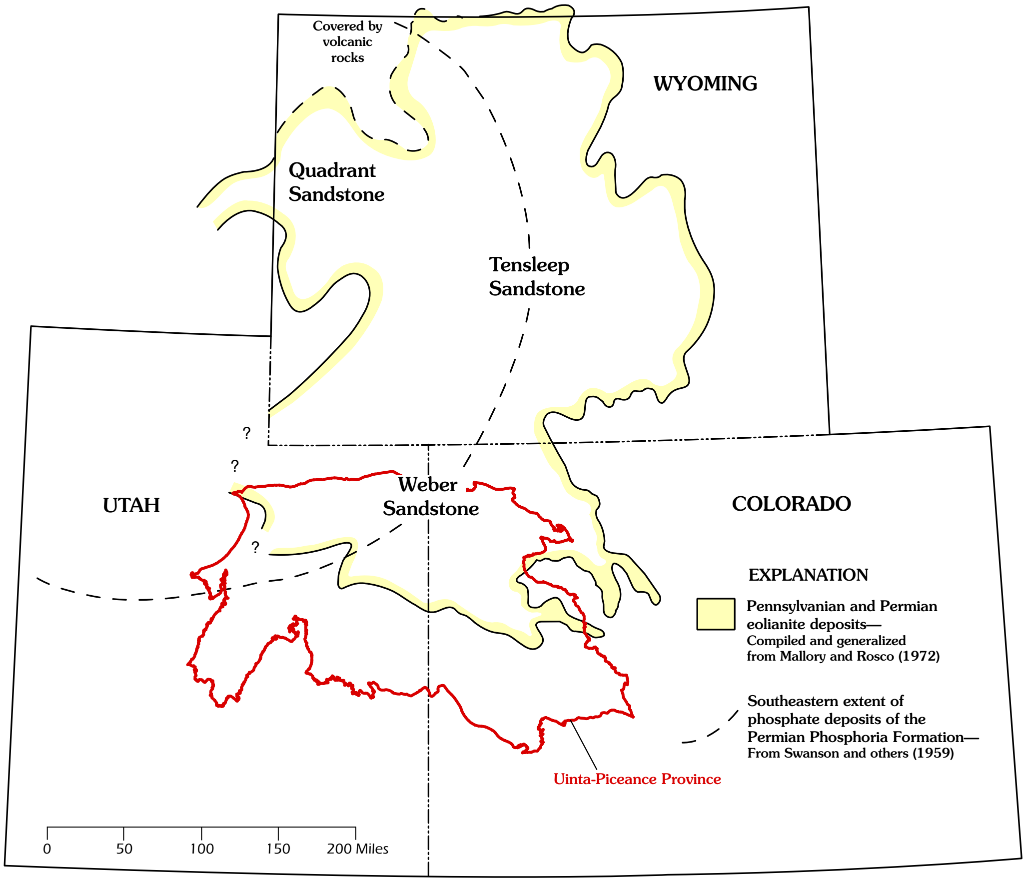


Figure 3. Approximate maximum extent of Pennsylvanian-Permian eolian deposits of the Quadrant-Tensleep-Weber erg in the northern Rocky Mountains.

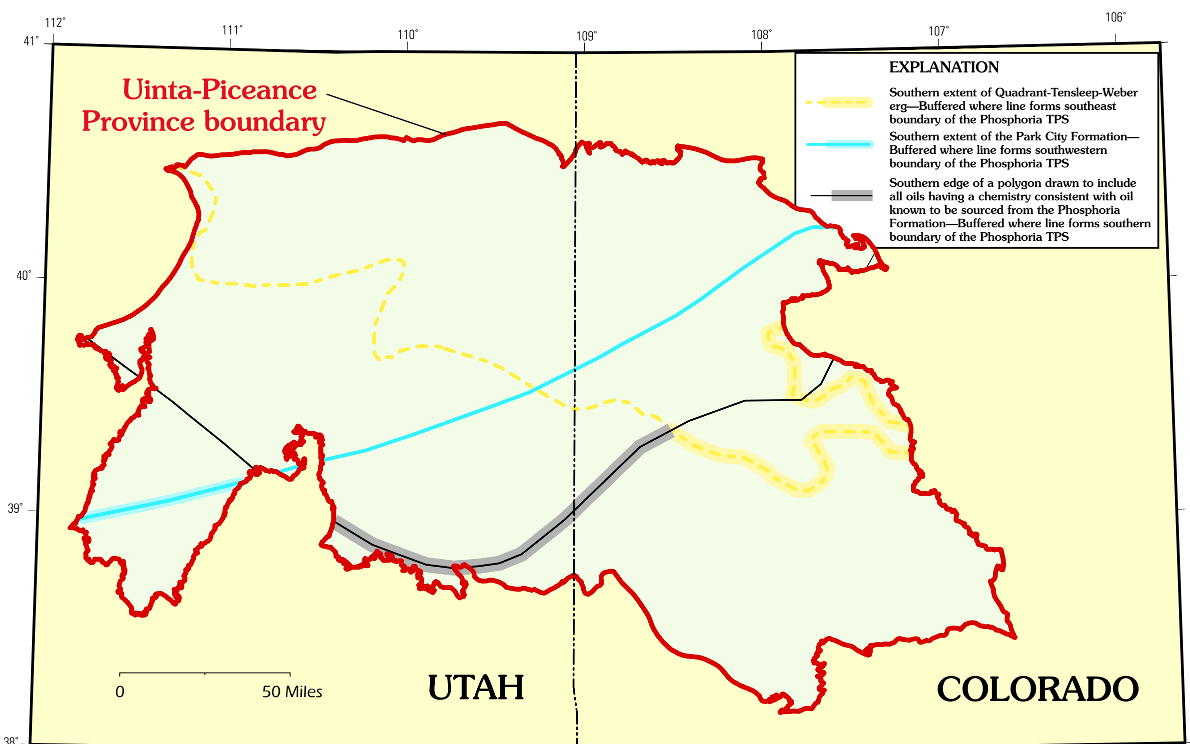


Figure 4. Criteria used in establishing the southern boundary of the Phosphoria Total Petroleum System (TPS) in the Uinta-Piceance Province.

area of the future Uinta-Piceance Basins to be situated between the Cordilleran highlands on the west and the Western Interior seaway on the east. Again, eustatic changes in sea level resulted in a variety of depositional environments ranging from coastal plains (for example, the Upper Cretaceous Iles Formation) to marine basins (for example, the Upper Cretaceous Mancos Shale). Starting in latest Cretaceous time [70–65 million years go (Ma)], the Laramide orogeny caused the Western Interior seaway to withdraw from the region, and a period of intense tectonism commenced, which created numerous uplifts and structural depressions throughout the Rocky Mountains. By the beginning of the Tertiary Period the present-day Uinta-Piceance Basins began to take form—first on the east with subsidence of the Piceance Basin followed shortly by the subsidence of the Uinta Basin on the west. At the end of the Paleocene Epoch, Laramide tectonism in the region had all but ceased and by the middle part of the Eocene the Uinta-Piceance Basins were fully developed; all post-Laramide sedimentary units reflect deposition in a basinal setting. The east-west-trending Uinta Basin is an asymmetrical structure with its steep side on the north along the southern front of the Uinta Mountain uplift (fig. 6). The north-south- to southeast-trending Piceance Basin is also asymmetrical with its steep side on the east as documented by the Grand Hogback monocline along the western side of the White River uplift. Spencer (1996) estimated that the Uinta Basin might contain more than 30,000 ft of Phanerozoic sedimentary rocks and the Piceance Basin might contain more than 20,000 ft.

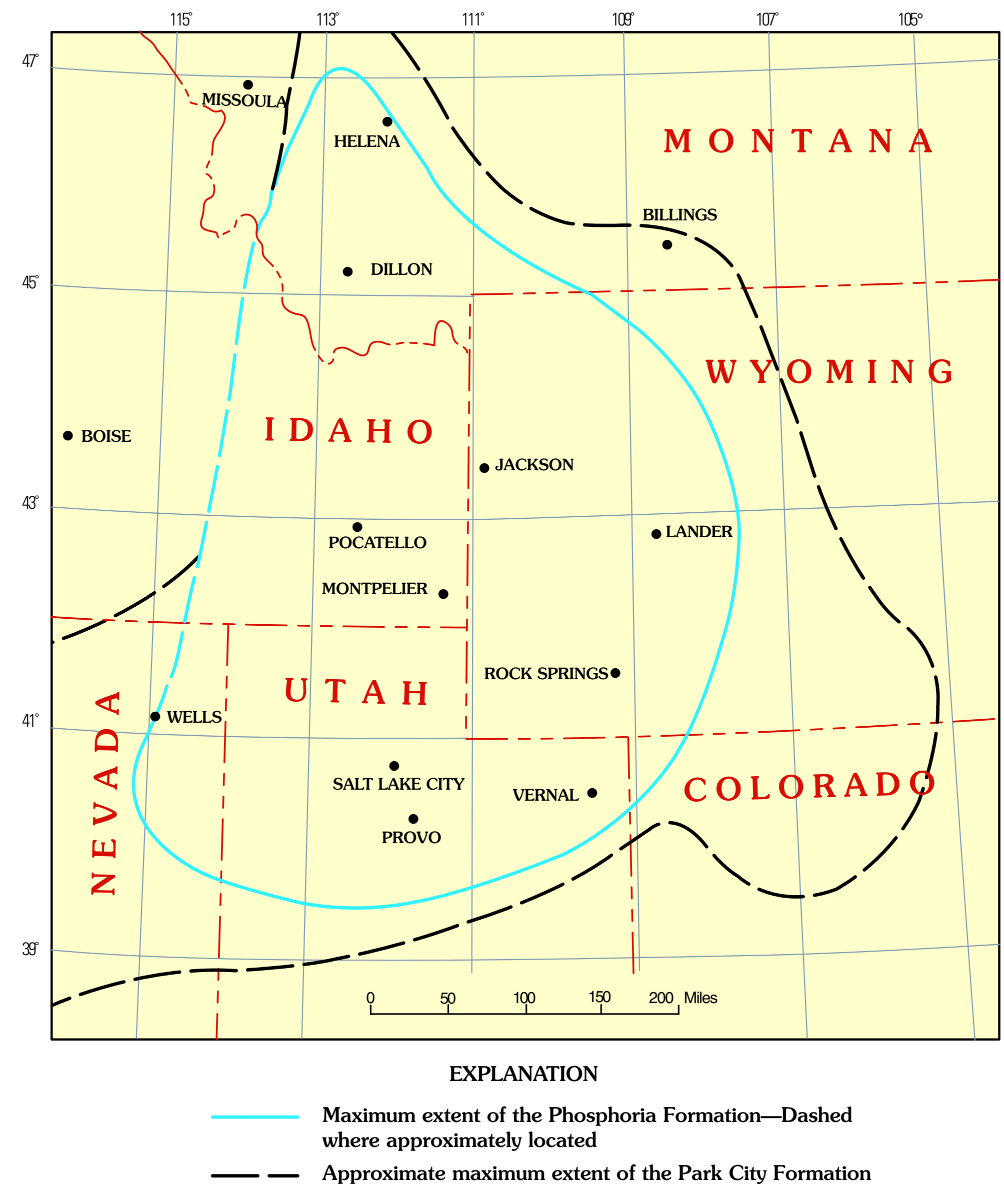


Figure 5. Regional extent of the Phosphoria and Park City Formations in the north-central Rocky Mountains (modified after Swanson and others, 1953).

Petroleum System

Although the Phosphoria Formation is the primary source rock under consideration, the unit cannot be described separately from the stratigraphically equivalent Park City Formation. The two units were deposited in the same depositional setting and intertongue over much of southwestern Montana, western Wyoming, northwestern Colorado, and northern Utah. The Park City was named by Boutwell (1907) for an interval of limestone and sandstone sandwiched between the Middle Pennsylvanian to Lower Permian Weber Quartzite and the Lower Triassic Woodside Shale in the Park City mining district, Utah. Use of the name Park City was extended into western Wyoming by Veatch (1907) and into southeastern Idaho by Gale and Richards (1910). Richards and Mansfield (1912) later applied the name Phosphoria to the upper two members of the Park City, as previously mapped in the phosphate districts of Idaho and Utah, and they designated Phosphoria Gulch, Bear Lake County, Idaho, as the type locality of the formation. In the vicinity of its type locality, the Phosphoria ranges from 250 to 450 ft thick. In the years following, the stratigraphic nomenclature of this interval grew more complicated as additional Permian sedimentary rocks were described in the region. Then in the late 1950's, McKelvey and others (1959) published what became the definitive work on the Park City and Phosphoria, establishing (or reconfirming) six members for the Phosphoria and three members for the Park City. In ascending order, the Phosphoria members are: lower chert member, Meade Peak Phosphatic Shale Member, Rex Chert Member, cherty shale member, Retort Phosphatic Shale Member, and Tosi Chert Member. For the Park City, in ascending order, the members are: Grandeur Member, Franson Member, and Ervay Member (see McKelvey and others, 1959, fig. 1). All members are Early to Late Permian (late Leonardian through Guadalupian) in age (Wardlaw and Collinson, 1986; Wardlaw, 1995).

The Meade Peak was the major contributor of hydrocarbons (Maughan, 1984), and the unit is often referred to as one of the two black shale facies of the Phosphoria. Where best developed in southeastern Idaho, the Meade Peak is 125–225 ft thick (McKelvey and others, 1959) and consists of organic claystone, muddy siltstone, phosphorite, and dolomitic calcilithite, in order of decreasing abundance. The claystone and siltstone are thinly laminated, and the phosphorite is mostly wackestone and packstone consisting of fine- to medium-grained, spherical to oblate peloids of carbonate fluorapatite. All of these rocks are very dark gray to black on both fresh and weathered surfaces. The calclithite is very fine grained and weathers light gray to light brown; the light-brown rocks are usually punky. In general, sedimentary structures and fossils are not commonly observed in the Meade Peak. Because it is poorly exposed in natural outcrops, the best descriptions of the unit come from the exposed highwalls of phosphate mines. At these locations the Meade Peak is separated into five subdivisions; in ascending order these are: lower waste, lower ore, middle waste, upper ore, and upper waste. The

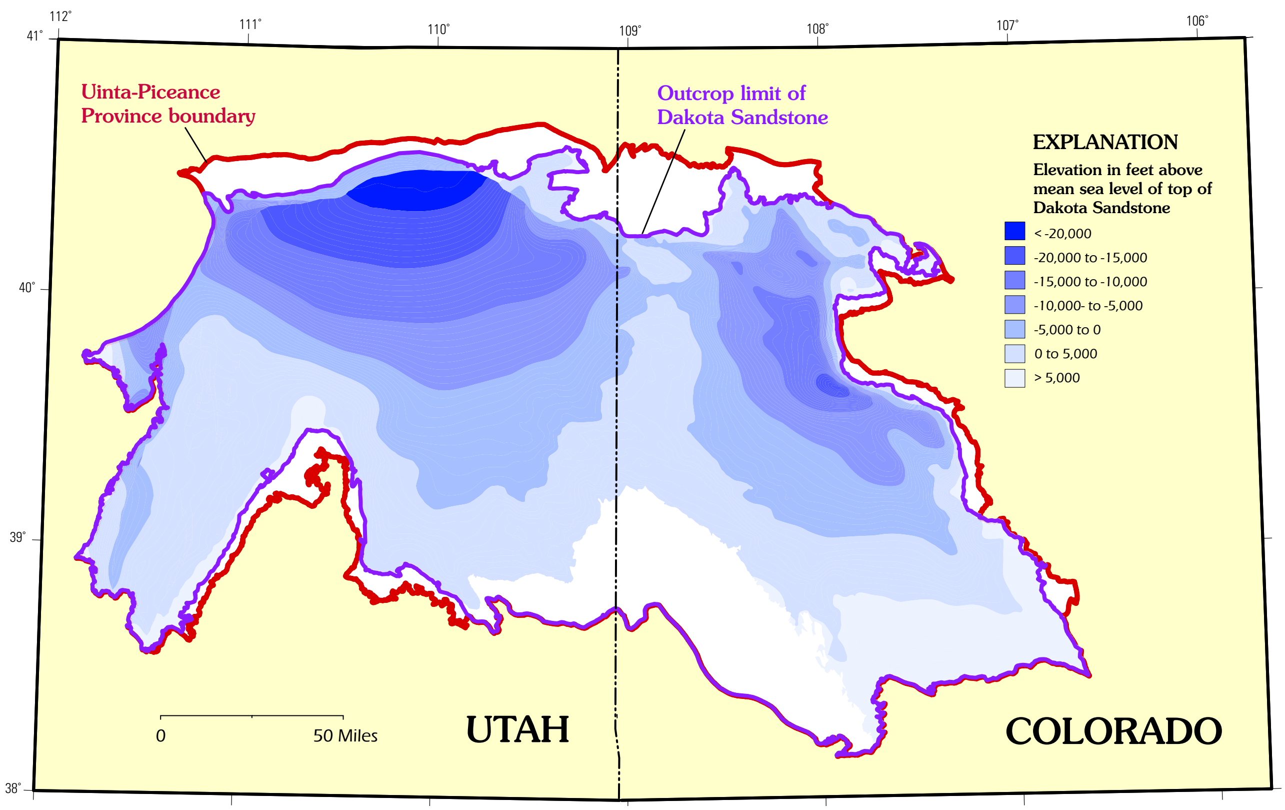


Figure 6. Structure contour map of the Uinta-Piceance Basins drawn on the top of the Dakota Sandstone.

mirror image observed above and below the middle waste has long been noted. Regionally, the Meade Peak lies unconformably on the Grandeur Member of the Park City, except where the lower chert member of the Meade Peak is locally present. The depocenter for the Meade Peak, as shown on regional isopach maps, was located in southeastern Idaho and northern Utah (Maughan, 1984).

The Retort, which also contributed large amounts of hydrocarbons (Maughan, 1984), is often referred to as the upper black shale facies of the Phosphoria. It contains rocks similar to those in the Meade Peak, although the proportions differ. In southwestern Montana, where best developed, the Retort ranges from 55 to 80 ft thick (less than one-half the thickness of the Meade Peak) and can be divided into three parts: lower phosphatic zone, middle calcareous mudstone, and upper phosphatic zone (McKelvey and others, 1959). At the type locality near Dillon, Mont., the Retort is an oil shale that has yielded oil upon distillation (McKelvey and others, 1959; Maughan, 1984). There, the Retort is thermally immature, but where more deeply buried to the southeast in west-central Wyoming, it is overmature. The depocenter for the Retort was in southwestern Montana, which represents a 68-mi, north-northwest shift from the position of the Meade Peak's depocenter (Maughan, 1984).

