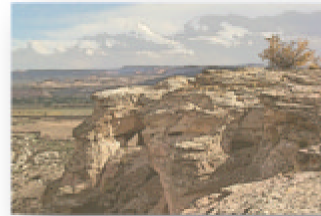
Chapter 5

Geology, Depositional Models, and Oil and Gas Assessment of the Green River Total Petroleum System, Uinta-Piceance Province, Eastern Utah and Western Colorado



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By R.F. Dubiel

Chapter 5 *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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Geology, Depositional Models, and Oil and Gas Assessment of the Green River Total Petroleum System, Uinta-Piceance Province, Eastern Utah and Western Colorado

By R.F. Dubiel

Abstract

The Green River Total Petroleum System, within the Uinta-Piceance Province of northeastern Utah and northwestern Colorado, is a prolific complex of entirely continental rocks that host gilsonite veins, oil shales, and tar sands, all sourced from lacustrine rocks within the Paleocene to Eocene Green River Formation. As of 1994, the Green River Total Petroleum System had produced almost 365 million barrels of recoverable high pour-point and paraffinic oil. An inferred in-place tar sand resource of 12–13 billion barrels is hosted in Cretaceous and Tertiary rocks. Source rocks include: (1) an open-lacustrine facies that contains mainly Type I kerogen; (2) a marginal-lacustrine facies with Types I, II, and III kerogen; and (3) an alluvial facies with mostly Type III kerogen. The open-lacustrine facies averages about 6.0 weight percent total organic carbon, and locally has total organic carbon contents as high as 60 weight percent. The kerogenous carbonate beds, referred to as oil shale, have hydrogen indices greater than 500 mg HC/g total organic carbon.

Oil from the Green River Total Petroleum System in the Uinta-Piceance Province is produced primarily from lenticular reservoirs in alluvial and marginal-lacustrine rocks. Bitumen-bearing sandstones (tar sands) represent the degraded expression of migrated oil in marginal-lacustrine strata that are continuous with the down-dip oil fields in the subsurface of the basins. Thus far, oil production has been primarily from reservoirs where the oil is above pour-point temperatures and is moveable. Reservoir permeabilities are commonly fracture enhanced; fracture porosity has developed due largely to overpressuring from active hydrocarbon generation. Oil-bearing reservoir rocks commonly extend beyond the currently known limits of the oil fields. In the deep subsurface of the Uinta-Piceance Province, wells are typically completed in overpressured pods where fracture networks provide formation permeability that is sufficiently high to drain reservoirs with "tight"matrix permeabilities. High fluid-pressure gradients are maintained in these pods where lacustrine source rocks with abundant Type I kerogen are presently subjected to temperatures sufficient to generate hydrocarbons at a rate greater than the rate of fluid migration and thus sustain the overpressuring.

Three assessment units are defined for the Green River Total Petroleum System in the Uinta-Piceance Province. The first assessment unit, the Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561), is in the Uinta Basin and includes strata deeper than about 8,500 ft that are overpressured and contain continuous-type oil and minor associated gas resources. The second assessment unit, the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501), is in the Uinta Basin and contains normally pressured reservoirs shallower than about 8,500 ft that stratigraphically trap oil migrated from deeper lacustrine source rocks. The third assessment unit, the Piceance Green River Conventional Oil Assessment Unit (AU 50200502), is in the Piceance Basin and is a hypothetical assessment unit of stratigraphically trapped, normally pressured, conventional oil resources.

Introduction

This report presents the results of a geologic assessment of the undiscovered oil and gas resources of the Green River Total Petroleum System (TPS) within the Uinta-Piceance Province in northeastern Utah and northwestern Colorado (fig. 1). The Tertiary Green River TPS represents the youngest of the five total petroleum systems defined for this project (fig. 2). The others are the Paleozoic Phosphoria TPS, the Cretaceous Mancos/Mowry TPS, the Cretaceous Ferron/Wasatch Plateau Coal TPS, and the Cretaceous TPS. Fouch and others (1994) were the first to define a Green River petroleum system in the Uinta Basin. At that time, this Green River petroleum system in the Uinta Basin had produced almost 365 million barrels of recoverable high pour-point and paraffinic oil and was host to an estimated 12–13 billion barrels of inferred tar sand accumulations. Tertiary rocks host numerous producing oil and associated gas fields in the Uinta Basin, and several wells are known to produce Green River-sourced oil and gas in the Piceance Basin. In addition to oil and gas, the Green River TPS includes significant resources of solid bitumen in tar sands and gilsonite veins. The source for these hydrocarbons is the kerogen-rich lacustrine rocks of the Green River Formation (see, for example, Ruble and Philp, 1998; Ruble