Phosphoria-sourced oil is present in a variety of Paleozoic formations in Wyoming, Colorado, and Utah, including the well known Weber Sandstone in Colorado and Wyoming, and the Middle Pennsylvanian to Lower Permian Tensleep Sandstone in Wyoming. In addition, Phosphoria-sourced oil is present in some Mesozoic formations, such as the Upper Jurassic Morrison Formation in Colorado.

Most reported accumulations involving Phosphoria-sourced hydrocarbons in the Uinta-Piceance Basins are conventional oil accumulations contained in Laramide structural traps. Although nonassociated gas contained in north-central Rocky Mountain Laramide basins has never been attributed to a Phosphoria source, the potential exists because of the high thermal maturity these basins achieved after Phosphoria-sourced oil had migrated into their domain.

Source Rock

During the Permian a large, relatively shallow, epicontinental embayment was present in what is now southeastern Idaho, southwestern Montana, western Wyoming, northwestern Colorado, northern Utah, and northeastern Nevada. This embayment, called the Sublett Basin (as used by Maughan, 1979), was open to the Cordilleran sea on the west and surrounded on the north, east, and south by various continental terranes on the North American craton. At that time, the area was located at about paleolatitide 20° N., and the North American continent was rotated about 40° clockwise with respect to its present position (summarized by Hiatt, 1997). The basin was composed of a central part, called the Phosphoria sea (as used by Sheldon, 1963), surrounded on three sides by a carbonate shelf. The basin covered about 100,000 mi^2 and had a maximum water depth of about 800 ft. Basically, the Phosphoria Formation was deposited in the Phosphoria sea and the Park City Formation was deposited on the carbonate shelf.

The depositional history of the Meade Peak Phosphatic Shale Member of the Phosphoria is complex and still the subject of debate. A generally accepted interpretation is that cold, nutrient-rich, oceanic water from the Cordilleran sea upwelled into the relatively shallow Sublett Basin, and the introduction of dissolved phosphorous, possibly from a volcanic source to the west, supported high organic productivity in the form of a phytoplanktonic biomass in the relatively warm photic zone in the upper part of the Phosphoria sea's water column. The lowermost part of the water column was cooler and chemically reducing, which caused the water to be anoxic. This euxinic environment allowed descending organic matter to remain unoxidized and to accumulate as sapropel on the sea floor. Thus, over a period of 2–4 million years organic matter accumulated and, through the process of phosphogenesis, phosphorite was alternately precipitated; upon lithification, these sediments became the Meade Peak. (A similar depositional history can be assumed for the Retort Phosphatic Shale Member.)

As deposition in the Sublett Basin proceeded, several eustatic sea level changes caused marine transgressions, which resulted in an interfingering of Phosphoria members with Park City members. The best example of this interfingering is in what is now western Wyoming, where the succession of members is, in ascending order: Grandeur (Park City), lower chert (Phosphoria), Meade Peak Phosphatic Shale (Phosphoria), Rex Chert (Phosphoria), Franson (Park City), Retort Phosphatic Shale (Phosphoria), Tosi Chert (Phosphoria), and Ervay (Park City). A useful illustration is the so-called "kidney" diagram (fig. 5) first published by McKelvey (1949) and subsequently reproduced in numerous publications. As originally described, this diagram shows the maximum regional extent of the Phosphoria and its partial stratigraphic equivalents (Park City). This area (black dashed line on fig. 5) approximates the maximum extent of the Sublett Basin. Also described on the original diagram is an area that represents the maximum extent of the phosphate deposits associated with these formations (blue line on fig. 5). Essentially, this is the Meade Peak Phosphatic Shale Member and Retort Phosphatic Shale Member of the Phosphoria, and the area approximates the maximum extent of the Phosphoria sea. Both of these areas are shown to extend south into northern Utah and northwestern Colorado.

In northeastern Utah the Phosphoria is strikingly different from its type locality in Idaho. Where best observed at the Little Brush Creek mine 11 mi north of Vernal, Utah, just the Meade Peak is present; there the unit is only 17–18 ft thick and appears to be the lateral equivalent of the lower ore zone of the Meade Peak in Idaho. At the mine, the Meade Peak unconformably overlies the Weber Sandstone and is conformably overlain by the lower part of the Franson Member of the Park City. Above this part of the Franson is an unnamed (and uncorrelated) redbed unit followed by the upper part of the Franson Member (fig. 7). Phosphorites are coarser grained than those in Idaho, and weathered exposures are medium to light brown. According to Maughan (1984), this area was located along the shallow southern edge of the Phosphoria sea and sediments were deposited under higher energy conditions than were present to the north in the main body of the sea. South and east of Vernal the Meade Peak pinches out into the Park City. All that remains of the Meade Peak in the Colorado part of Dinosaur National Monument is a faint zone of dispersed phosphate peloids in the lower part of the Franson.

In the area of the former Sublett Basin, the Meade Peak and Retort have an average maximum total organic carbon (TOC) of about 10 percent, and in the organically richest beds, as high as 30 percent (Maughan, 1984). The average TOC in the Meade Peak is 2.4 percent based on the analyses of 285 samples collected from 40 localities; the average maximum TOC of 9 percent is found east of Pocatello, Idaho, near the Wyoming State line. The average TOC in the Retort is 4.9 percent, double the average of the Meade Peak, based on the analyses of 82 samples from 22 localities; the average maximum TOC of 10 percent is found near Dillon, Mont.

Deposition of the Phosphoria in relatively shallow water along the southern margin of the Phosphoria sea might have caused the TOC in the Meade Peak (the Retort is missing in this area) to be well below regional values. Britt and Howard (1982) discussed the analyses of nine proprietary Phosphoria samples from central Utah and reported the average TOC to be 1.26 percent. Maughan (1984), without citing values, reported that the TOC in the Meade Peak of northern Utah is low despite having relatively high values of phosphate. Hefner and Barrow (1992) reported that the Phosphoria in western Wasatch County, Utah, has a TOC of 7 percent, which in comparison to other reported values seems high. A few samples of the Meade Peak collected along the southern margin of the Uinta Mountains by Hendrix and Byers (2000) yielded TOC values ranging from 0.11 to 0.45 percent, but samples of the dolomite facies of the Meade Peak collected by these workers in the same area yielded TOC values ranging from 0.29 to 2.04 percent. Two samples of mudrock collected from the Meade Peak at the Little Brush Creek mine north of Vernal, Utah, yielded TOC values of 0.16 and 0.25 percent (P.G. Lillis,

Figure 7. Permian rocks exposed at the Little Brush Creek mine, northeastern Utah. In ascending order, Weber Sandstone, Phosphoria Formation (Meade Peak Member), Park City Formation (Franson Member, lower part), uncorrelated redbeds, and Park City Formation (Franson Member, upper part)

USGS, written commun., 2000). Considering the generally accepted minimum amount of organic carbon necessary to produce petroleum, 1.5 percent (Hunt, 1996), the Meade Peak in northern Utah appears to be a poor source rock, and the Phosphoria-sourced oil in the Uinta-Piceance Province probably migrated into the area from another region. However, when considering these TOC values, as well as other TOC values in the region, it should be emphasized that in most areas the Phosphoria has passed through the oil window and is overmature, in which case the original TOC values might have been much higher.

Question: did the Meade Peak in northern Utah originally have an organic carbon content comparable to that of the Meade Peak in areas to the north? If so, then perhaps the organic carbon was altered by chemical weathering and removed from the system by ground water. However, according to Michael Lewan (USGS, oral commun., 2000) during such processes pyrite tends to leave the system before organic carbon, and since the rocks in the Meade Peak in northern Utah typically contain noticeable amounts of pyrite, the original organic carbon content must have been low.

Because the Phosphoria was deposited in a marine environment and the generated hydrocarbons are almost exclusively oil, it is presumed that the rocks contained Type II organic matter. This assumption is supported by analyses of a single sample of Retort collected at the unit's type locality in southwest Montana that document the presence of Type II organic matter (Lewan, 1985).

When the Meade Peak is considered as a whole, there is a general correlation between areas of high phosphate content and areas of high organic carbon content (Maughan, 1984). However, when individual beds within the Meade Peak are considered separately there is a negative correlation between rocks of high phosphate content and rocks of high organic carbon content. That is, organic carbon is commonly high in rocks with low phosphate and low in rocks with high phosphate. In support of Maughan's observations, analyses of organic claystone from the Meade Peak in southeastern Idaho show relatively high values of organic carbon, whereas analyses of phosphorite beds show relatively low values of organic carbon (R.I. Grauch, USGS, oral commun., 2000).

Maturation

Complete catagenesis of kerogen to hydrocarbons has taken place throughout most of the former Sublett Basin as indicated by vitrinite reflectance measurements in excess of 1.35 percent from samples of organic claystone collected from the Meade Peak Phosphatic Shale Member. In southeastern Idaho and western Wyoming this fact is supported by negligible yields in laboratory distillations of Meade Peak mudrocks (Maughan, 1984). In contrast, high yields, as much as 30 gallons (gal) per ton, have been obtained from organic claystone mudrocks of the Retort Phosphatic Shale Member in southwestern Montana where burial is thought to have been less than about 6,560 ft (2 km). Thus the Retort in this area is classified as thermally immature and did not become a source rock for hydrocarbons. Because these claystones have a high organic content and are thermally immature, they are best referred to as oil shales.

According to Claypool and others (1978), hydrocarbon generation began in most areas of the former Sublett Basin when the depth of burial of the Meade Peak and Retort exceeded about 6,560 ft and continued through the oil window until a depth of about 16,400 ft (5 km) was reached. At greater depths, liquid hydrocarbons would have been thermally destroyed, but the cracking of oil contained in stratigraphic traps leaves open the possibility of late thermogenic gas accumulations. The critical depth of burial in eastern Idaho might have been reached as early as Late Triassic and, regionally, the maximum depth of burial was reached by the end of the Cretaceous (Maughan, 1984). Maughan cited the Late Triassic as the possible onset of hydrocarbon generation in the deepest part of the Sublett Basin and implied that most hydrocarbon generation took place before the close of the Cretaceous. Undoubtedly, rocks in the deepest part of the basin passed through the oil window first, and with time the area of oil generation moved progressively away from southeastern Idaho to the depositional limits of the Meade Peak and Retort. Most likely the time of maximum hydrocarbon generation was the Late Jurassic through Early Cretaceous (fig. 8).

Additional loading and subsequent increase in ambient temperature of the Meade Peak and Retort in the Overthrust Belt of western Wyoming and eastern Idaho probably did not significantly increase hydrocarbon generation because most of the source rocks had essentially passed through the oil window prior to the onset of major thrusting (Maughan, 1984). However, Maughan does mention that some hydrocarbon generation probably continued into the Tertiary in western Wyoming under the increased loading caused by late-stage thrusts, and that hydrocarbon generation possibly continues into the present in some intermontane basins under the increasing weight of post-Laramide deposits.

Wardlaw and others (1979) noted that the Phosphoria in northwestern Utah has a high Conodont Alteration Index (CAI), which indicates that the formation in this area reached temperatures necessary to produce oil. Britt and Howard (1982) concluded that in central Utah oil generation in the Phosphoria peaked in the Early Cretaceous. Based on a thermal history diagram in Hefner and Barrow (1992) for the Phosphoria in western Wasatch County, Utah, oil generation from the unit in that area began in the Late Jurassic; this is within the regional time frame suggested by Maughan (1984). However, Hefner and Barrow reported an organic carbon content of 7 percent for the Phosphoria in this area, which might be anomalously high. The organic carbon content reported for the Phosphoria in other areas of northern Utah seems too low to have produced much oil and gas. Huntoon and others (1999) reported that the Park City Formation in the Salt Lake City area that contains an interbed of the Meade Peak passed through the oil window between Middle the Jurassic and Late

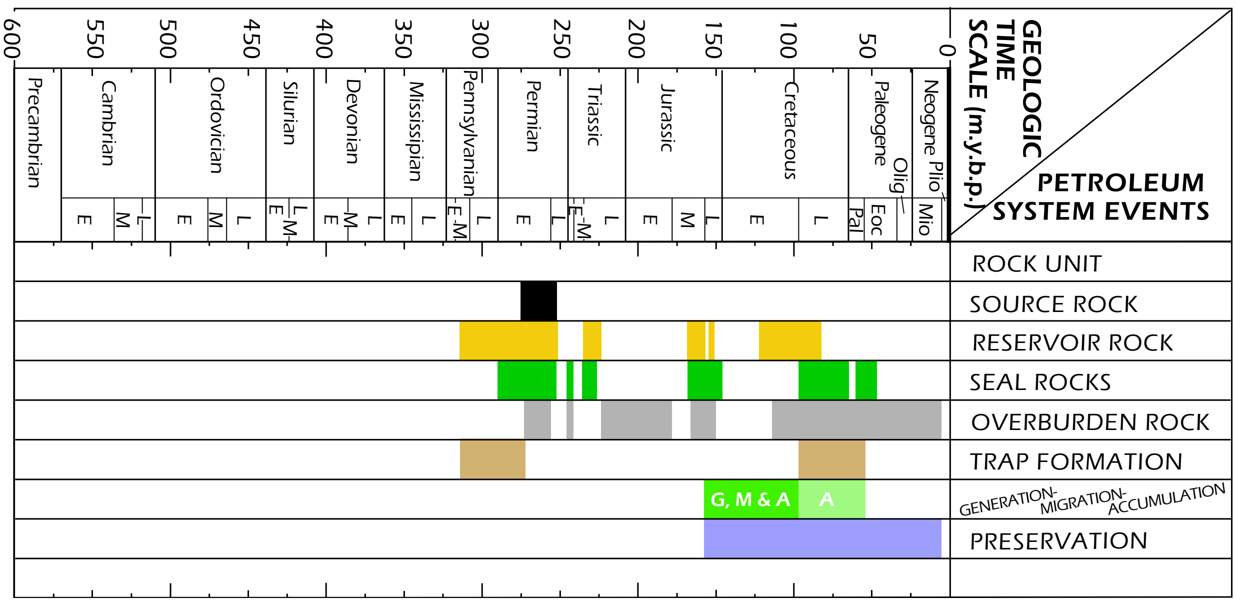


Figure 8. Petroleum system events chart for the Phosphoria Total Petroleum System in the Uinta-Piceance Province.

Cretaceous; again, this is within the regional time frame suggested by Maughan (1984).

Claypool and others (1978) estimated that 225 billion barrels of petroleum were ultimately generated from the Phosphoria.

Migration Summary

Most workers (Sheldon, 1967; Stone, 1967; Claypool and others, 1978; and Momper and Williams, 1984) who have studied hydrocarbon generation in the Phosphoria Formation thought that migration into the Weber and Tensleep Sandstones in western Wyoming took place during the Late Jurassic and Early Cretaceous. In other studies, Fryberger and Koelmel (1986) interpreted Phosphoria-sourced oil to have migrated into the Weber in northwestern Colorado during the Early Cretaceous, and Britt and Howard (1982) concluded that in central Utah Phosphoria oil began migrating during the middle part of the Cretaceous.

The Weber and Tensleep served as major carrier beds for Phosphoria-sourced oil throughout the region. As pointed out by Fryberger and Koelmel (1986), permeable sandstones of the Quadrant-Tensleep-Weber eolian system functioned as a single regional hydrostratigraphic unit until disturbed by the Laramide orogeny. Fluid movement through these units was controlled by paleodip—that is, hydrocarbons generated in the area of the former Phosphoria sea of the Sublett Basin managed to permeate the Quadrant-Tensleep-Weber system and subsequently migrated laterally up dip into the basin margin and beyond.

The Park City Formation also served as a carrier bed for basin-to-shelf, up-dip migration. For example, hydrocarbons generated in the Meade Peak Phosphatic Shale Member of the Phosphoria probably migrated eastward through the adjacent carbonate members of the Park City and provided oil for reservoirs in that formation in central Wyoming (Cheney and Sheldon, 1959).

Initially, unimpeded migration pathways distributed hydrocarbons over a broad area (Sheldon, 1967) until Late Cretaceous and early Tertiary time, when intervening Laramide uplifts formed barriers to regional fluid flow. In the northern part of the Uinta-Piceance Basins, for example, the southward migration of Phosphoria-sourced oil came to an end with the uplift of the Uinta Mountains.

Hydrocarbons contained in pre-Laramide stratigraphic traps that were subsequently down folded within Laramide basins could have remigrated up dip into secondary stratigraphic or structural traps, or escaped to the surface by way of vents and seeps. Evidence of remigration is usually lacking, but in the case of the Rangely oil field in northwestern Colorado it might have taken place. The anticline at Rangely was discovered by its surface expression early in the twentieth century, and initial production was from the Upper Cretaceous Mancos Shale. In 1933, a deep well was drilled that discovered oil in a series of folded, oil-bearing stratigraphic traps in the Weber, and subsequently this formation became the major producer in the field. Geologists have long pondered the migration history of oil in the Weber reservoir at Rangely. Did the oil contained in the original stratigraphic traps remigrate and concentrate in the anticline during the structure's formation in Laramide time, or did the exploration drilling fortuitously penetrate the stratigraphic traps that with their original oil had simply been folded up into the anticline? Most likely some remigration occurred but the debate continues (Whitaker, 1975; Fryberger and Koelmel, 1986; Waechter and Johnson, 1986).

Reservoir Rocks

Phosphoria oil, that is oil with a chemical composition consistent with oil known to be sourced from the Phosphoria Formation, has been identified in seven lithostratigraphic units in the Uinta-Piceance Province, and is suspected to be present in an eighth unit (fig. 9).

Weber Sandstone

The Middle Pennsylvanian through Lower Permian (Desmoinesian through Wolfcampian) Weber Sandstone is the dominant producer of Phosphoria-sourced oil in the Uinta-Piceance Province. The formation is spectacularly exposed in Dinosaur National Monument and is present in the subsurface throughout the northern part of the province (fig. 3). Along its eastern, southeastern, and southern depositional margins, it intricately interfingers with the Middle Pennsylvanian through Lower Permian Maroon Formation, and toward the southwest and west the Weber includes an increasing amount of marine carbonate. In Dinosaur National Monument the Weber is about 1,000 ft thick (Fryberger, 1979), but 20 mi to the south the formation starts to include interbeds of the Maroon and thickens to about 1,150 ft at the Rangely oil field (pl. 1). From Rangely the Weber thins toward the east, and is only about 370 ft thick at the Maudlin Gulch oil field north of Meeker, Colo. (Gibbs, 1982). It rests conformably on the Lower and Middle Pennsylvanian Morgan Formation and is unconformably overlain by the Lower Permian Phosphoria or Park City Formations in northeastern Utah or the Lower Permian to Lower Triassic State Bridge Formation in northwestern Colorado. At Rangely the Weber is a yellowish-white, fine-grained subarkose to quartzarenite (Fryberger and Koelmel, 1986), with an average porosity of 13 percent and an average permeability of 10 millidarcies (mD) (Hefner and Barrow, 1992).

Sandstones in the Weber were subjected to four stages of diagenesis (Koelmel, 1986). Stage 1 occurred during or shortly after deposition and involved the precipitation of carbonate cements, locally including traces of detrital and authigenic clay, in both the Uinta and Piceance Basins. Stage 2 entailed the development of quartz overgrowths produced by the precipitation of silica, which tended to occlude the primary porosity of Weber sandstones in both basins, but most effectively in the Uinta Basin. Stage 3 involved the replacement of framework feldspars, framework and matrix biotite, and Stage 1 carbonate cements by high-magnesium calcite, ferron calcite, dolomite, and ferron dolomite. Alumina released from the feldspars and biotite was reprecipitated as authigenic illite. Anhydrite, a late-stage pore-filling cement, further reduced the rocks' remaining primary porosity. Stage 3 diagenesis was particularly important in the Piceance Basin where it essentially terminated Stage 2 diagenesis. However, in the Uinta Basin both stages proceeded concurrently. Stage 4 diagenesis seems to have impacted Weber sandstones only in the Piceance Basin. During this stage, Stage 3 carbonate cements were preferentially removed and secondary porosity was created, perhaps concurrently with the arrival of hydrocarbons.

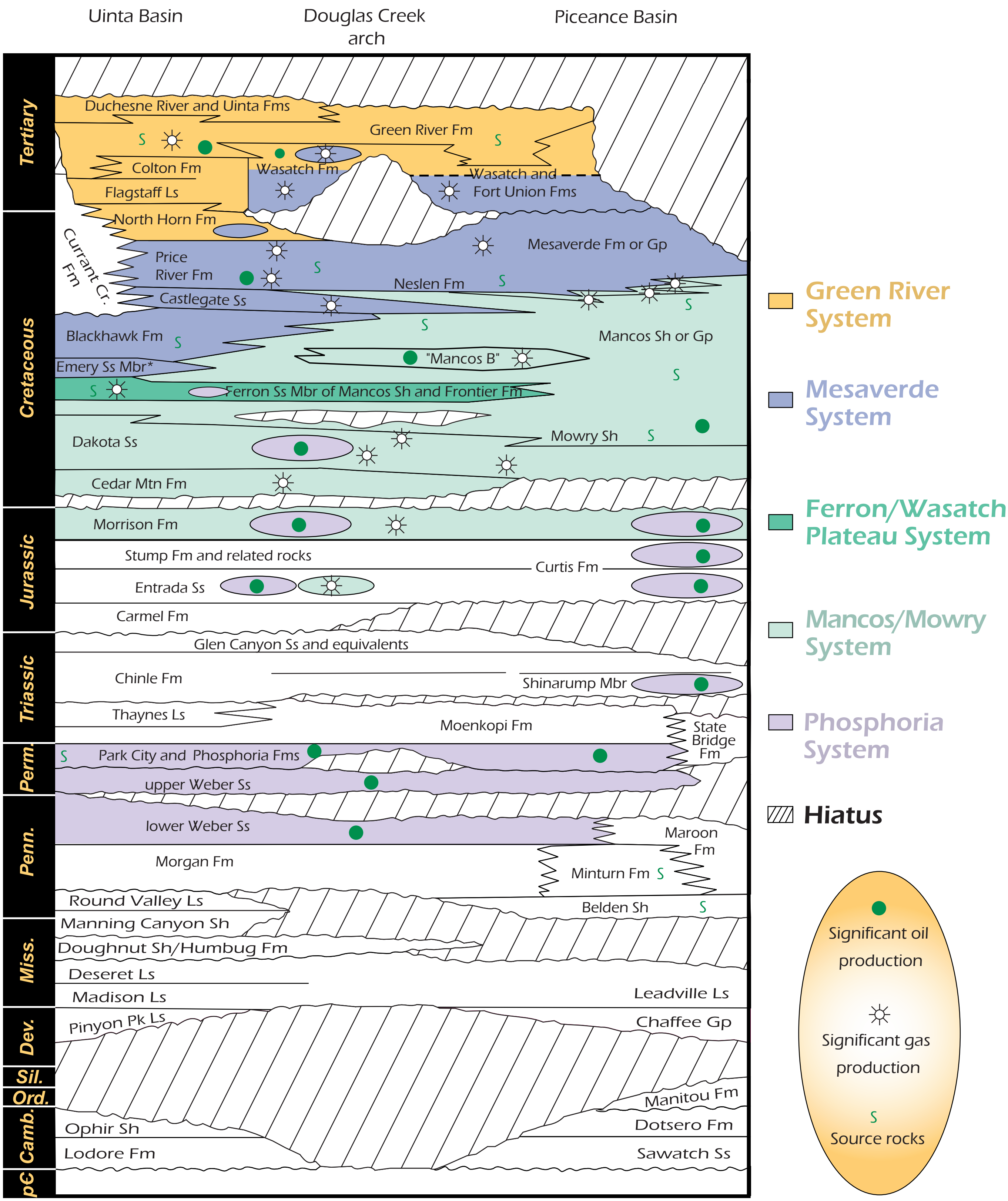
The oil produced from the Weber at Rangely is described as black and asphaltic, with an API gravity of 34.2°, a pour point of 10° F, and a sulfur content of 0.70 percent (Smith, 1954; Mendeck, 1986; Hefner and Barrow, 1992). Phosphoria-type oil has been identified in the Weber from the Rangely, Elk Springs, Maudlin Gulch, and Scott Hill oil fields in the northern Piceance Basin (Lillis and others, Chapter 3, this CD-ROM). In addition, Lillis and others have confirmed that Phosphoria-type oil mixed with Cretaceous-type oil has been reported from the formation at the Ashley Valley oil field in the northern Uinta Basin. Oil is also known to be present in the Weber at the Winter Valley, Douglas Creek, Douglas Creek North, Danforth Hills, Danforth Hills North, Thornburg, White River Dome, and Rifle Creek oil fields in the northern Piceance Basin, and this oil is likely sourced from the Phosphoria as well.

Park City Formation

A Permian limestone is reported to produce oil at the Ashley Valley oil field (Stone, 1967; Stowe, 1979; Whitaker, 1975). The source is probably the underlying Meade Peak Phosphatic Shale Member of the Phosphoria Formation (Lillis and others, Chapter 3, this CD-ROM). In addition, Lillis and others reported that oil supposedly collected from the Phosphoria at the Maudlin Gulch and Temple Canyon oil fields in the Danforth Hills area of northwestern Colorado is possibly sourced from the Phosphoria. Actually, Phosphoria is not present in this part of northwestern Colorado but the Park City Formation is. This brings up a long-standing inconsistency in the identification of these two formations in the subsurface. Where the two formations interfinger with each other, the interval is variously reported as being either the Phosphoria or the Park City—not both. Even more exasperating, even in areas where only one of the two formations is present, the name is often arbitrarily assigned. Therefore, the only way to establish the identity of the formations (or members of the formations) is from the lithologic description: if it is a limestone it is Park City; if it is a black shale it is Phosphoria. The limestones in the Park City make that formation a favorable reservoir candidate, whereas the highly argillaceous Phosphoria probably nowhere contains significant amounts of moveable hydrocarbons.

Shinarump Member

Phosphoria-type oil has been identified in the Shinarump Member of the Upper Triassic Chinle Formation at the Danforth Hills oil field about 23 mi northwest of Meeker, Colo.



* Emery Sandstone Member of the Mancos Shale

Figure 9. Generalized stratigraphic column showing the distribution of reservoir rocks containing oil and gas derived from the five major source rocks contributing hydrocarbons to the Uinta-Piceance Province (modified after Sanborn, 1977, and Spencer and Wilson, 1988).

Click on image below to bring up high-resolution image of plate 1.

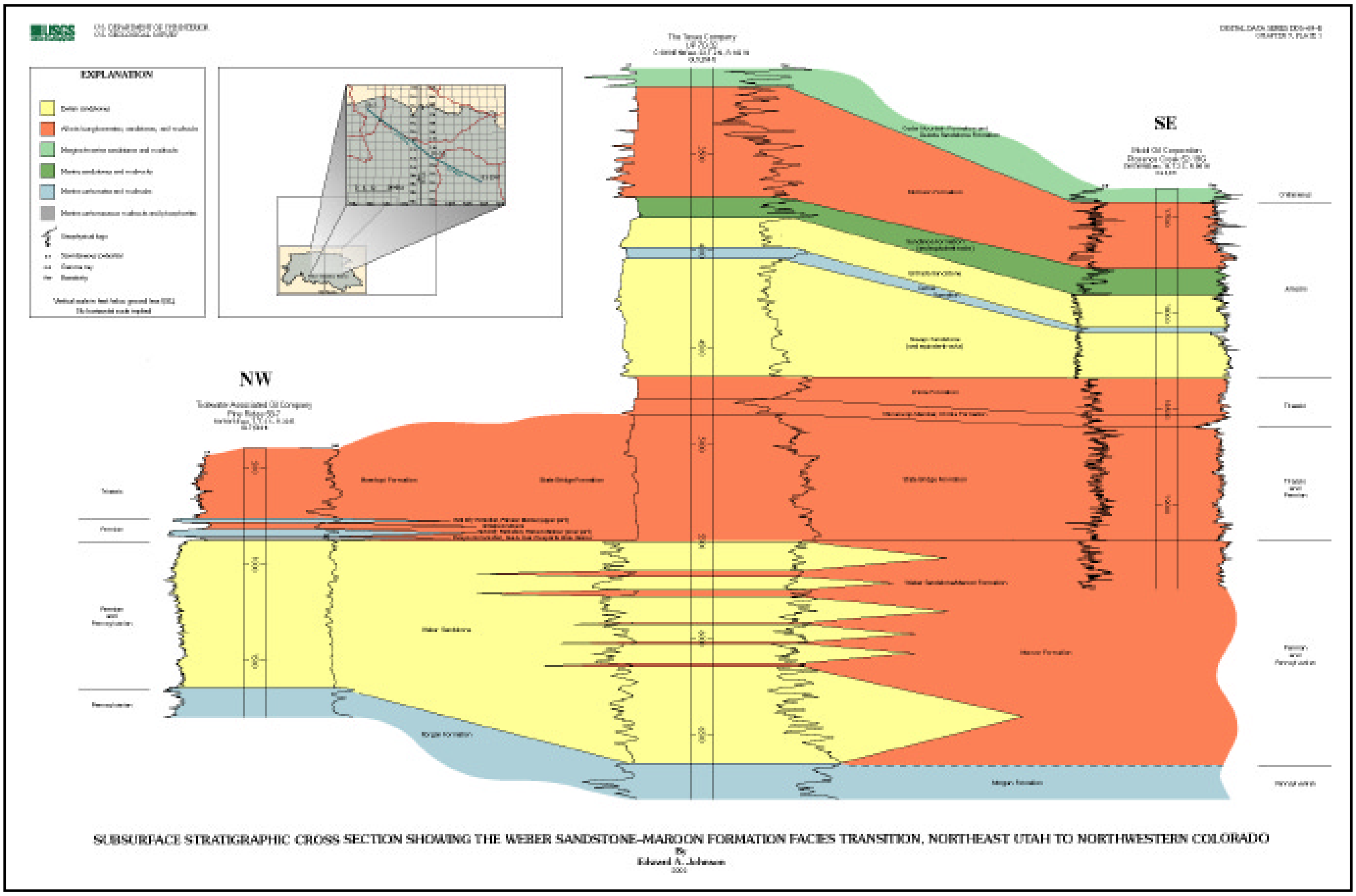


Plate 1. Subsurface stratigraphic cross section showing the Weber Sandstone–Maroon Formation facies transition, northeast Utah to northwestern Colorado.

(Lillis and others, Chapter 3, this CD-ROM). No description of the Shinarump at Danforth Hills is available, but the unit is exposed in the Yellowjacket anticline 12 mi northeast of Meeker (Bookstrom, 1964). In that area the Shinarump is described as a 50-ft-thick interval of lenticular, quartz-pebble conglomerates and cross-stratified, quartzose sandstones. The unit unconformably overlies the Permian-Triassic State Bridge Formation and grades upward into the main body of the Chinle. Oil is present in the Shinarump at Rangely and was probably sourced from the Phosphoria.

Entrada Sandstone

Phosphoria-type oil has been identified in the Middle Jurassic Entrada Sandstone collected from a well drilled in the western part of the Uinta Basin (Lillis and others, Chapter 3, this CD-ROM). In addition, Lillis and others reported that oil contained in the Entrada at the Danforth Hills oil field is probably sourced from the Phosphoria. West of the Danforth Hills, the Entrada is underlain by the Middle Jurassic Carmel Formation, which separates the Entrada from the underlying Lower Jurassic Glen Canyon Sandstone, and is overlain by the Middle Jurassic Curtis Formation (Pipiringos and O'Sullivan, 1978). In the area of the Danforth Hills, the Carmel is not present and the Entrada is underlain by the Lower Jurassic Nugget Sandstone (an equivalent of the Glen Canyon), and is overlain by the Upper Jurassic Redwater Shale Member of the Middle and Upper Jurassic Sundance Formation. The absence of the Carmel places two eolian formations (Nugget and Entrada) in direct contact and, because of the difficulty in separating them in the field, they are commonly combined into one lithostratigraphic unit consisting of light-brown to pink, strikingly cross-stratified, quartzarenites. However, where best exposed in the Yellowjacket anticline the combined unit can be divided into a lower resistant part, 188 ft thick, and an upper less resistant part, 63 ft thick. At the contact between these two parts a thin line of chert pebbles and granules was identified by Bookstrom (1964) as the regional disconformity that separates the Nugget from the Entrada (the J-2 unconformity of Pipiringos and O'Sullivan, 1978). Gibbs (1982), in citing the thickness of the Entrada at Maudlin Gulch to be 450 ft, might have been referring to the combined Nugget-Entrada interval. Most production is from the upper 24 ft, which would be from the Entrada part of the combined unit. The producing rocks are reported to have a porosity of 20 percent, a permeability of 323 mD, and an API gravity of 35.5° (Gibbs, 1982).

Sundance Formation

Phosphoria-type oil has been identified in the Middle and Upper Jurassic Sundance Formation at the Maudlin Gulch oil field (Lillis and others, Chapter 3, this CD-ROM), but not much is known about this accumulation. Based on Pipiringos and O'Sullivan (1978), only the upper two of the Sundance's seven members are present in northwestern Colorado: (1) the Redwater Shale Member, which rests on the Entrada Sandstone, and (2) the overlying Windy Hill Sandstone Member, which underlies the Upper Jurassic Morrison Formation. Bookstrom (1964) recognized this interval in the Yellowjacket anticline, but erroneously referred it to the Middle Jurassic Curtis Formation. His description of the interval seems to imply that the Redwater Shale Member consists of 7 ft of siltstone and fine- to medium-grained sandstone, a 0.5-ft-thick limestone bed, and 3 ft of dark-green shale. The Windy Hill consists of 4.5 ft of white, well-sorted sandstone. Any oil produced from the Sundance at Maudlin Gulch is most likely from the Windy Hill. Since the work of Pipiringos and O'Sullivan (1978), the Windy Hill has been reassigned as the basal member of the overlying Morrison Formation (Peterson, 1994), but for the purpose of this resource assessment it is discussed with the Sundance.

Morrison Formation

Phosphoria-type oil mixed with Cretaceous-type oil has been identified in the Upper Jurassic Morrison Formation at the Rangely oil field (Lillis and others, Chapter 3, this CD-ROM). In that area of the Piceance Basin the Morrison overlies the Sundance Formation or, farther to the west, the Curtis Formation, and underlies the Lower Cretaceous Cedar Mountain Formation. Geophysical logs show the Morrison to be about 620 ft thick at Rangely (pl. 1), but no physical description of the formation is available. The closest surface exposures are in Dinosaur National Monument about 20 mi to the north. There, the formation consists mainly of varicolored mudrocks with isolated, lenticular sandstone bodies, which are especially common in the lower part of the formation. Traditionally, the Morrison is divided into three members, which are, in ascending order, the Tidwell, Salt Wash, and Brushy Basin Members. As mentioned earlier, a basal member, the Windy Hill Sandstone Member, was reassigned to the Morrison (Peterson, 1994) from its previous position at the top of the underlying Sundance Formation. Most of the sandstones are in the Salt Wash. Oil is common in the Morrison in the Danforth Hills area at the Danforth Hills, Danforth Hills North, Temple Canyon, and Maudlin Gulch oil fields, and significant production is reported from several of these fields (Smythe, 1954; Turner, 1955; Brainerd and Carpen, 1962; Cummings and Pott, 1962; Dunn, 1974; Gibbs, 1982). In most publications it is stated or implied that the oil is present in sandstone units contained in the Salt Wash. The sandstones have reported porosities ranging from 12 to 23 percent and permeabilities ranging from 35 to 170 mD. The oils contained are reported to have API gravities ranging from 32.0° to 50° and sulfur contents ranging from 0.12 to 0.35 percent. All of the oil in the Morrison in the Danforth Hills area, especially at Maudlin Gulch, might be sourced from the Phosphoria (Lillis and others, Chapter 3, this CD-ROM).

In the southern Uinta Basin, Phosphoria-type oil has been identified from the Morrison at the Seiber Nose and Cisco Springs oil fields; oil from the Morrison at the Agate oil field is probably also Phosphoria type (Lillis and others, Chapter 3, this CD-ROM). In the greater Cisco area the Morrison is 680–730 ft thick, and overlies the Middle Jurassic Wanakah Formation and underlies the Cedar Mountain Formation (Hintze, 1988).

Dakota Sandstone

In the southern Uinta Basin, Phosphoria-type oil mixed with Cretaceous-type oil has been identified from the Upper Cretaceous Dakota Sandstone at the Cisco Springs oil field (Lillis and others, Chapter 3, this CD-ROM). The Dakota is a mixed marine and nonmarine unit of regional extent composed primarily of well-sorted sandstone interbedded with minor amounts of mudrock. In the Cisco area the Dakota is about 100 ft thick, and overlies the Lower Cretaceous Cedar Mountain Formation and underlies the Tununk Shale Member of the Upper Cretaceous Mancos Shale (Hintze, 1988). In many areas of the Uinta-Piceance Basins, the Cedar Mountain and Dakota are combined for the purpose of geologic mapping, and together the two formations directly underlie thousands of feet of argillaceous marine rocks. Many workers believe the oil produced from the Cedar Mountain–Dakota interval was derived from source rocks in the Mancos or Upper Cretaceous Mowry Shale. The presence of some Phosphoria-type oil must indicate that a unique set of geologic circumstances caused Phosphoria oil to penetrate certain parts of the stratigraphic section in this area.