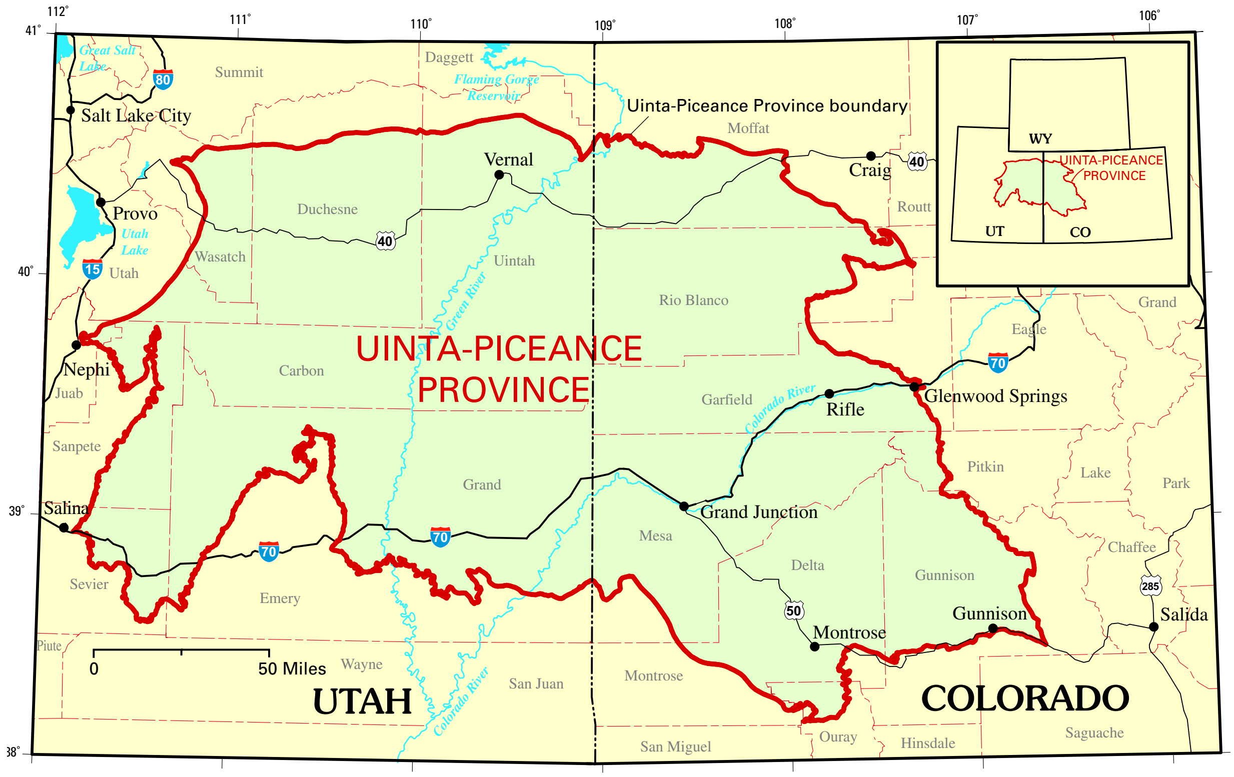


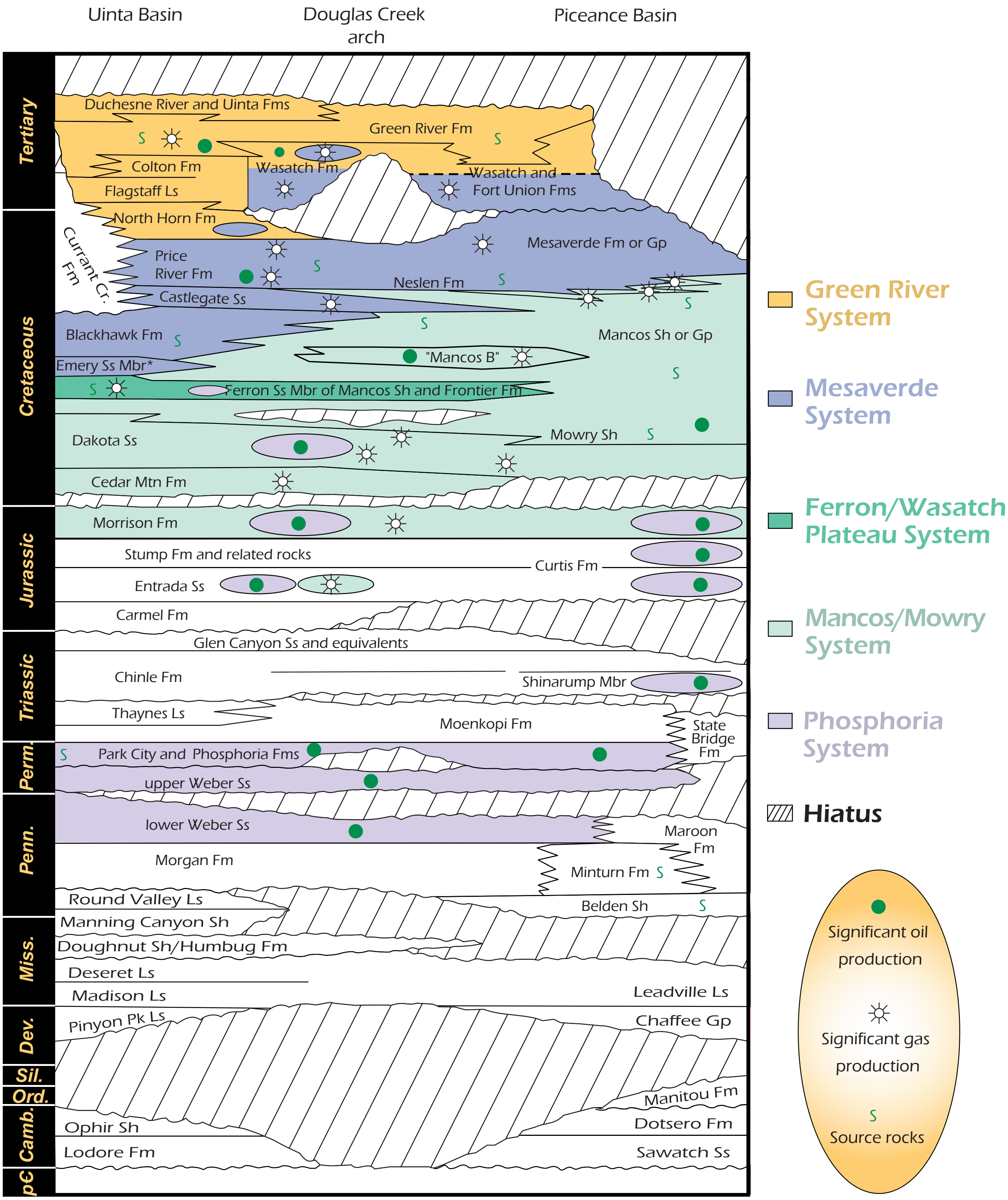
Figure 1. Location of the Uinta-Piceance Province and associated cultural and physiographic features.

and others, 2001), which host the largest oil-shale deposit in the world (see, for example, Donnell, 1961; Cashion, 1964; Johnson, 1985; Cashion, 1992). This extensive distribution of known producing oil and gas fields and wells, the demonstrated lacustrine source rocks, and the occurrence of oil shales, gilsonite, and other solid hydrocarbons all constitute the Green River TPS in the Uinta-Piceance Province. Hydrocarbon source rocks, migration pathways, traps, seals, and reservoir units all occur in uppermost Cretaceous and Tertiary continental rocks of the Green River TPS.