Mancos Shale

One sample from the Cisco Townsite oil field collected from the Ferron Sandstone Member of the Mancos Shale has been identified as Phosphoria-type oil (Lillis and others, Chapter 3, this CD-ROM). In the greater Cisco area, the Ferron is about 50 ft thick, and overlies the Tununk Shale Member of the Mancos and is overlain by the main body of the Mancos (Hintze, 1988).

Traps and Seals

The most important and well-studied accumulation of Phosphoria-sourced oil in the Uinta-Piceance Basins is the Weber-Maroon stratigraphic-structural trap at the Rangely oil field (pl. 1). From Middle Pennsylvanian through Early Permian time, two opposing depositional systems competed in what is now the northern part of the Piceance Basin: (1) from the south and southeast, poorly sorted detritus moved northward away from the Uncompahgre uplift and Ancestral Front Range, and (2) from the north and northwest, well-sorted sand drifted southward away from the main part of the Quadrant-Tensleep-Weber erg (Fryberger and Koelmel, 1986). The interface between the two depositional systems created an intricate transition zone, and the lateral shifting of these systems within the zone resulted in a complicated vertical succession of deposits. At Rangely, for example, the Pennsylvanian-Permian stratigraphic section contains interbeds of both the Weber Sandstone and the Maroon Formation. The Weber consists of yellowish-white, fine-grained, quartzose sandstone representing dune, interdune, and sand sheet depositional facies. Hefner and Barrow (1992) reported the sandstones to have an average porosity of 13 percent and an average permeability of 10 mD. The Maroon consists of reddish, arkosic sandstone and siltstone, and lesser amounts of conglomerate and mudrock representing alluvial plain and fluvial channel depositional facies. According to Hefner and Barrow (1992), the Maroon is tightly cemented with calcite, which limits the porosity to 0–8 percent and permeability to less than 0.01 mD.

Most of the Pennsylvanian-Permian interval at Rangely is composed of the Weber Sandstone, but the upper one-half contains five interbeds of the Maroon formation that vary in thickness from 5 to 45 ft, with an average of 20 ft. The five Maroon units thus serve as barriers to vertical fluid migration, and divide the Weber into six separate sandstone packages, each of which functions as an individual reservoir. The upper five packages range from 80 to 160 ft thick, with an average of 120 ft; the lower package constitutes the remainder of the Weber and is typically about 500 ft thick. Campbell (1955) was the first to describe the basic trapping mechanism at Rangely. Later, Fryberger and Koelmel (1986) more precisely identified the mechanism as a system-bound stratigraphic trap, the largest class of stratigraphic traps found in eolian deposits, which, by definition, develop where permeable eolian sandstones intertongue with impermeable rocks of an adjacent depositional environment. From Rangely, the interbeds of Maroon are known to pinch out toward the north, and at the Skull Creek anticline, only 8 mi north of the field, exposures of the Weber show no trace of the Maroon. Some workers (Whitaker, 1975; Waechter and Johnson, 1986; Fryberger and Koelmel, 1986) attempted to map the transition zone between the eolian and alluvial depositional systems in the subsurface based on drill-hole and seismic information, but were unable to establish recognizable trends useful for petroleum exploration.

Confirmed or suspected Phosphoria-type oil is also produced from the Weber and seven other formations in strictly structural traps associated with the Late Cretaceous through Paleocene Laramide orogeny (Lillis and others, Chapter 3, this CD-ROM). These traps are present in one of three structural settings. The first setting is a discontinuous belt of thrusted anticlines that extends along the northern part of the Uinta-Piceance Province from the Ashley Valley oil field in northeastern Utah to the Thornburg oil field in northwestern Colorado. Thirteen oil fields are included in this category. The second involves a cluster of anticlines in the greater Cisco area in the southern Uinta Basin, where four oil fields contain confirmed or suspected Phosphoria-type oil in three different formations. These structures were formed by Laramide reactivation of structural elements associated with the Uncompahgre uplift (Stone, 1977). Two categories of anticlines are recognized: drape folds (formed in response to reactivated faults) and parafolds (formed in response to reactivated folds). The third structural setting involves two anticlines in the Douglas Creek area in the northern Piceance Basin associated with the Douglas Creek arch.

The top of the Weber at Rangely is sealed by the State Bridge Formation, which Hefner and Barrow (1992) reported as having porosity of less than 3 percent and permeability of only 0.1 mD. In some areas, the Weber is overlain by carbonate rocks of the Park City Formation or mudrocks of the Meade Peak Phosphatic Shale Member of the Phosphoria Formation, and these units might also provide an adequate seal for the Weber. The oil reported in the Park City at the Ashley Valley oil field is probably sourced from the Phosphoria. If that oil is (1) in the Grandeur Member of the Park City, it is sealed by the overlying Meade Peak; (2) in the Franson Member (lower part) of the Park City, it is sealed by the overlying unnamed redbeds; or (3) in the Franson Member (upper part), it is sealed by marine argillaceous rocks in the overlying Lower Triassic Dinwoody Formation. The Shinarump Member of the Chinle Formation is sealed by the hundreds of feet of argillaceous rocks contained in the overlying main body of that formation. In northwestern Colorado, the Entrada Sandstone is sealed by marine shales in the overlying Redwater Shale Member of the Sundance Formation, or farther west and southwest, by the overlying argillaceous rocks of the Curtis Formation. The sandy unit at the top of the Sundance, the Windy Hill Sandstone Member (now considered the basal member of the Morrison Formation), is sealed by argillaceous rocks in the lower part of the Morrison. Individual channel sandstone bodies in the Salt Wash Member of the Morrison are sealed by the surrounding argillaceous overbank deposits. The Cedar Mountain Formation–Dakota Sandstone interval is sealed by thousands of feet of overlying marine shale in the Mowry and Mancos Shales.

Hanging Wall Assessment Unit (AU 50200401)

The Hanging Wall Assessment Unit (AU) was established to include all conventional hydrocarbon accumulations contained in structural and stratigraphic-structural traps associated with, or assumed to be associated with, thrusted anticlines that, when considered as a group, form a trend of such structures marginal to the northern and northeastern boundary of the Uinta-Piceance Province (fig. 10). Thrusted anticlines, as defined in this assessment, are single, asymmetrical folds that dominate the hanging walls of some thrust faults. In the case of the Uinta-Piceance Province, the thrusts and their associated folds are basin vergent (display structural movement toward the basin), and the faults are blind (do not extend to the surface). These structures were created during the Late Cretaceous through Paleocene Laramide orogeny as the Uinta Mountains were uplifted during the formation of the Uinta and Piceance Basins, although there is some evidence of Late Paleozoic incipient folding (Whitaker, 1975; Waechter and Johnson, 1986). The Rangely anticline (fig. 11) is a classic example of one of these thrust-fold complexes that probably developed as regional compression created a deep, asymmetrical fold that subsequently broke out into a low-angle thrust fault. As thrusting proceeded upward through the stratigraphic section, stresses that developed in the rocks above and below the fault plane resulted in additional folding in both the footwall and hanging-wall blocks. With time, as the leading edge of the thrust penetrated higher stratigraphic levels, the fault plane steepened into a high-angle reverse fault. A prime example of an exposed thrusted anticline is the Skull Creek anticline located about 15 mi north of Rangely, Colo. (fig. 12), where the Weber Sandstone is folded in the hanging wall of the Willow Creek thrust fault.

The anticlines in the Hanging Wall AU are known to contain conventional accumulations of hydrocarbons in 18 lithostratigraphic units. At least three source rocks are involved, Middle Pennsylvanian Minturn Formation, Phosphoria Formation, and Mancos Shale (Lillis and others, Chapter 3, this CD-ROM), with the Phosphoria being the principal source. Nonassociated gas produced from the Upper Cretaceous Mesaverde Group, Paleocene Fort Union Formation, and Paleocene and Eocene Wasatch Formation in the hanging-wall folds is probably derived from various Mesaverde coals (Johnson, 1989). Because all of these hydrocarbons accumulated in similar structural settings, it was decided to combine them within a single assessment unit.

There is one other possible source of nonassociated gas. A significant amount of Phosphoria-sourced oil might have been contained in various stratigraphic traps in the region prior to the formation of the Uinta-Piceance Basins. As the basins began to form and pre-Laramide rocks were buried under increasing amounts of younger sediments, the Phosphoria-sourced oil was subjected to escalating burial temperature. When oil reaches a thermal maturity equivalent to a vitrinite reflectance (R_o) value of about 1.0 percent, it starts to break down (crack) and by about R_o=2.0 percent it is totally destroyed, leaving in its place thermogenic gas and bitumens (Hunt, 1996). The potential for gas from this source is only a factor in the western part of the assessment unit where the Uinta Basin is the deepest and burial temperatures were the highest (fig. 13). Gas sourced in this way was considered in the assessment although no produced gas has ever been attributed to this process.

The northern and northeastern boundary of the Hanging Wall AU conforms to the Uinta-Piceance Province boundary, but establishing the basinward part of the assessment unit boundary is more difficult. Numerous maps showing the geologic structures in the northern part of the province have been published (for example, fig. 14), and by considering a number of these maps, a boundary was established that approximates the southern limit of thrusted anticlines in the province.

Hydrocarbons present in the 18 lithostratigraphic units in the Hanging Wall AU are predominantly oil and associated gas, but locally appreciable amounts of nonassociated gas are also present. Of the 18 units, 11 are variously present in the oil fields that exceed the minimum size used in the assessment. The remaining seven units either contain insignificant amounts of hydrocarbons or are present in smaller oil fields that were not used in the assessment. The economically significant units produce from primary or secondary porosity in sandstones, except for the Park City Formation, which produces from secondary carbonate porosity, and the Mancos Shale, which produces from fracture permeability. Almost all of the production is from units folded into structural traps associated with thrusted anticlines. In the case of the Phosphoria-sourced hydrocarbons at the Rangely oil field, original accumulations were probably in stratigraphic traps, as discussed earlier, with some remigration following folding. In the case of hydrocarbons sourced from the Mancos Shale at Rangely, initial migration might have been up dip in the footwall to the plane of the fault where migration was blocked by abutting nonpermeable rocks. Migration then continued up the fault plane into permeable rocks in the hanging wall (Stone, 1990).

In addition to these known anticlinal structures, there is a possibility of Phosphoria-sourced oil or thermogenic gas in stratigraphic traps between structures, and the possible occurrence of such accumulations was considered in the assessment. As shown on figure 11, the potential for a subthrust play exists, but to date the drilling and testing of the footwall rocks has been limited.

All of the reservoirs are sealed by overlying low-permeability units in the anticlinal structures. The only exception is the stratigraphic-structural trap present at Rangely, which involves the interfingering of the Weber Sandstone and Maroon Formation. There, hydrocarbons in the Weber are sealed below, above, and up dip by low-permeability rocks of the Maroon.

As a method of recording the information necessary to evaluate the undiscovered hydrocarbon potential of the

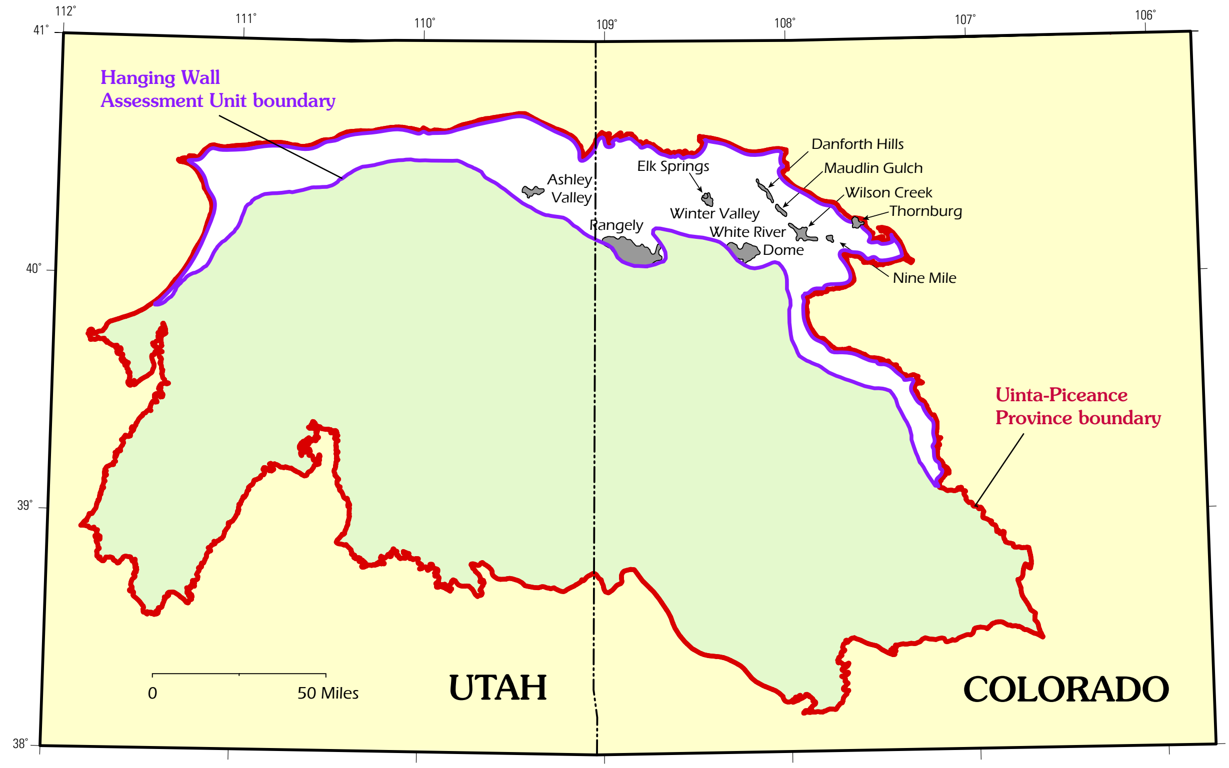


Figure 10. Position of the Hanging Wall Assessment Unit in the Uinta-Piceance Province and locations of the qualifying (>0.5 MMBOE) oil and gas fields (shaded gray) used in the assessment.

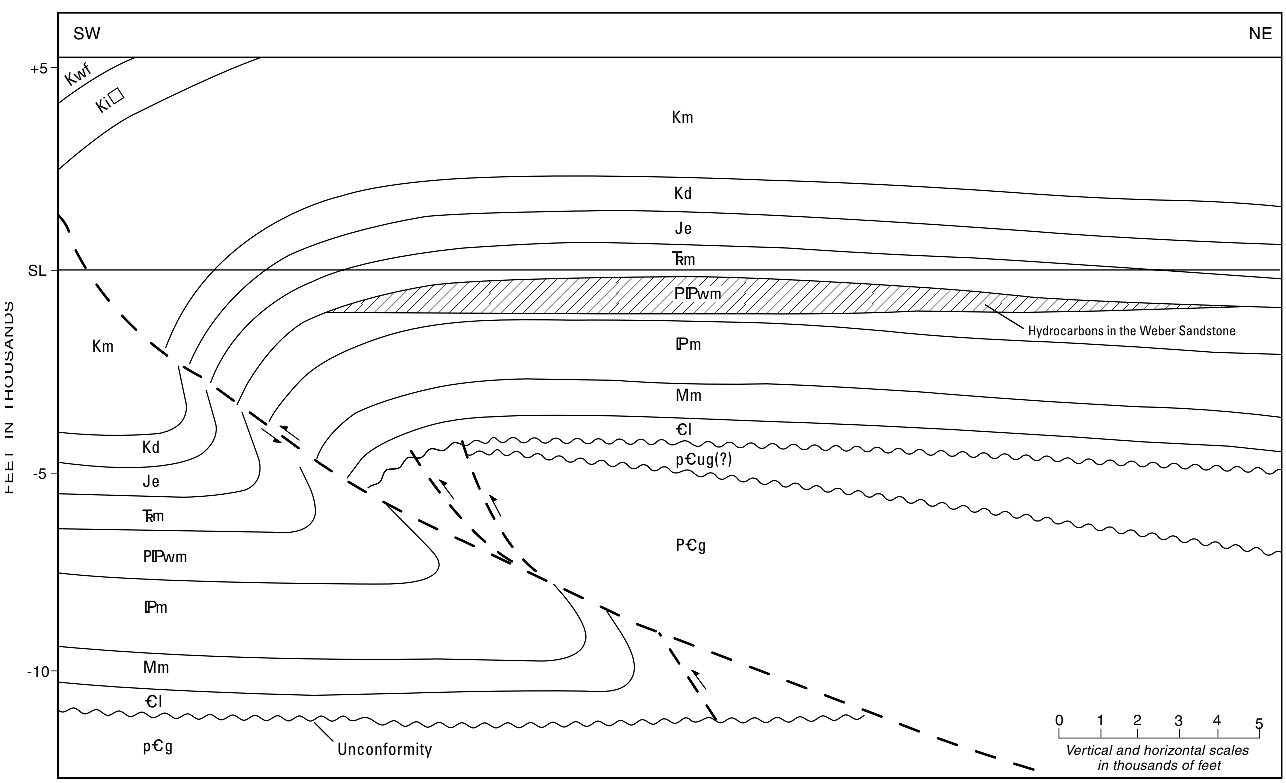


Figure 11. Generalized cross section of the thrusted anticlinal structure (Rangely anticline) that forms the trap for the Rangely oil field in northwest Colorado (modified after Mendeck, 1986). Abbreviations: Kwf, Williams Fork Formation; Ki, Iles Formation; Km, Mancos Shale; Kd, Dakota Sandstone; Je, Entrada Sandstone; TRm, Moenkopi Formation; PIPwm, Weber Sandstone and Maroon Formation; IPm, Morgan Formation; Mm, Madison Limestone; €l, Lodore Formation; p€ug, Uinta Mountain Group(?); p€g, granitic rocks.

Figure 12. Weber Sandstone exposed in the core of the Skull Creek anticline, 15 mi north of Rangely, Colo.