In 1995, the U.S. Geological Survey (USGS) (Gautier and others, 1996) presented an assessment of the oil and gas resources of the United States wherein Spencer (1996) assessed the resources of the Uinta-Piceance Basin. That assessment included most of the geologic units and geographic area of the present report. The present geologic investigation and assessment of oil and gas resources incorporates an updated petroleum system approach using detailed stratigraphic well-log cross sections and depositional models to assess the undiscovered resources of the Green River TPS. It is a total petroleum system/assessment unit approach, rather than the assessment by play approach used by the USGS in 1995 (Gautier and others, 1996). The present total petroleum system/assessment unit approach was also used in the recently released USGS World Petroleum Assessment 2000 (Klett and others, 1997; USGS World Energy Assessment Team, 2000). The methodology, data, and resource assessments are comparable to the previous play assessment approach because the assessment units defined in the present assessment may represent either a play or a group of plays. An advantage of the present total petroleum system approach is that by incorporating the assessment unit within a petroleum system one can examine and evaluate relations between elements and processes such as source rock, hydrocarbon generation, migration, and trapping units and mechanisms. This report assesses the undiscovered oil and gas resources within the Green River TPS in the Uinta-Piceance Province that may be developed in the next 30 years. This contrasts with the 1995 USGS assessment, which dealt with ultimate recovery.

Structural and Geologic Setting

The Uinta-Piceance Province in northeastern Utah and northwestern Colorado comprises the Uinta Basin on the west, the Piceance Basin on the east, and the intervening Douglas Creek arch, which separates the two basins (fig. 3*A*). Several major structural features surround the Uinta-Piceance Province, and a variety of minor structural elements lie within its boundaries (fig. 3*B*). The Uinta-Piceance Province roughly parallels, and is bounded on the north by, the Uinta Mountains. The province is bounded on the west by the Wasatch Mountains and the Wasatch Plateau, on the east by the White River uplift and the Elk Mountains, and on the south by the Uncompahgre uplift and the San Rafael Swell. The Uinta and Piceance Basins are structural and topographic features of latest Cretaceous and Tertiary age that extend east-southeast in northeastern Utah and northwestern Colorado. The two basins



* Emery Sandstone Member of the Mancos Shale

Figure 2. Stratigraphic column for the Uinta-Piceance Province showing major stratigraphic units, stratigraphic occurrence of hydrocarbons, and the total petroleum systems defined in this province.

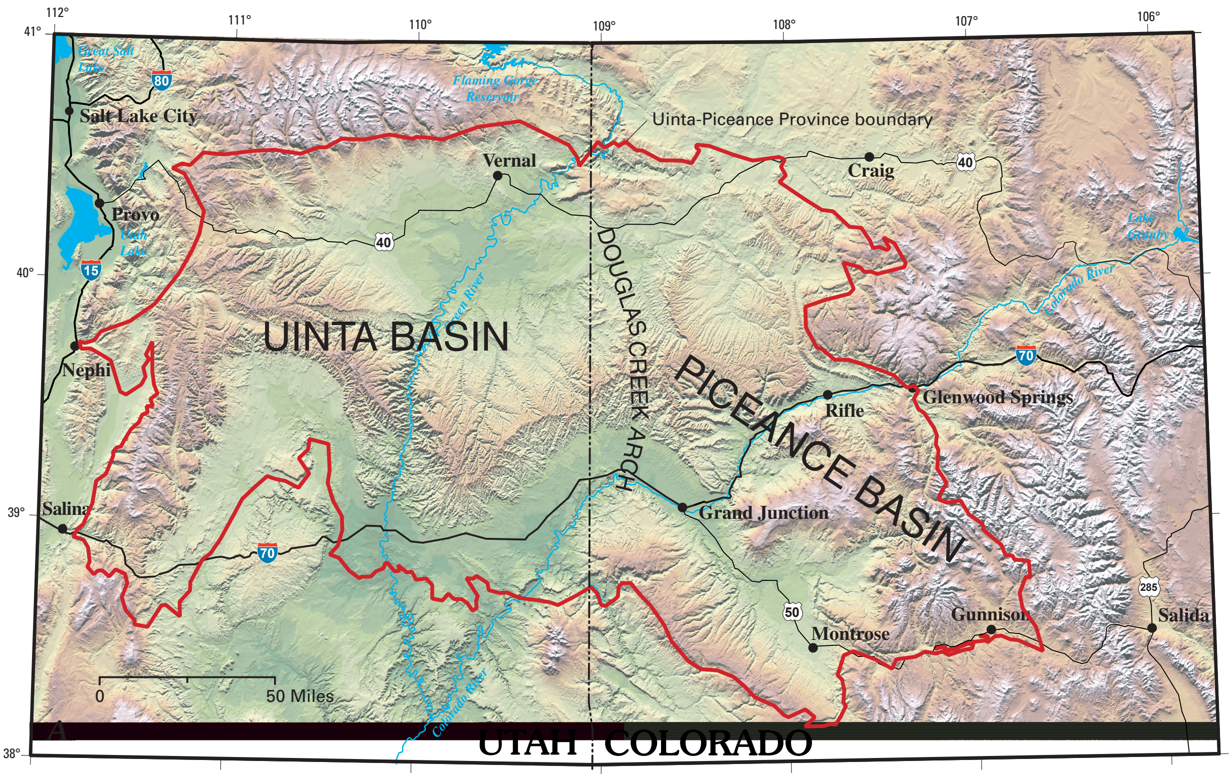


Figure 3*A*. Digital elevation model of the Uinta-Piceance Province showing major physiographic features.

are asymmetrical, with structural troughs adjacent to reverse-faulted uplifts of Laramide age (Late Cretaceous through Eocene) (fig. 3*B*). Numerous anticlines and synclines deform the strata within the two basins (fig. 3*B*). A major fault, the Uinta Basin boundary fault, lies in the subsurface near the northern margin of the Uinta Basin (fig. 3*B*) (Campbell, 1975). In the Wastach Plateau along the western margin of the Uinta-Piceance Province, several north-south fault systems that are an eastward extension of Basin and Range-style tectonism disrupt the geologic units (fig. 3*B*). The Uinta and Piceance Basins are filled by as much as 17,000 ft of Maastrichtian and Paleogene lacustrine and fluvial sedimentary rocks (figs. 4, 5) (Bradley, 1925; Cashion, 1967; Fouch, 1985). On the Douglas Creek arch, the majority of Tertiary rocks within the Green River TPS have been eroded (fig. 5). Uppermost Cretaceous and lowermost Tertiary strata dip 4º–6º toward the troughs of the two basins. The younger Uinta and Duchesne River Formations of late Eocene to earliest Oligocene age dip less steeply (fig. 5). Maximum depth to the base of the Green River TPS is about 20,000 ft in the north-central part of the Uinta Basin in the Altamont-Bluebell field along the basin axis (fig. 6; pl. 1) (Fouch and others, 1994).

Stratigraphy

The Green River Total Petroleum System encompasses Upper Cretaceous and Tertiary continental rocks that are assigned to a variety of stratigraphic units (fig. 4). These units form an alluvial-lacustrine depositional system that includes the Maastrichtian to lower Eocene North Horn Formation, the Paleocene and Eocene Wasatch, Colton, and Green River Formations, the Eocene Uinta Formation, and the Eocene to lower Oligocene Duchesne River Formation (figs. 2, 4; pl. 1) (Fouch and others, 1992). Structural and stratigraphic cross sections based on correlation of rocks from both outcrop and well logs (figs. 6, 7, pl. 1) indicate a complex depositional system characterized by intricate interfingering of fluvial, marginal-lacustrine, and lacustrine environments that formed in and around ancient Lake Uinta (fig. 7*A*). The interfingered lithologies were formed by repeated expansions and contractions of the low-gradient fluvial-lacustrine Lake Uinta system in response to tectonic and climatic changes. The nomenclature used in the present report for both stratigraphic names and for depositional systems incorporates terminology from a variety of sources but is primarily that advocated by Fouch (1975), Johnson (1985), and Fouch and others (1994).

The cyclic nature of the Tertiary units and the interbedding of the drab lacustrine and alluvial strata of the Green River Formation with the red alluvial rocks of the Wasatch, Colton, and North Horn Formations have resulted in some confusion in the application of stratigraphic names in the literature and in digital databases. Many petroleum industry operators in the Uinta-Piceance Province have historically assigned all strata containing some red beds to the Wasatch Formation; however, the hydrocarbon-producing units are generally tongues of the Green River Formation within the alluvial rocks (pl. 1; Fouch and others, 1992; Fouch and others, 1994).