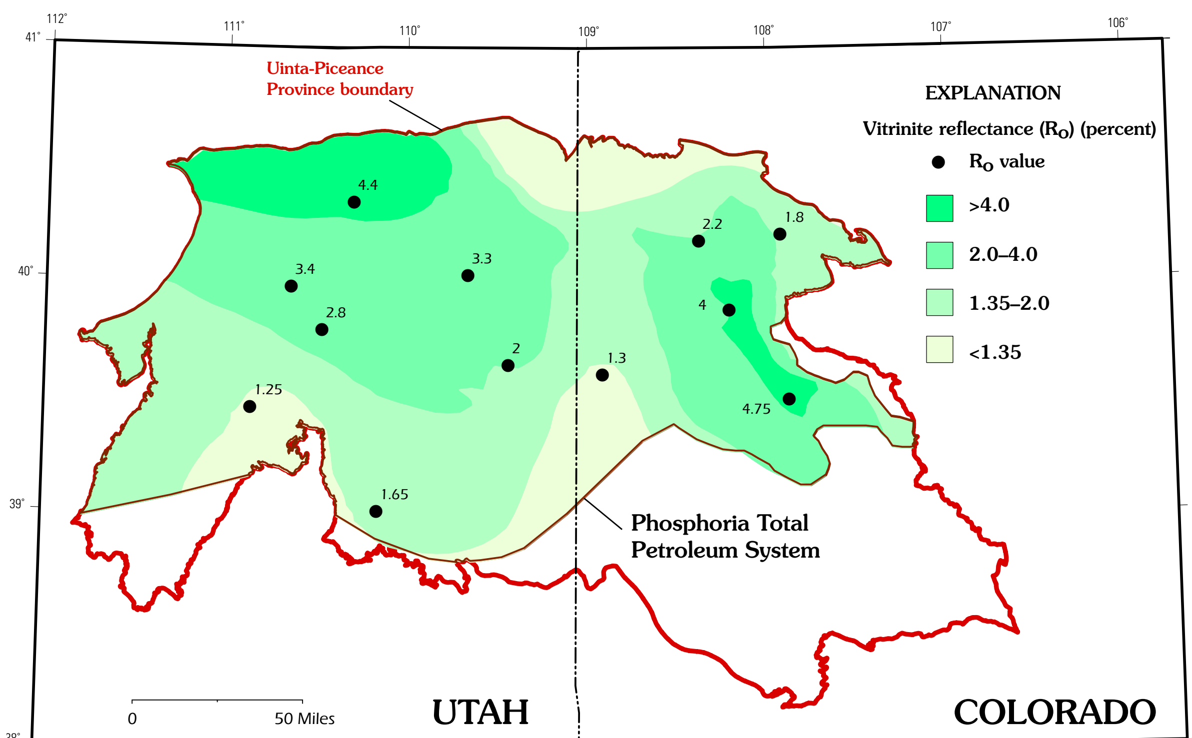


Figure 13. Vitrinite reflectance (R_0) isolines in the Uinta-Piceance Province. Data points derived from burial history curves constructed at the stratigraphic level of the Phosphoria Formation (Nuccio and Roberts, Chapter 4, this CD-ROM).

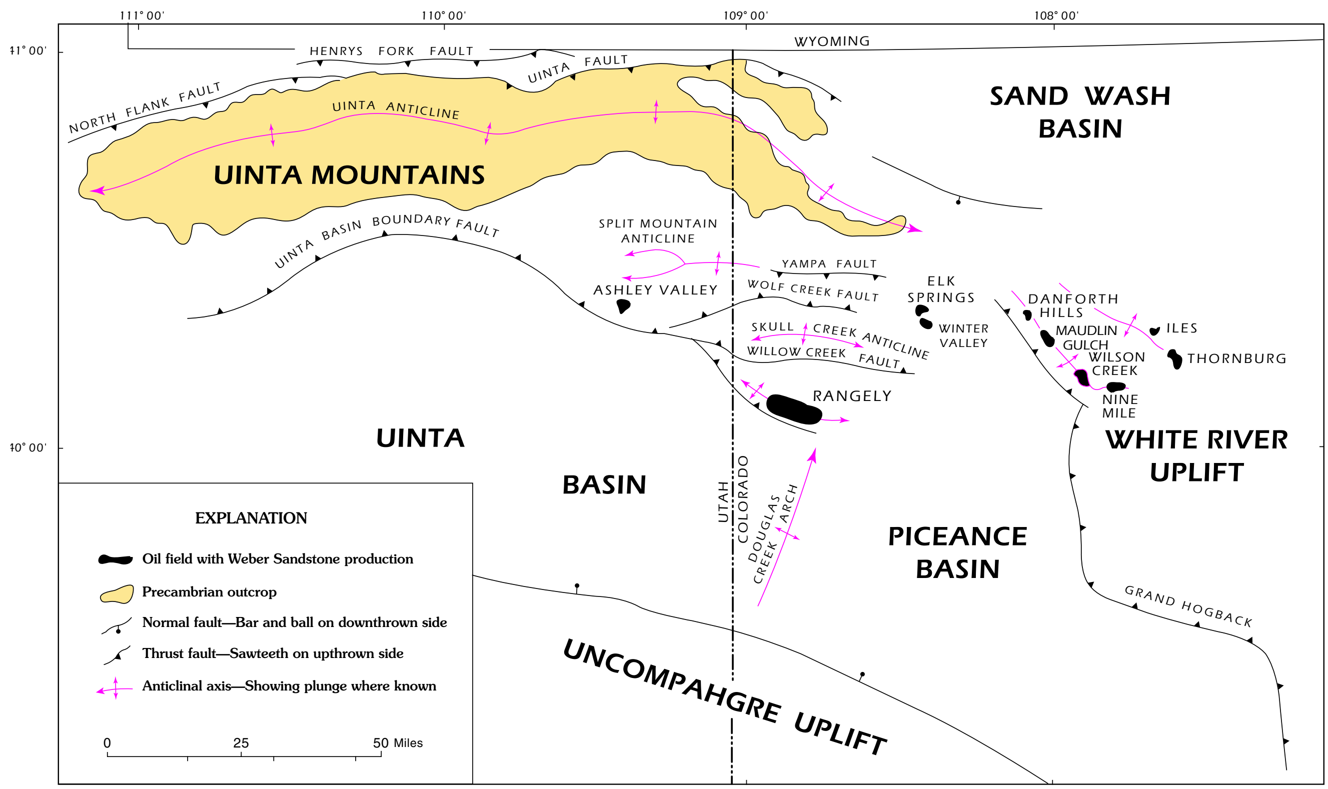


Figure 14. Structural features in the northern part of the Uinta-Piceance Province (modified after Hefner and Barrow, 1992).

Hanging Wall AU, a four-page data form, Seventh Approximation Data Form for Conventional Assessment Units, was completed (Schmoker and Klett, 1999); this form is reproduced in this report as Appendix A. The first section of the form, Identification Information, contains general information and the entries follow a nomenclature and numbering scheme established by the USGS. The remaining sections are more complex and some explanation of selected entries is in order.

In the Characteristics of Assessment Unit section, the Hanging Wall AU is described as oil prone because the majority of known fields produce primarily oil. The minimum field size, 0.5 million barrels of oil equivalent (MMBOE), was thought to be the smallest field for which size and number of undiscovered fields could be reasonably estimated based on geologic criteria. Also, the Nehring database (NRG Associates, 1999), one of the major sources of information used in the assessment, is reasonably complete for known fields exceeding this minimum size. A search of the Nehring database for fields larger than the minimum size finds 10 such fields in the assessment unit: 7 oil fields (Rangely, Wilson Creek, Elk Springs, Maudlin Gulch, Ashley Valley, Danforth Hills, and Nine Mile) and 3 gas fields (White River Dome, Thornburg, and Winter Valley). There are 10 other oil or gas fields in the assessment unit—Colorow Gulch, Danforth Hills North, Dinosaur, McHatton, Pinyon Ridge, Powell Park, Rifle Creek, Scott Hill, Starr Flat, and Temple Canyon—that do not exceed the minimum field size. Values for the median size (grown) of discovered oil and gas fields of minimum size or larger were calculated from data contained in the Nehring database. In most assessments, three values are listed for oil and for gas—the first third, second third, and third third. However, in the case of this assessment unit the first and second halves are listed because the assessment unit contains only 10 fields. Mean values for gas are not shown on Appendix A to ensure confidentiality of the proprietary database. Because the assessment unit has discovered fields and involves multiple source and reservoir rocks, and because the Uinta-Piceance Basins have a thermal history conducive to hydrocarbon generation, all assessment-unit probability attributes were rated high (1.0). Moreover, accessibility was rated high (1.0) because much of the assessment unit is potentially available for petroleum-related activities.

Before explaining entries in the Undiscovered Fields section, a short discussion of the exploration maturity of the Hanging Wall AU is in order. Although the assessment unit contains 20 oil or gas fields, only 10 exceeded the established minimum size. This is not an impressive number considering the fact that exploration in the area covered by the assessment unit has been ongoing for almost 100 years.

The largest oil field in the Hanging Wall AU, Rangely, was also the first to be discovered. Since that time (1902) there has been a steady decrease in the size of discovered fields. Moreover, the last field discovered, Nine Mile, was in 1966—35 years prior to this assessment. A similar trend holds for gas fields. The largest gas field, White River Dome, was also the first to be discovered. Since that time (1890) there have been only two small fields discovered. Moreover, the last field discovered, Winter Valley, was in 1958—43 years prior to the year of this assessment report.

Figure 15 shows the number of new-field wildcats versus completion year. A new-field wildcat is defined as an exploratory well drilled at least 2 mi from established production on a trap that has never produced oil or gas (Hyne, 1991). In total, 473 new-field wildcats (hereafter shortened to wildcats) have been drilled in the assessment unit. During the period 1911 through 1947, several wildcats were drilled every few years, but a period of increased exploration began in 1948. This period peaked with 20 wildcats in 1956 and then declined over the next few years to a low of 1 wildcat in 1991. A shorter exploration period from 1992 through 1994 peaked at 13 wildcats, but since then exploration drilling has dropped off significantly. In sum, despite a considerable amount of exploration drilling since 1966, the last year in which a significant field was discovered, no new significant fields have been added to the assessment unit.

All of the known fields in the Hanging Wall AU involve anticlinal structures that were discovered by observing their surface expression. Based on the limited distribution of post-Laramide deposits in the Uinta-Piceance Province that might conceal such structures (fig. 16), the potential for discovering additional anticlinal traps within the assessment unit is considered to be extremely low.

Considering the exploration maturity of the Hanging Wall AU and the low probability of finding new anticlinal structures, the minimum number of undiscovered oil fields of minimum size or larger was set at one. The maximum of five undiscovered oil fields represents the highest number that could be justified under "best case" conditions; the median number is three. Because undiscovered gas fields would be found in the same structural and stratigraphic settings as undiscovered oil fields, the minimum, median, and maximum values for the number of undiscovered gas fields are the same as those for undiscovered oil fields. In regard to the sizes of undiscovered oil fields, the minimum was set equal to the minimum size of 0.5 MMBO for oil fields to be considered in the assessment. The maximum size of undiscovered oil fields, 10 MMBO, represents the largest size that could be justified under "best case" conditions, and a median size of 1.2 MMBO was selected. Because of the parallel nature of undiscovered oil and gas fields, the minimum, median, and maximum values for the sizes of undiscovered gas fields were set equal on an energy basis to the size of undiscovered oil fields, assuming an energy equivalent factor of 6,000 ft^3 of gas per barrel of oil.

The Nehring database was used to assign numbers for the minimum, median, and maximum values in the Average Ratios for Undiscovered Fields, to Assess Coproducts section. The database contains values for each subsection (for example gas/oil ratio) for each of the qualifying discovered fields in the Hanging Wall AU. By examining the ranges of these known values, and taking into consideration the span of values that could be expected for undiscovered fields, a median value was established for each subsection. The minimum value was then set at 50 percent less than the median value and the maximum was set at 50 percent more than the median value. This somewhat arbitrary procedure of setting the minimum and maximum values was established as a means of assuring uniformity of methodology among assessment units.

Assigning numbers for the minimum, median, and maximum values in the Selected Ancillary Data for Undiscovered Fields section also assumes that undiscovered fields in the Hanging Wall AU would have similar ancillary characteristics as the discovered fields, which allows values to be taken directly out of the Nehring database. Hence, the minimum and maximum values for each data element (for example, API gravity) were picked directly off the posted values in the database, and the median value was calculated from the range of posted values.

Within the Hanging Wall AU, there are 1,529 producing oil wells, 151 producing gas wells, and 1,437 dry holes (IHS Energy Group, 2000). Almost all of the producing wells are in Colorado, with a large cluster of oil wells in the Rangely oil field and a large cluster of gas wells in the White River Dome gas field. In addition, a small number of oil and gas fields are in eastern Utah, with the Ashley Valley oil field being the largest. Figure 17 shows the pattern of surface land ownership in the assessment unit. The western part is dominated by Ashley National Forest on the north and the Uinta and Ouray Indian Reservation on the south, with the privately owned part of the reservation adjoining on the west. The eastern part, including that part in easternmost Utah, is dominated by Federal lands administered by the Bureau of Land Management (BLM) and by privately owned lands. This part of the assessment unit also contains Dinosaur National Monument on the north and two small areas of the White River National Forest on the east and southeast.

Potential additions to reserves for the Phosphoria TPS in the Uinta-Piceance Province are reported by hydrocarbon type (oil, gas, and natural gas liquids) in Appendixes C and D. The Hanging Wall AU contains mean values of 4.47 MMBO, 28.15 billion cubic feet of gas (BCFG), and 0.94 million barrels of natural gas liquid (MMBNGL) as estimated potential additions to reserves over the next 30 years of petroleum in undiscovered conventional accumulations.

Paleozoic/Mesozoic Assessment Unit (AU 50200402)

The Paleozoic/Mesozoic AU was established to include all conventional hydrocarbon accumulations known or suspected to be sourced from Paleozoic rocks, or in one case from a combination of Paleozoic and Mesozoic rocks, south of the Hanging Wall AU (fig. 18). Although several Paleozoic units are possible source rocks, hydrocarbons derived from the Phosphoria Formation probably predominate.

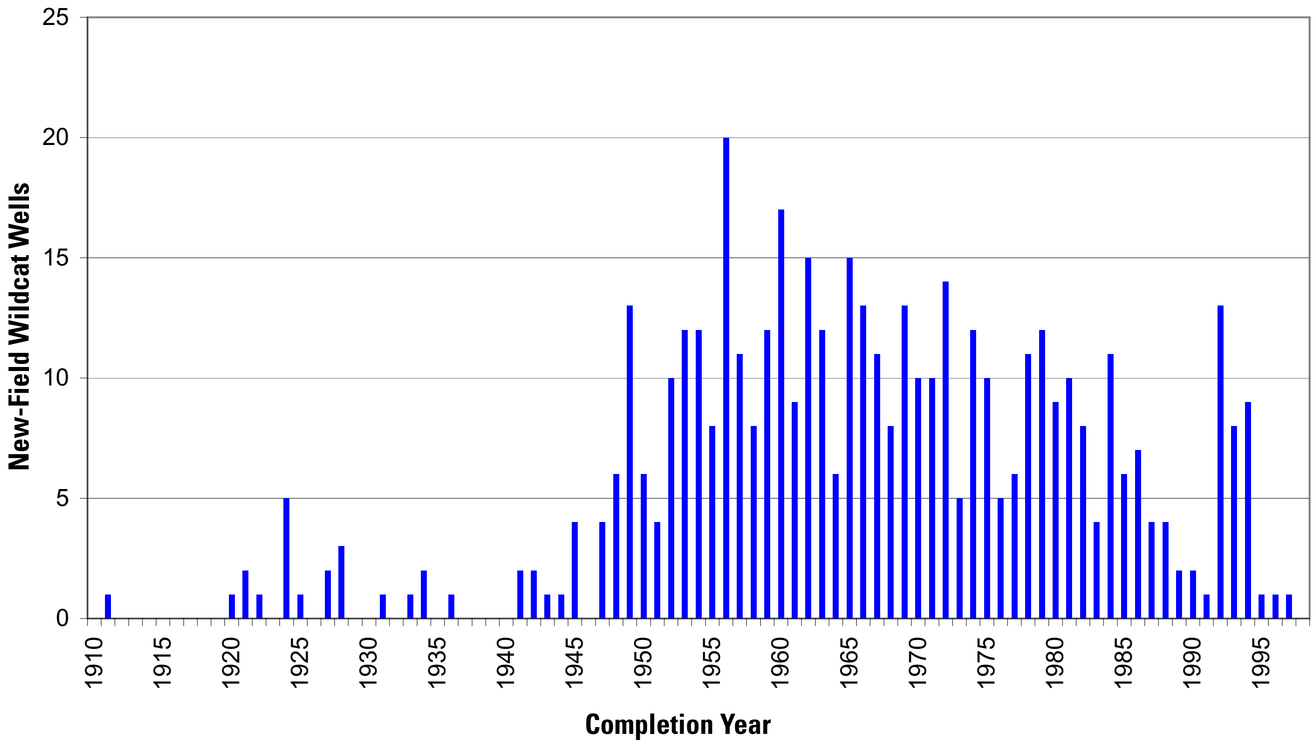


Figure 15. Number of wildcat wells versus completion year in the Hanging Wall Assessment Unit.