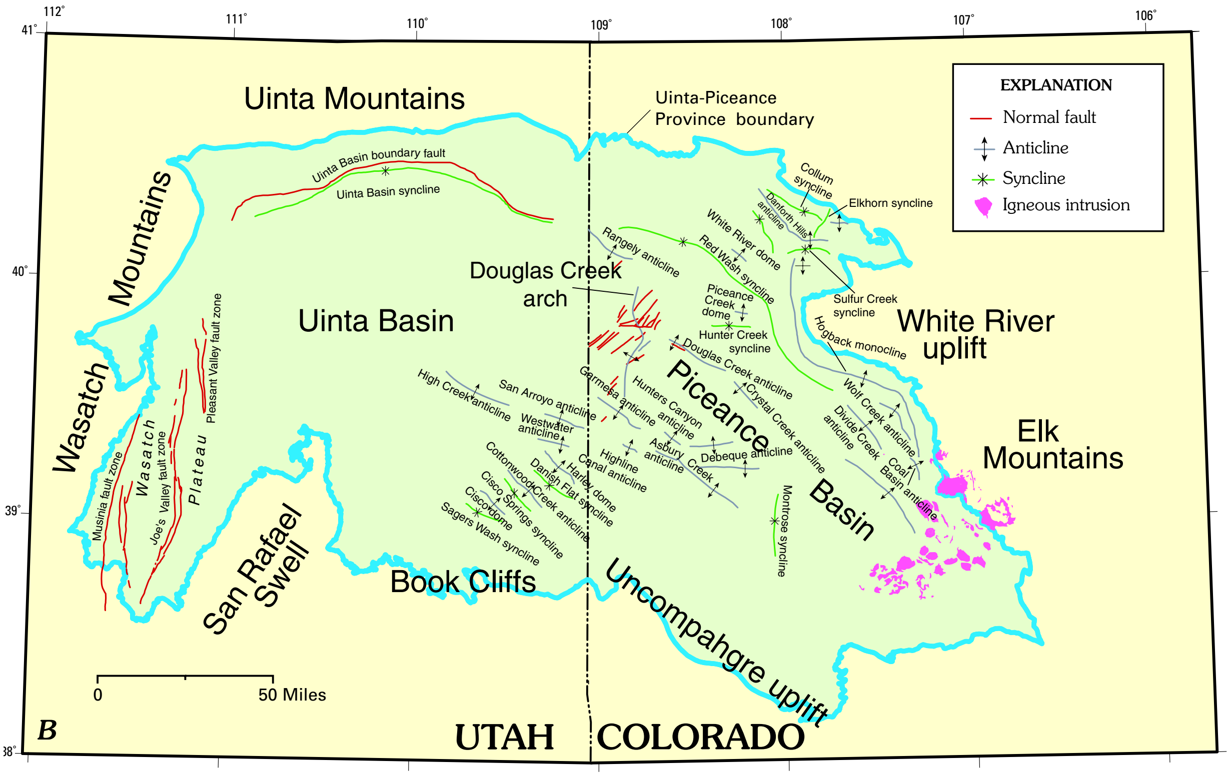


Figure 3*B*. Major geologic structures of the Uinta-Piceance Province.