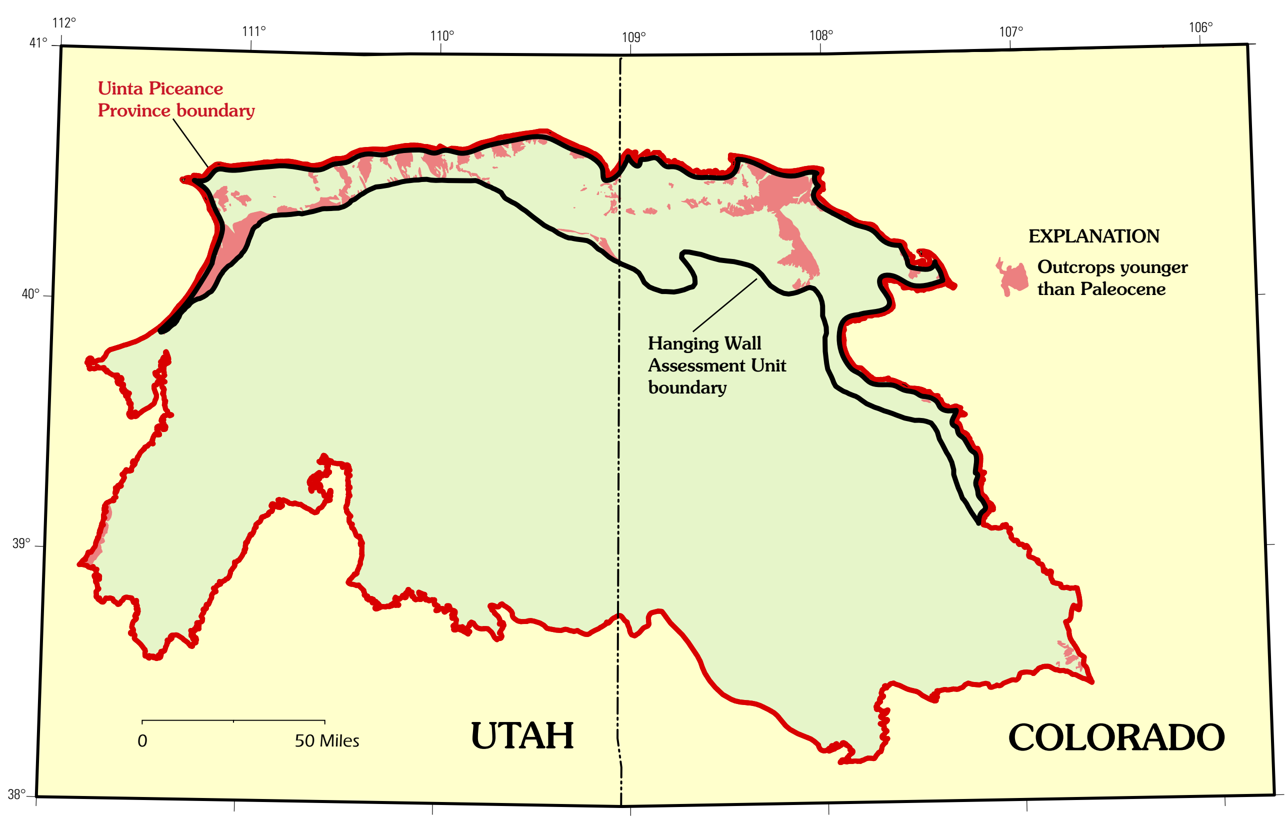


Figure 16. Distribution of post-Laramide (Eocene) deposits in the Hanging Wall Assessment Unit, Uinta-Piceance Province (modified from Green, 1992; Hintze and others, 2000).

Table 1 lists the 15 fields that are included in the assessment unit, as well as their source and reservoir rocks. Two oil fields in the northwestern Piceance Basin form the Douglas Creek cluster—Douglas Creek and Douglas Creek North (fig. 19). Both of these fields have produced oil from the Weber Sandstone, but no samples are contained in the USGS collection of oils. Because these fields are in close proximity to the Rangely oil field, it is assumed that the oil was derived from the Phosphoria. The greater Cisco cluster in the southeastern Uinta Basin comprises five oil fields—Agate, Cisco Dome, Cisco Springs, Cisco Townsite, and Seiber Nose. Certain oil samples from four of these fields in the USGS collection have chemistries consistent with oil known to be sourced from the Phosphoria (Lillis and others, Chapter 3, this CD-ROM). In addition, one sample appears to be Phosphoria-type oil mixed with Cretaceous-type oil, and one sample is from an unknown Paleozoic source. Six oil fields in the southern Uinta Basin form the Grassy Trail Creek cluster—Blaze Canyon, Buzzard Bench, Ferron, Flat Canyon, Grassy Trail Creek, and Indian Creek (table 1). Oil samples from three of these fields—Buzzard Bench, Ferron, and Grassy Trail Creek—in the USGS collection have chemical characteristics consistent with Paleozoic-age oils, but the specific source rocks are unknown. The remaining three fields are also reported to contain oil from an unknown Paleozoic source (Doug Sprinkel, Utah Geological Survey, written commun., 2000). The San Arroyo cluster in the western Piceance Basin comprises two gas fields—Bar X and San Arroyo. These fields were included in the assessment unit because analyses of gas produced here from the Entrada Sandstone are high in CO_2 and inert gases (Otto and Picard, 1975), which are characteristics often associated with Paleozoic source rocks.

The northern boundary of the Paleozoic/Mesozoic AU coincides with the southern boundary of the Hanging Wall AU. This line separates two different styles of anticlinal structures. Because the anticlines in the Paleozoic/Mesozoic AU have developed alongside two large regional structures, the Douglas Creek arch and the Uncompahgre uplift, the assessment unit was expanded to include the remainder of the Uinta-Piceance Province.

Hydrocarbons contained in the Paleozoic/Mesozoic AU are mostly oil and associated gas, but locally some nonassociated gas is present. The hydrocarbons are reported to be present in nine lithostratigraphic units: Lower Permian Kaibab Limestone (equivalent to the Grandeur Member of the Park City Formation), Weber Sandstone, Lower Triassic Moenkopi Formation, Lower Jurassic Navajo Sandstone, Entrada Sandstone, Morrison Formation, Cedar Mountain Formation, Dakota Sandstone, and Mancos Shale (table 1). However, two of the units, the Weber and Navajo, do not produce in fields large enough to be used in this assessment. All units produce from primary or secondary porosity in sandstones or carbonate rocks.

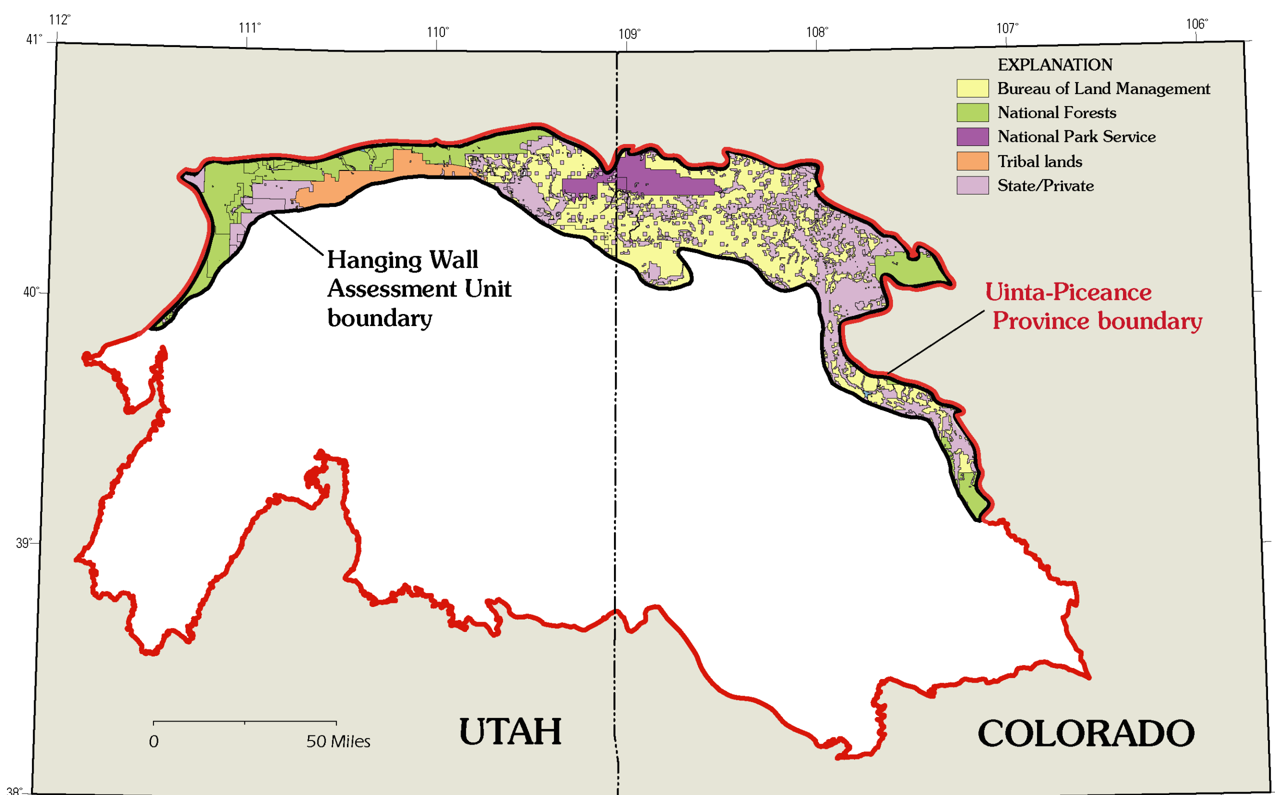


Figure 17. Pattern of surface land ownership in the Hanging Wall Assessment Unit, Uinta-Piceance Province.

The principal hydrocarbon traps in the Paleozoic/Mesozoic AU are anticlinal structures associated with two major structural elements—the Douglas Creek arch and the Uncompahgre uplift. The Douglas Creek arch is a broad, north-trending regional uplift, located just east of the Utah-Colorado State line (Cashion, 1973; Rowley and others, 1985), that formed during the Laramide orogeny (fig. 19). The arch, which separates the Uinta Basin from the Piceance Basin (fig. 1), is approximately 40 mi long and 20 mi wide, and the somewhat sinuous axial trace is concave toward the west. Most structural maps show the northern limit of the arch just south of the northwest-trending Rangely anticline, and the southern limit just north of the Garmesa anticline (see, for example, Johnson and Finn, 1986). Two sets of secondary structures are superimposed on the arch: northwest-trending folds and a slightly younger swarm of northeast-trending, high-angle normal faults (Kopper, 1962a, b; Osmond, 1964; Kellogg, 1977). Both the Douglas Creek and Douglas Creek North oil fields produce from faulted anticlines, which represent the intersection of these two secondary types of structures. Kopper (1962b) noted that the folds probably predate the formation of the arch because Triassic and Jurassic sedimentary units thin across the structures. He postulated that the original folding was in response to the formation of the Uncompahgre uplift, and that later compressional forces that developed between the southward-thrusting Uinta uplift and the stationary Uncompahgre uplift reactivated the folds during the Laramide orogeny.

The ancestral Uncompahgre uplift is a buried tectonic feature that trends northwest and extends across the Colorado-Utah State line at about the latitude of Grand Junction, Colo. (Stone, 1977). The uplift covers an area of about 4,500 mi^2, and is bounded on the northeast by the Garmesa fault zone and on the southwest by the Uncompahgre fault zone (fig. 20). Tectonic activity might have commenced as early as the late Precambrian with postulated left-lateral movement along two basement shear zones now represented by the Garmesa and Uncompahgre fault zones. Following this initial activity, the region experienced a period of tectonic quiescence until the mid-Paleozoic. The major uplift of the region took place during Pennsylvanian and Permian time, as evidenced by the voluminous amounts of arkosic rocks of that age that were deposited adjacent to the uplift. This period of tectonic activity culminated at the close of the Early Triassic when the uplift was eroded down to its Precambrian core. Thus, a major unconformity exists in the central part of the uplift where the Upper Triassic Shinarump Member of the Moenkopi Formation rests on Precambrian crystalline rocks. Subsequently, the uplift was covered with Mesozoic and Cenozoic deposits. Starting in the Late Cretaceous, a new period of tectonic activity associated with the Laramide orogeny caused renewed movement along the uplift's bounding faults. The whole feature was tilted toward the northeast, and many smaller structural elements, on and adjacent to the uplift, were reactivated. It was during this deformational period that many of the anticlines pertinent to this assessment were developed in their present form. Two categories of reactivated anticlines are recognized: drape folds and parafolds. Drape folds formed in the central part of the uplift in response to movement along reactivated faults in the crystalline basement, and parafolds formed along the flanks of the uplift in response to reactivated folding of structures that originally formed along the Precambrian shear zones. Stone (1977) showed the San Arroyo anticline as a drape fold and the Cisco dome as a parafold. Most likely, the Bar X structure is also a drape fold, and the structures responsible for the other oil fields in the greater Cisco cluster and for the oil fields in the Grassy Trail Creek cluster are parafolds.

All of the producing lithostratigraphic units in the Paleozoic/Mesozoic AU are sealed by the low-permeability units that cap them in the anticlinal structures.

The data form, Seventh Approximation Data Form for Conventional Assessment Units, for the Paleozoic/Mesozoic AU is reproduced in this report as Appendix B. In the Characteristics of Assessment Unit section, the Paleozoic/Mesozoic AU is described as gas prone because most of the production from the fields used in the assessment is natural gas. Four fields—two gas fields, Bar X and San Arroyo, and two oil fields, Grassy Trail Creek and Cisco Dome—exceed the minimum size of 0.5 MMBOE. Eleven other oil or gas fields—Agate, Blaze Canyon, Buzzard Bench, Cisco Springs, Cisco Townsite, Douglas Creek, Douglas Creek North, Ferron, Flat Canyon, Indian Creek, and Seiber Nose—are less than the minimum field size. Two gas fields and two oil fields are not enough fields for median size (grown) of discovered oil and gas fields to be a significant parameter. Therefore, this part of the form is left blank. Because (1) the assessment unit has discovered fields and involves several source and reservoir rocks, and (2) the Uinta-Piceance Basins have a thermal history conducive to hydrocarbon generation, all assessment-unit probability attributes were rated high (1.0). Moreover, accessibility was rated high (1.0) because much of the assessment unit is potentially available for petroleum-related activities.

Before explaining entries in the Undiscovered Fields section, a short discussion on the exploration maturity of the Paleozoic/Mesozoic AU is in order. Although the assessment unit contains 15 oil or gas fields, only 4 exceed the established minimum size. This is an unimpressive number considering the fact that exploration in the area covered by the assessment unit has been ongoing since just after the beginning of the twentieth century.

Thirty-six years elapsed between the discovery of the first oil field, Cisco Dome in 1925, and that of the next oil field, Grassy Trail Creek in 1961. No oil fields have been discovered in the Paleozoic/Mesozoic AU for the 40 years prior to this assessment. A similar trend holds for gas fields. Only 7 years elapsed between the first gas field discovered, Bar X in 1948, and the other gas field discovered, San Arroyo in 1955, but none of minimum size have been discovered in the assessment unit for the 46 years prior to this assessment.

Figure 21 shows the number of wildcats drilled to the Dakota Sandstone or deeper formations versus completion

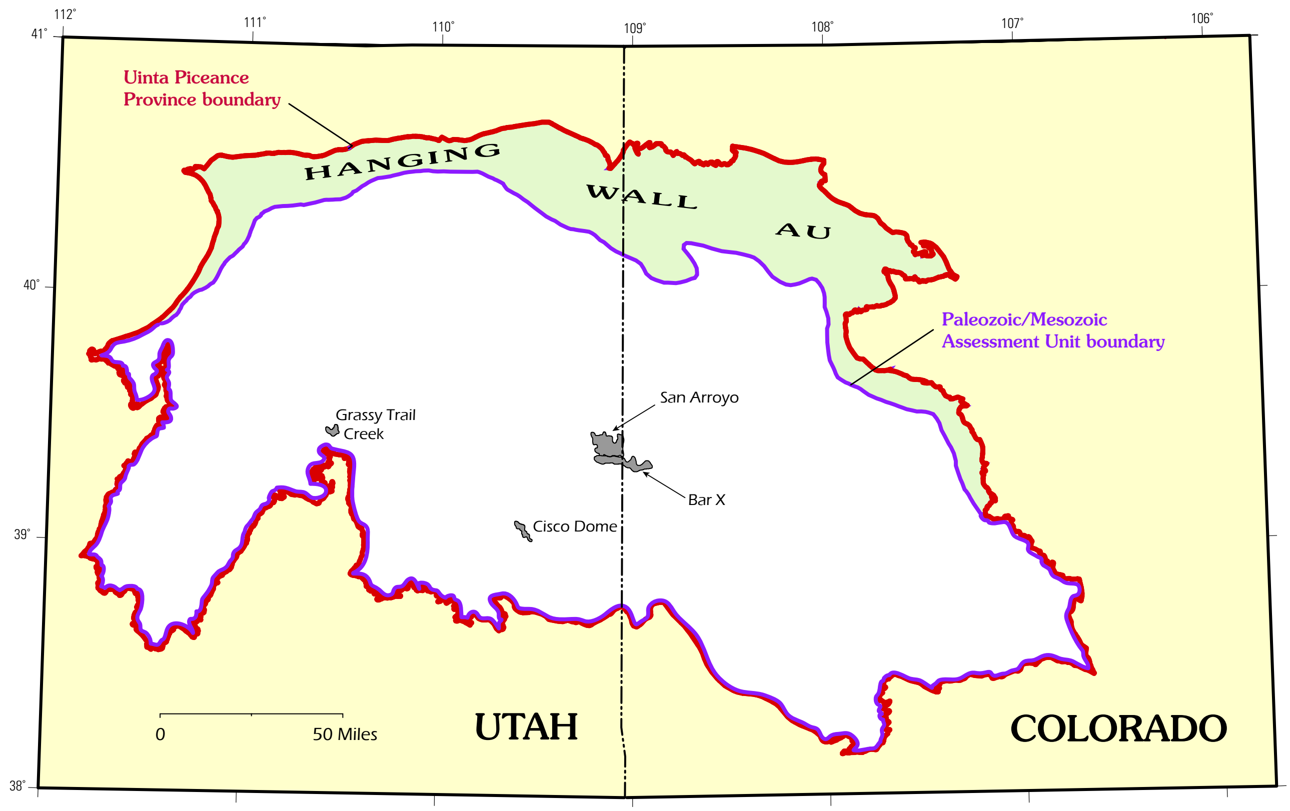


Figure 18. Position of the Paleozoic/Mesozoic Assessment Unit in the Uinta-Piceance Province and locations of the qualifying (>0.5 MMBOE) oil and gas fields (shaded gray) used in the assessment.