Depositional System

The latest Cretaceous through Eocene depositional system of the Green River Total Petroleum System evolved following the final eastward regression of the Cretaceous Seaway in the region. Kirschbaum (Chapter 6, this CD-ROM) and Roberts and Johnson (Chapter 7, this CD-ROM) summarize the development of Cretaceous depositional systems of the Uinta-Piceance Province. Latest Cretaceous and Tertiary uplift on the San Rafael Swell, Uinta Mountains, Uncompahgre uplift, and White River uplift (fig. 3*B*) disrupted the former depositional pattern of primarily marine and marginal-marine Cretaceous sedimentation in the Uinta-Piceance Province and ultimately produced a continental lacustrine basin with internal drainage (Fouch, 1975; Johnson, 1985). Strata deposited and preserved in the resulting Lake Uinta contain a wide variety of lithofacies deposited in numerous depositional environments (figs. 7*B*, 8). Of primary importance to the Green River TPS are the central-basin profundal lacustrine facies of organic-rich claystones and mud-supported carbonates. They grade laterally into marginal-lacustrine facies of sandstone, claystone, and mud- to grain-supported carbonate that were deposited in a variety of deltaic, interdeltaic, and lake-margin carbonate-flat environments. Alluvial claystone, sandstone, and conglomerate beds sourced from nearby highlands in the Wasatch Mountains, San Rafael Swell, Uncompahgre uplift, White River uplift, and Uinta Mountains were deposited lateral to the marginal-lacustrine strata and either incised into them or prograded over them as lake level fluctuated. Fluctuations over time in water level and lake margins were the result of interactions of tectonic and climatic influences on the low-gradient periphery of the lake basin. The following discussion describes the depositional system as it relates to the key elements of the total petroleum system. Fouch (1975), Johnson (1985), and Fouch and others (1992, 1994) provided detailed descriptions of lithofacies and depositional environments, and their distribution within the Uinta-Piceance Province.

The upper Paleocene to upper Eocene lacustrine deposits are characterized by calcium sulfate salts, halite, sodium bicarbonate salts, and kerogen-rich shales containing biologically derived carbonates. These mineral and facies associations indicate an organically productive but hydrologically closed lacustrine system (Bradley, 1925, 1931; Johnson, 1985; Fouch and others, 1992, 1994). Both long- and short-term changes in climate and tectonic regime are reflected in the Green River Formation lacustrine deposits (Fouch and others, 1994; Fouch and Pitman, 1991, 1992). Regional reconfigurations of Lake Uinta were probably in response to faulting along the basin margins, which commonly expanded the topographic and hydrologic basin on a scale of millions of years (Fouch and others, 1994). Coincident changes in climate, probably related to changes in solar radiation, drove relatively rapid rises and falls in lake level and caused extensive lateral migrations of lacustrine-margin facies across the low-relief basin margin in events that lasted several thousand years (Fouch and others, 1994). These changes provided a mechanism for the production and preservation of intercalated petroleum source rocks, reservoirs, and seal rocks, and provided the migration