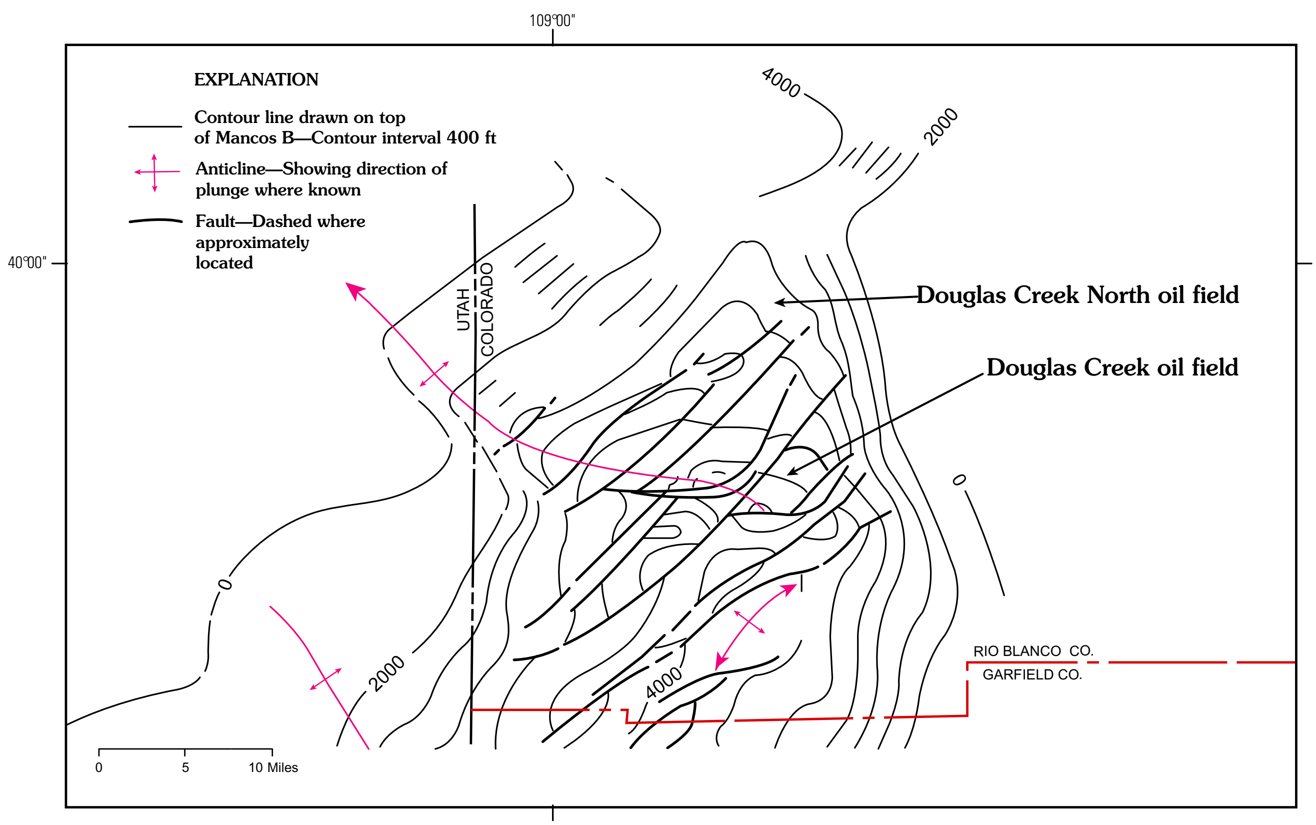


Figure 19. Structural features associated with the Douglas Creek arch (modified from Kellogg, 1977).

Table 1. Oil or gas fields, source rocks, and reservoir rocks in the Paleozoic/Mesozoic Assessment Unit.

Field	Source rocks	Reservoir rocks
	Douglas Creek cluster	
Douglas Creek	Phosphoria	Weber
Douglas Creek North	Phosphoria	Weber
	Greater Cisco cluster	
Agate	Phosphoria	Morrison
Cisco Dome	Unknown Paleozoic	Morrison
Cisco Springs		
	Phosphoria/Cretaceous	Dakota
	Unknown Paleozoic	Cedar Mountain
	Phosphoria	Morrison
Cisco Townsite	Phosphoria	Mancos
Seiber Nose	Phosphoria	Morrison
	Grassy Trail Creek cluster	
Blaze Canyon	Unknown Paleozoic	Navajo
Buzzard Bench	Unknown Paleozoic	Moenkopi
Ferron	Unknown Paleozoic	Kaibab
Flat Canyon	Unknown Paleozoic	Dakota
Grassy Trail Creek	Unknown Paleozoic	Moenkopi
Indian Creek	Unknown Paleozoic	Dakota
	San Arroyo cluster	
Bar X	Suspected unknown Paleozoic	Entrada
San Arroyo	Suspected unknown Paleozoic	Entrada

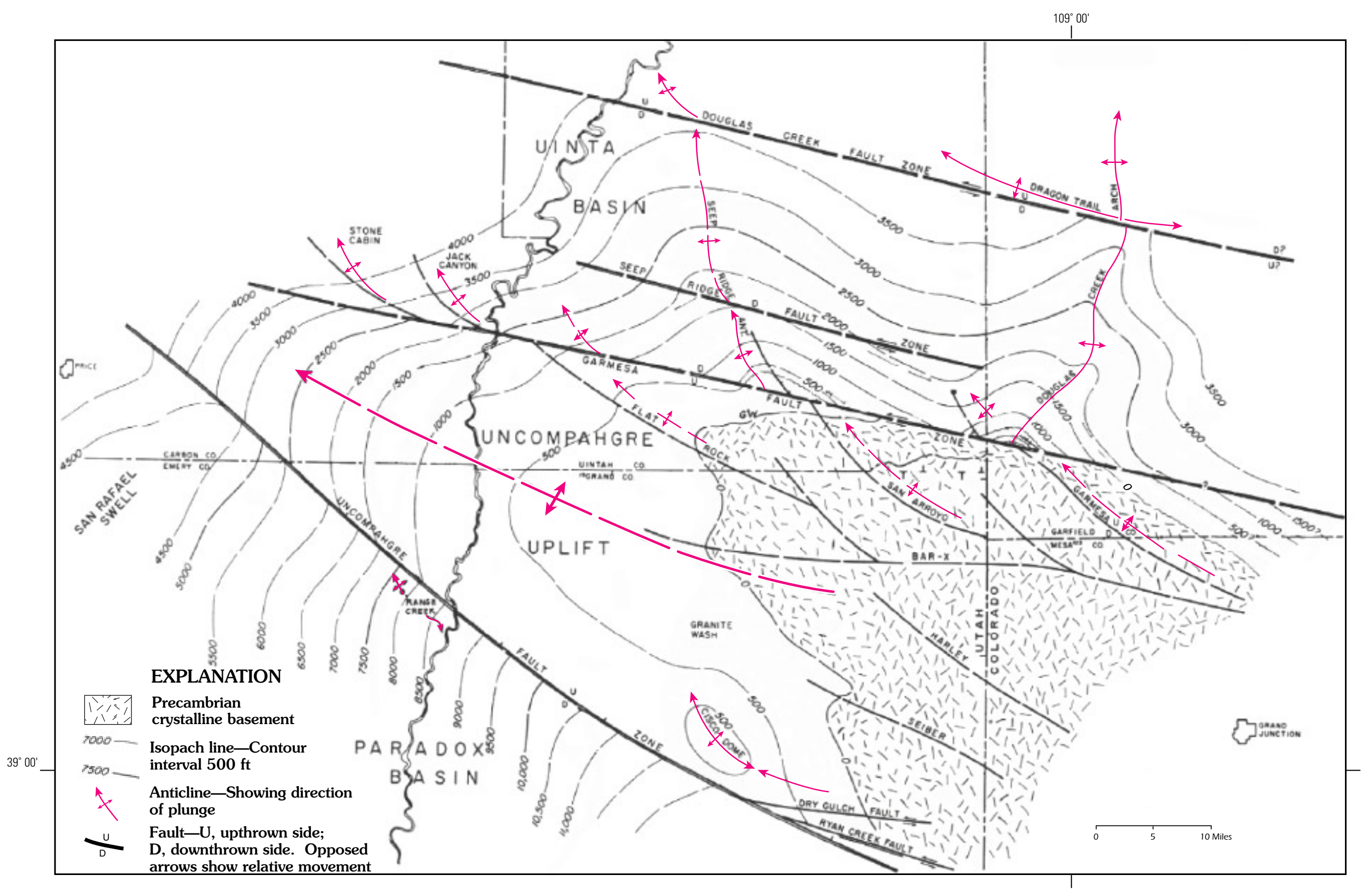


Figure 20. Structural features associated with the Uncompahgre uplift. Isopach interval is from the top of the Precambrian to the base of the Shinarump Member of the Chinle Formation (modified from Stone, 1977).

year. A total of 576 wildcats have been drilled in the Paleozoic/Mesozoic AU. Two broad periods of exploratory drilling can be identified on figure 21. The first period spans the years 1951 through 1971. During this time exploration drilling peaked at 23 wildcats in 1956 followed by a steady decline to a low of 5 wildcats in 1971. The second and more significant period spans the years 1972 through 1984. During this time exploration drilling exceeded 15 wildcats per year during a 10-year span, and in one year, 1981, 59 wildcats were drilled. Since 1984, only 37 wildcats have been drilled in the assessment unit. In sum, despite a considerable amount of exploration drilling since 1961, the last year a significant field was discovered, no new fields have been added to the assessment unit.

All of the fields in the assessment unit involve anticlinal structures that were discovered by observing their surface expression. Figure 22 shows the distribution of post-Laramide deposits in the Uinta-Piceance Province that might conceal such structures. As shown, the areas of the Douglas Creek arch and Uncompahgre uplift are largely free of these deposits. However, the flanks of the Douglas Creek arch and the area northeast and northwest of the nose of the Uncompahgre uplift are covered, and in these areas anticlinal structures could be hidden beneath these deposits.

Other more complicated trapping mechanisms have been reported. Stone (1969) noted that the long history of movement along the Uncompahgre uplift's boundary faults has undoubtedly resulted in the juxtaposition of permeable and nonpermeable lithofacies, and this geometry could have set up substantial stratigraphic traps along the length of these buried structures. Potter and others (1992) presented seismic reflection data that detected buried, northwest-vergent thrust faults off the nose of the Uncompahgre uplift in the southern part of the Uinta Basin (fig. 23) that might have resulted from compressional forces set up by the northwest progression of the Uncompahgre uplift during late Paleozoic time. As observed on seismic profiles, the Upper Mississippian Doughnut Formation is displaced by the faults but the overlying Kaibab Limestone is not. Because these faults are not exposed at the surface, buried structural or stratigraphic traps associated with the faults might contain undiscovered accumulations of hydrocarbons.

Considering the overall exploration maturity of the Paleozoic/Mesozoic AU, the minimum number of undiscovered oil fields of minimum size or larger is estimated to be two. The maximum number of undiscovered oil fields is estimated to be eight, which represents the highest number that could be justified under "best case" conditions; the median number is four.

The Paleozoic/Mesozoic AU covers large areas where any Phosphoria-sourced oil contained in stratigraphic traps would have been heated above R_o=2.0 percent (fig. 13) and thermogenic gas would have been released. Because of this, the potential for undiscovered gas fields was rated slightly higher than for oil fields, with estimates of 2 (minimum), 5 (median), and 12 (maximum).

In reference to the sizes of undiscovered oil fields, the minimum was set equal to the minimum size of 0.5 MMBO for oil fields to be considered in the assessment. The maximum size of undiscovered oil fields, 10 MMBO, represents the largest size that could be justified under "best case" conditions; the median size is 1.2 MMBO. The minimum, median, and maximum values for the sizes of undiscovered gas fields were set equal on an energy basis to the size of undiscovered oil fields, assuming an energy equivalent factor of 6,000 ft^3 of gas per barrel of oil.

All of the values for the numbers of undiscovered oil and gas fields are higher than the corresponding values in the Hanging Wall AU because of (1) the greater potential for Phosphoria-sourced oil and thermogenic gas in stratigraphic traps between anticlinal structures, (2) the possibility of undetected hydrocarbon accumulations in stratigraphic traps associated with the Uncompahgre uplift's two boundary faults, and (3) the possibility of undetected hydrocarbon accumulations in structural or stratigraphic traps associated with buried thrusts in front of the uplift. Although no production is known from any of these postulated traps, the potential was considered in the assessment.

Within the Paleozoic/Mesozoic AU, there are 156 producing oil wells, 1,018 producing gas wells, and 840 dry holes that were completed in the Dakota Sandstone or deeper formations (IHS Energy Group, 2000). More than one-half of the producing wells are in Colorado. Of note is the northwestern trend of gas wells in the northwestern part of the Piceance Basin, and the cluster of oil wells representing the greater Cisco area in the southeastern part of the Uinta Basin.

Figure 24 shows the pattern of surface land ownership in the assessment unit. The western part is dominated by Federal lands contained in the Ashley, Uinta, and Manti-LaSal National Forests, and Indian lands contained in the Uinta and Ouray Indian Reservation. The southeastern part is dominated by Federal lands in the Grand Mesa, Gunnison, and Uncompahgre National Forests. The central part contains mostly Federal lands administered by the BLM, with minor portions controlled by the States or privately owned. In addition, a large enclave of the Uinta and Ouray Indian Reservation is also present.

Potential additions to reserves for the Phosphoria TPS in the Uinta-Piceance Province are reported by hydrocarbon type (oil, gas, and natural gas liquids). The Paleozoic/Mesozoic AU contains mean values of 6.29 MMBO, 49.93 BCFG, and 1.65 MMBNGL as estimated potential additions to reserves over the next 30 years of petroleum in undiscovered conventional accumulations.

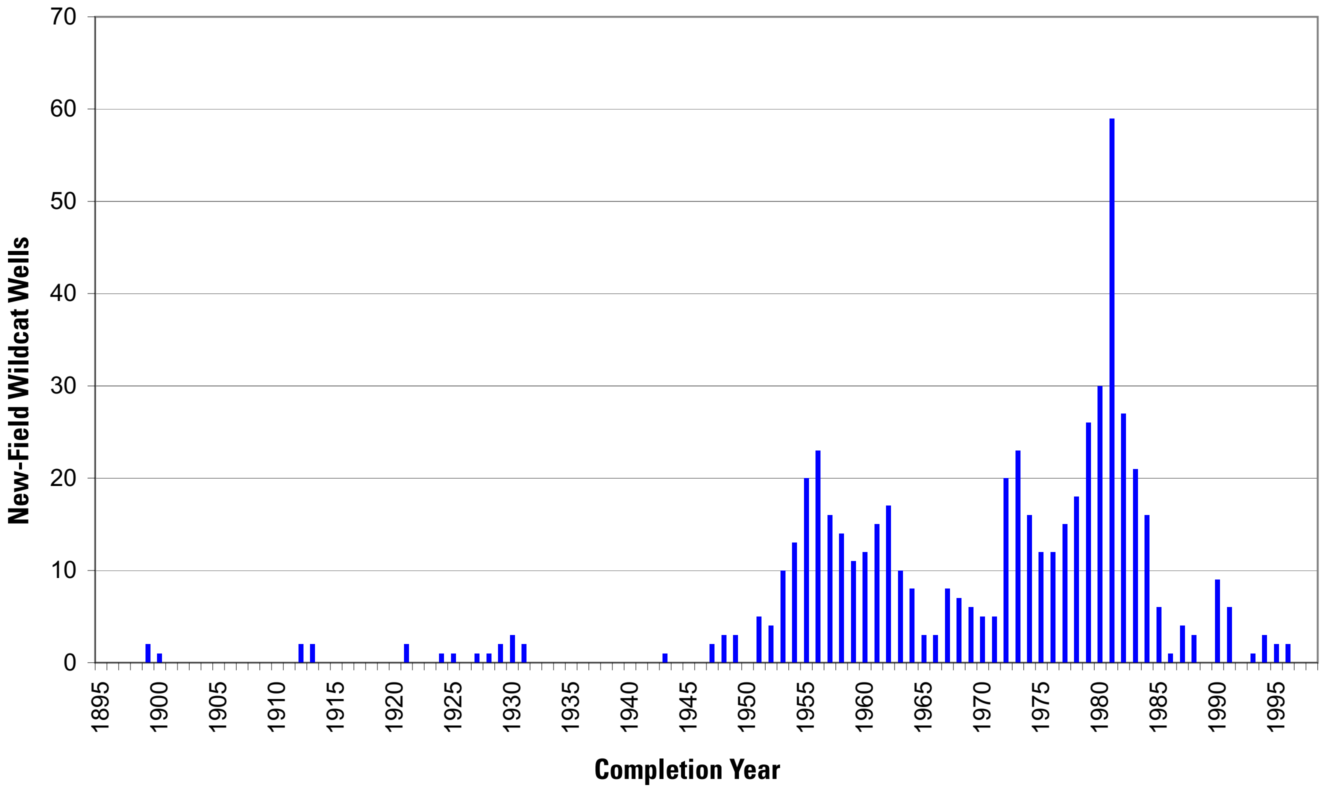


Figure 21. Number of wildcat wells versus completion year in the Paleozoic/Mesozoic Assessment Unit.

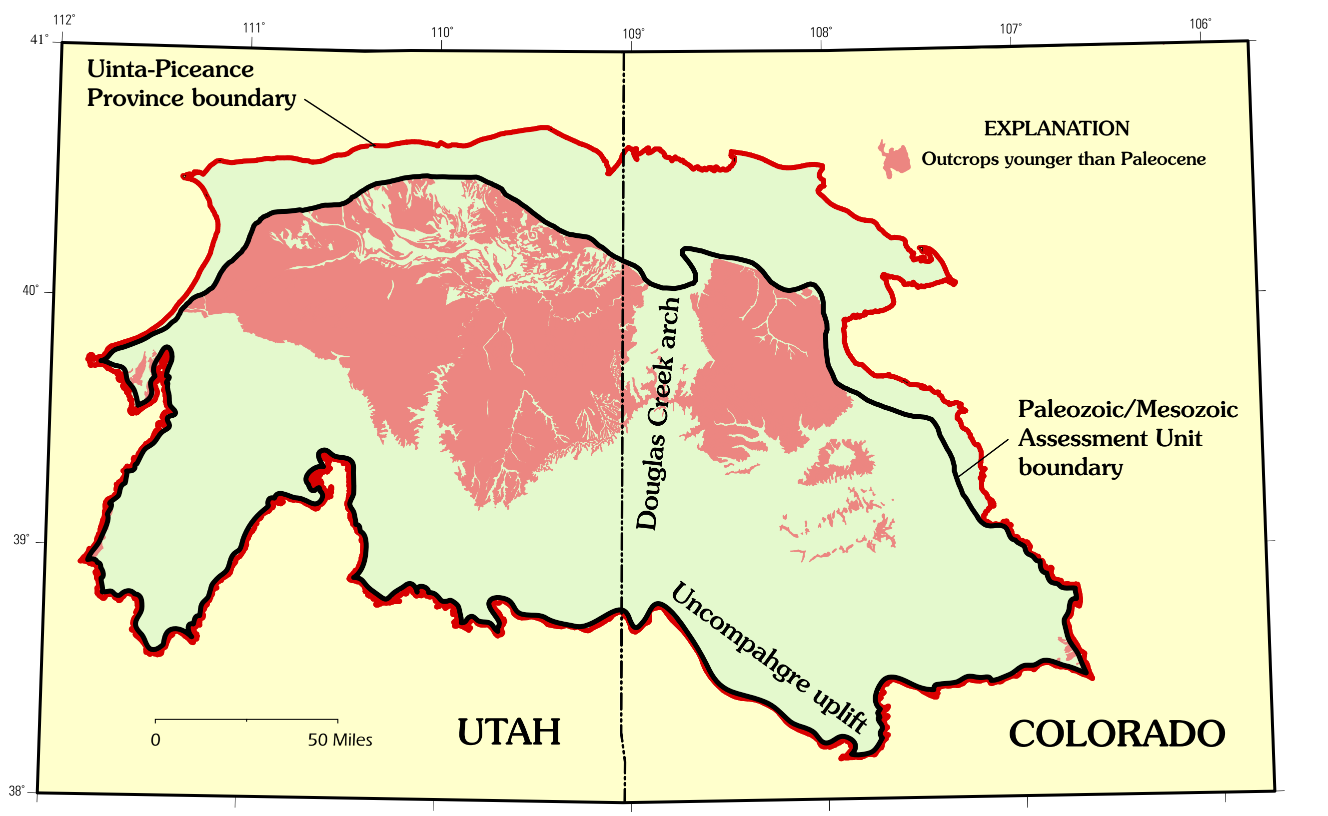


Figure 22. Distribution of post-Laramide (Eocene) deposits in the Paleozoic/Mesozoic Assessment Unit (modified from Green, 1992; Hintze and others, 2000).

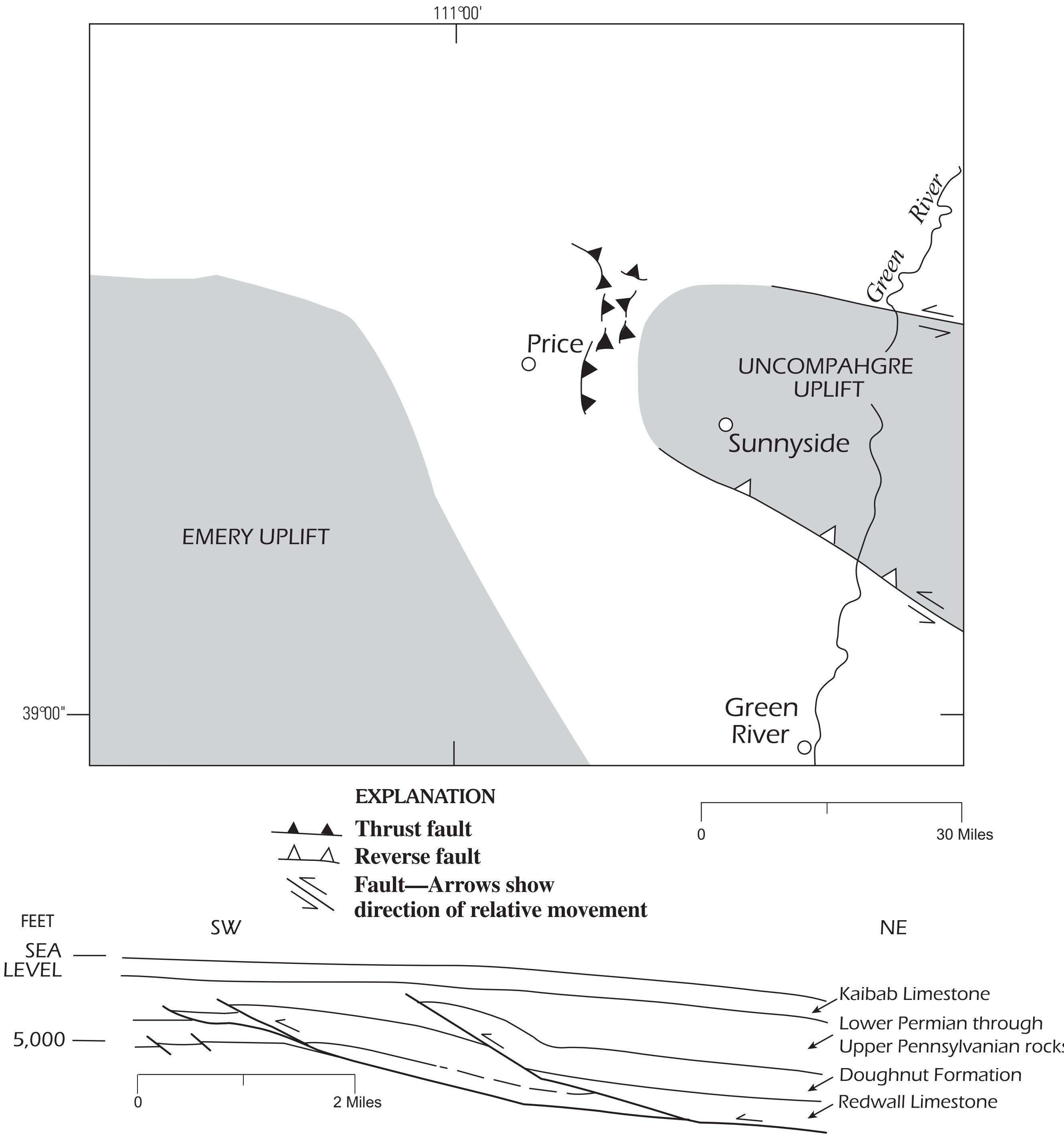


Figure 23. Structural features associated with the northwest nose of the Uncompahgre uplift. Cross section interpreted from migrated seismic section located about 6 mi east of Price, Utah. (Modified from Potter and others, 1992.)

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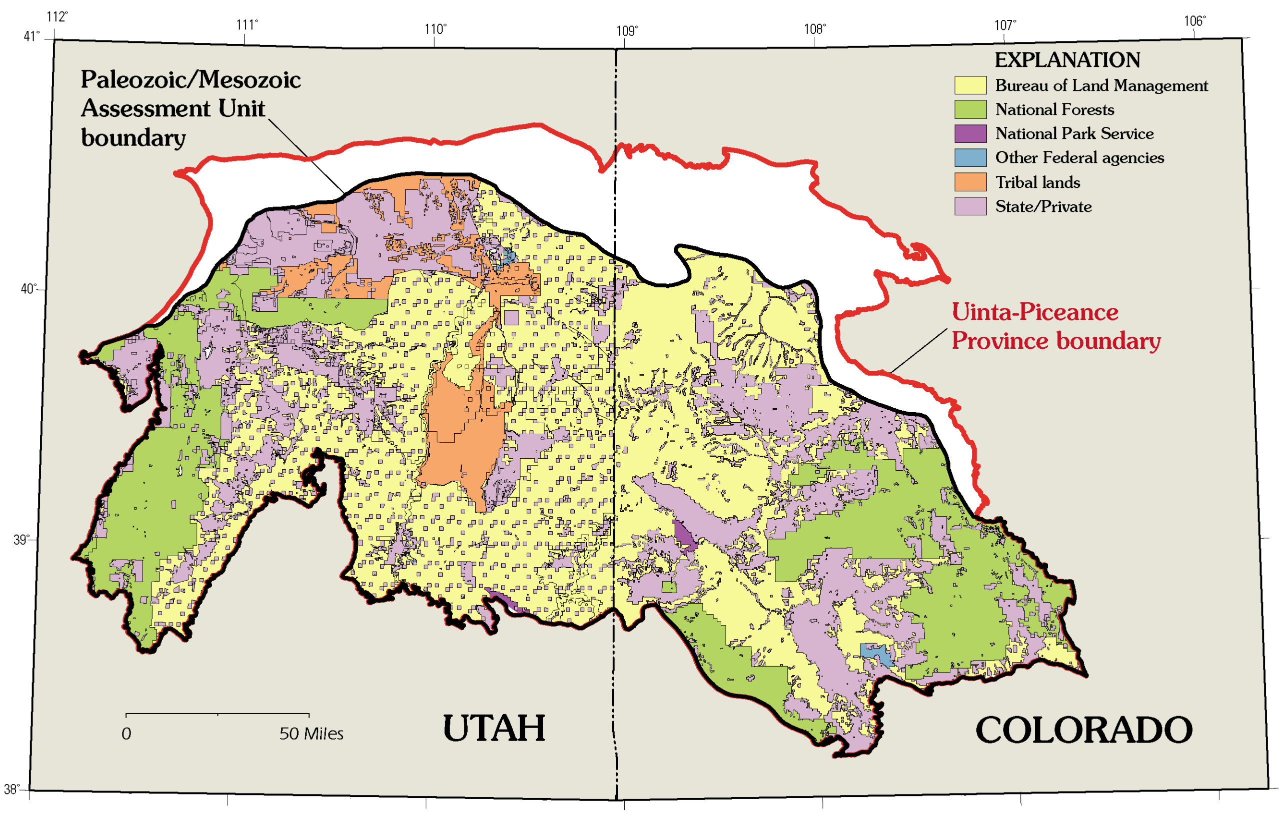

Figure 24. Pattern of surface land ownership in the Paleozoic/Mesozoic Assessment Unit, Uinta-Piceance Province.

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Appendix A. Data form used in evaluating the Hanging Wall Assessment Unit (AU 50200401), Phosphoria Total Petroleum System, Utah and Colorado.

IDENTIFICATION INFORMATION

Date:…………………………..	10/17/00		
Assessment Geologist:……..	E.A. Johnson		
Region:………………………..	North America	Number:	5
Province:………………………	Uinta-Piceance	Number:	5020
Priority or Boutique.…………			
Total Petroleum System:……	Phosphoria	Number:	502004
Assessment Unit:……………	Hanging Wall	Number:	50200401
Based on Data as of:……….	NRG Associates (2000) through 1998		
* Notes from Assessor	Function e2, U.S. Lower 48 States Conventional Growth Function		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas ($\geq$20,000 cfg/bo overall):… Oil

What is the minimum field size?………. 0.5 mmboe grown
(the smallest field that has potential to be added to reserves in the next 30 years)

Number of discovered fields exceeding minimum size:………… Oil: 7 Gas: 3
Established (>13 fields) ____ Frontier (1-13 fields) X Hypothetical (no fields) ____

Median size (grown) of discovered oil fields (mmboe):
1st 1/2 60.1 2nd 1/2 4.9
Median size (grown) of discovered gas fields (bcfg):
1st 1/2 ____ 2nd 1/2 ____

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered field $\geq$ minimum size………………	1.0
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered field $\geq$ minimum size……	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered field $\geq$ minimum size	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3):……..……....…. 1.0

4. **ACCESSIBILITY:** Adequate location to allow exploration for an undiscovered field $\geq$ minimum size…………………………………………………..………………..……..………… 1.0

UNDISCOVERED FIELDS

Number of Undiscovered Fields: How many undiscovered fields exist that are $\geq$ minimum size?:
(uncertainty of fixed but unknown values)

Oil fields:…………………………………min. no. (>0)	1	median no.	3	max no.	5
Gas fields:………………………………min. no. (>0)	1	median no.	3	max no.	5

Size of Undiscovered Fields: What are the anticipated sizes (**grown**) of the above fields?:
(variations in the sizes of undiscovered fields)

Oil in oil fields (mmbo)………………..……min. size	0.5	median size	1.2	max. size	10
Gas in gas fields (bcfg):……………………min. size	3	median size	7.2	max. size	60

Appendix A—Continued. Data form used in evaluating the Hanging Wall Assessment Unit (AU 50200401), Phosphoria Total Petroleum System, Utah and Colorado.

AVERAGE RATIOS FOR UNDISCOVERED FIELDS, TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil Fields:	minimum	median	maximum
Gas/oil ratio (cfg/bo)………………………...………	150	300	450
NGL/gas ratio (bngl/mmcfg)…………………....….	30	60	90

Gas fields:	minimum	median	maximum
Liquids/gas ratio (bngl/mmcfg)….…………..……..	16	32	48
Oil/gas ratio (bo/mmcfg)………………………….…			

SELECTED ANCILLARY DATA FOR UNDISCOVERED FIELDS

(variations in the properties of undiscovered fields)

Oil Fields:	minimum	median	maximum
API gravity (degrees)…………………….………….	25	37	55
Sulfur content of oil (%)………………………...…..	0.1	0.5	1.4
Drilling Depth (m) ……………...…………….……..	150	2000	3000
Depth (m) of water (if applicable)……………...…..			

Gas Fields:	minimum	median	maximum
Inert gas content (%)……………………….....……	0.4	0.8	1.8
CO_2 content (%)……………………………….....…	0.2	3	20
Hydrogen-sulfide content (%)………………...…….	0	0	0
Drilling Depth (m)……………………………………	150	1200	3000
Depth (m) of water (if applicable)………………….			

Appendix B. Data form used in evaluating the Paleozoic/Mesozoic Assessment Unit (AU 50200402), Phosphoria Total Petroleum System, Utah and Colorado.

IDENTIFICATION INFORMATION

Date:..............................	10/17/00		
Assessment Geologist:........	E.A. Johnson		
Region:............................	North America	Number:	5
Province:..........................	Uinta-Piceance	Number:	5020
Priority or Boutique............			
Total Petroleum System:......	Phosphoria	Number:	502004
Assessment Unit:...............	Paleozoic/Mesozoic	Number:	50200402
Based on Data as of:..........	NRG Associates (2000) through 1998		
* Notes from Assessor	Function e2, U.S. Lower 48 States Conventional Growth Function This is a composite assessment unit involving Phosphoria Formation and other unknown Paleozoic and Mesozoic source rocks.		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall):... Gas

What is the minimum field size?.......... 0.5 mmboe grown
(the smallest field that has potential to be added to reserves in the next 30 years)

Number of discovered fields exceeding minimum size:............ Oil: 2 Gas: 2
Established (>13 fields) ______ Frontier (1-13 fields) X Hypothetical (no fields) ______

Median size (grown) of discovered oil fields (mmboe):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______
Median size (grown) of discovered gas fields (bcfg):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered field ≥ minimum size..................	1.0
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered field ≥ minimum size......	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered field ≥ minimum size	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3):......................... 1.0

4. **ACCESSIBILITY:** Adequate location to allow exploration for an undiscovered field ≥ minimum size.. 1.0

UNDISCOVERED FIELDS

Number of Undiscovered Fields: How many undiscovered fields exist that are ≥ minimum size?:
(uncertainty of fixed but unknown values)

Oil fields:......................................min. no. (>0)	2	median no.	4	max no.	8
Gas fields:....................................min. no. (>0)	2	median no.	5	max no.	12

Size of Undiscovered Fields: What are the anticipated sizes (**grown**) of the above fields?:
(variations in the sizes of undiscovered fields)

Oil in oil fields (mmbo)........................min. size	0.5	median size	1.2	max. size	10
Gas in gas fields (bcfg):.......................min. size	3	median size	7.2	max. size	60

Appendix B—Continued. Data form used in evaluating the Paleozoic/Mesozoic Assessment Unit (AU 50200402), Phosphoria Total Petroleum System, Utah and Colorado.

AVERAGE RATIOS FOR UNDISCOVERED FIELDS, TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil Fields:	minimum	median	maximum
Gas/oil ratio (cfg/bo)…………………………..………	150	300	450
NGL/gas ratio (bngl/mmcfg)…………………….….….	30	60	90

Gas fields:	minimum	median	maximum
Liquids/gas ratio (bngl/mmcfg)….…………..……..	16	32	48
Oil/gas ratio (bo/mmcfg)………………………………			

SELECTED ANCILLARY DATA FOR UNDISCOVERED FIELDS

(variations in the properties of undiscovered fields)

Oil Fields:	minimum	median	maximum
API gravity (degrees)…………………….………….	25	37	55
Sulfur content of oil (%)…………………………...…..	0.1	0.5	1.4
Drilling Depth (m) ……………...…………….……..	300	1500	4000
Depth (m) of water (if applicable)……………...…..			

Gas Fields:	minimum	median	maximum
Inert gas content (%)……………………….....……	0.1	5	30
CO_2 content (%)………………………………...…..	0.2	10	25
Hydrogen-sulfide content (%)………………...…….	0	0	0
Drilling Depth (m)……………………………………	300	1500	4000
Depth (m) of water (if applicable)………………….			

Appendix C. Summary of assessment results for the Phosphoria Total Petroleum System.

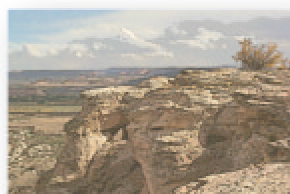
[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Minimum, for conventional resources this is the minimum field size assessed (MMBO or BCFG); for continuous-type resources this is the minimum cell estimated ultimate recovery assessed. Prob., probability (including both geologic and accessibility probabilities) of at least one field (or, for continuous-type resources, cell) equal to or greater than the minimum. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Code and Field Type	Minimum	Prob. (0-1)	Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Conventional resources														
Oil Fields		1.00	4.41	9.95	19.92	10.76	1.18	2.91	6.36	3.23	0.07	0.17	0.40	0.19
Gas Fields							26.30	68.52	144.57	74.85	0.77	2.14	4.91	2.40
Total		1.00	4.41	9.95	19.92	10.76	27.48	71.43	150.93	78.08	0.84	2.31	5.31	2.59
Continuous-type resources														
Oil		1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas							0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total resources														
Total			4.41	9.95	19.92	10.76	27.48	71.43	150.93	78.08	0.84	2.31	5.31	2.59

Appendix D. Summary of results for each assessment unit in the Phosphoria Total Petroleum System.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Minimum, for conventional resources this is the minimum field size assessed (MMBO or BCFG); for continuous-type resources this is the minimum cell estimated ultimate recovery assessed. Prob., probability (including both geologic and accessibility probabilities) of at least one field (or, for continuous-type resources, cell) equal to or greater than the minimum. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Code and Field Type	Minimum	Prob. (0-1)	Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
502004	**Phosphoria Total Petroleum System- Conventional Resource Assessment Unit Summary**													
50200401	Hanging Wall Assessment Unit													
Oil Fields	0.5	1.00	1.75	4.13	8.37	4.47	0.47	1.21	2.67	1.34	0.03	0.07	0.17	0.08
Gas Fields	3						10.48	24.78	50.27	26.81	0.30	0.78	1.70	0.86
Total		1.00	1.75	4.13	8.37	4.47	10.95	25.99	52.94	28.15	0.33	0.85	1.87	0.94
50200402	Paleozoic/Mesozoic Assessment Unit													
Oil Fields	0.5	1.00	2.66	5.82	11.55	6.29	0.71	1.70	3.69	1.89	0.04	0.10	0.23	0.11
Gas Fields	3						15.82	43.74	94.30	48.04	0.47	1.36	3.21	1.54
Total		1.00	2.66	5.82	11.55	6.29	16.53	45.44	97.99	49.93	0.51	1.46	3.44	1.65



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