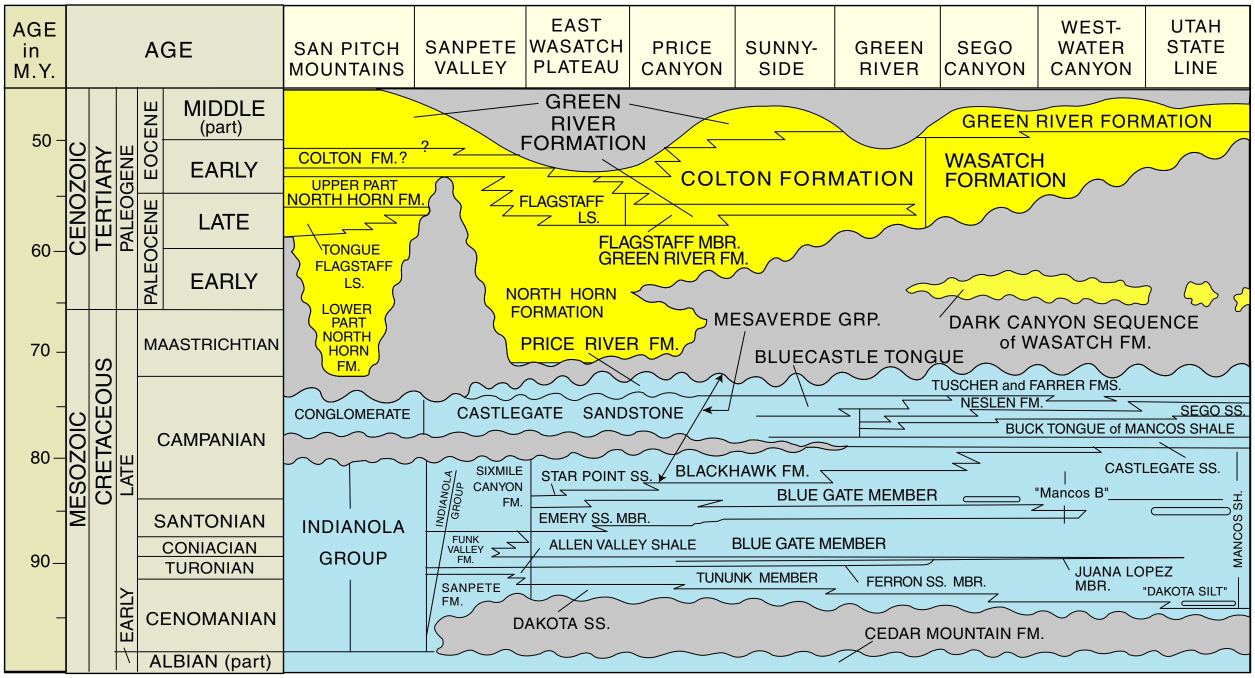


Figure 4. Stratigraphic diagram of Cretaceous and Tertiary units in the Uinta-Piceance Province. Yellow denotes units within the Green River Total Petroleum System. Blue denotes older geologic units, and gray denotes lacunas (modified from Fouch and others, 1992).

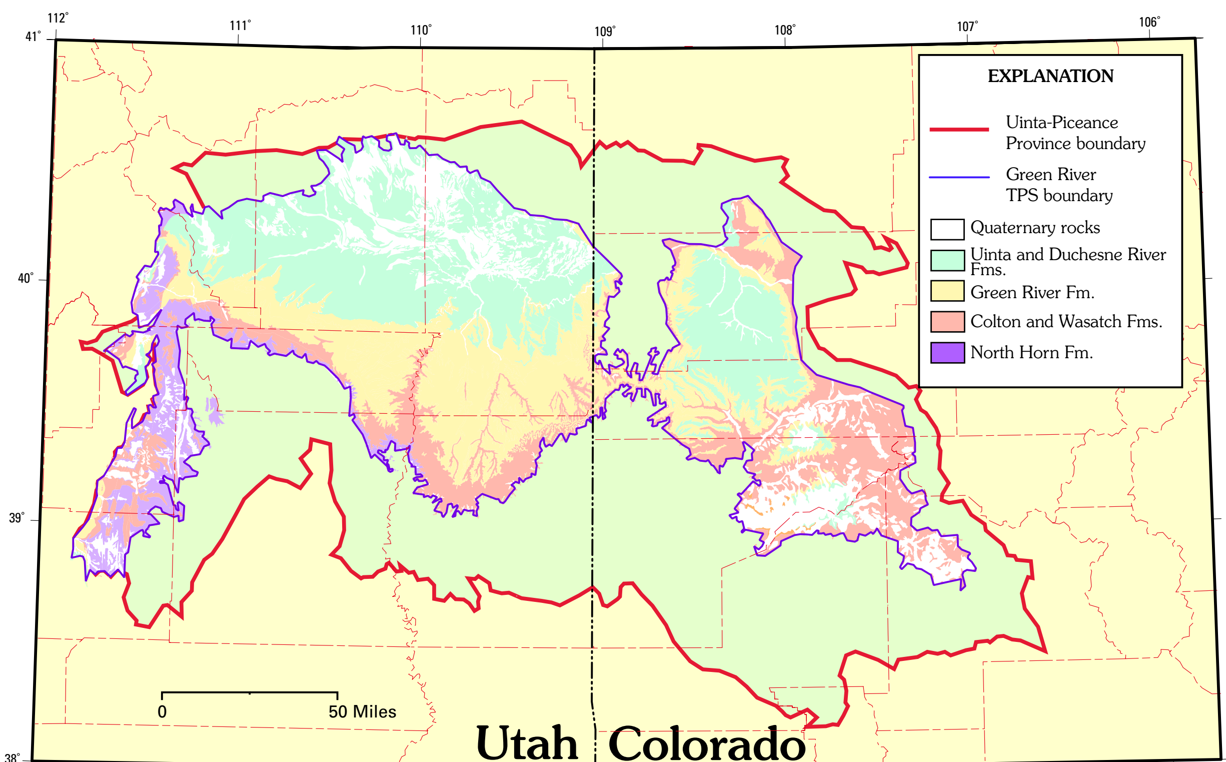


Figure 5. Generalized geology of units within the Green River Total Petroleum System.

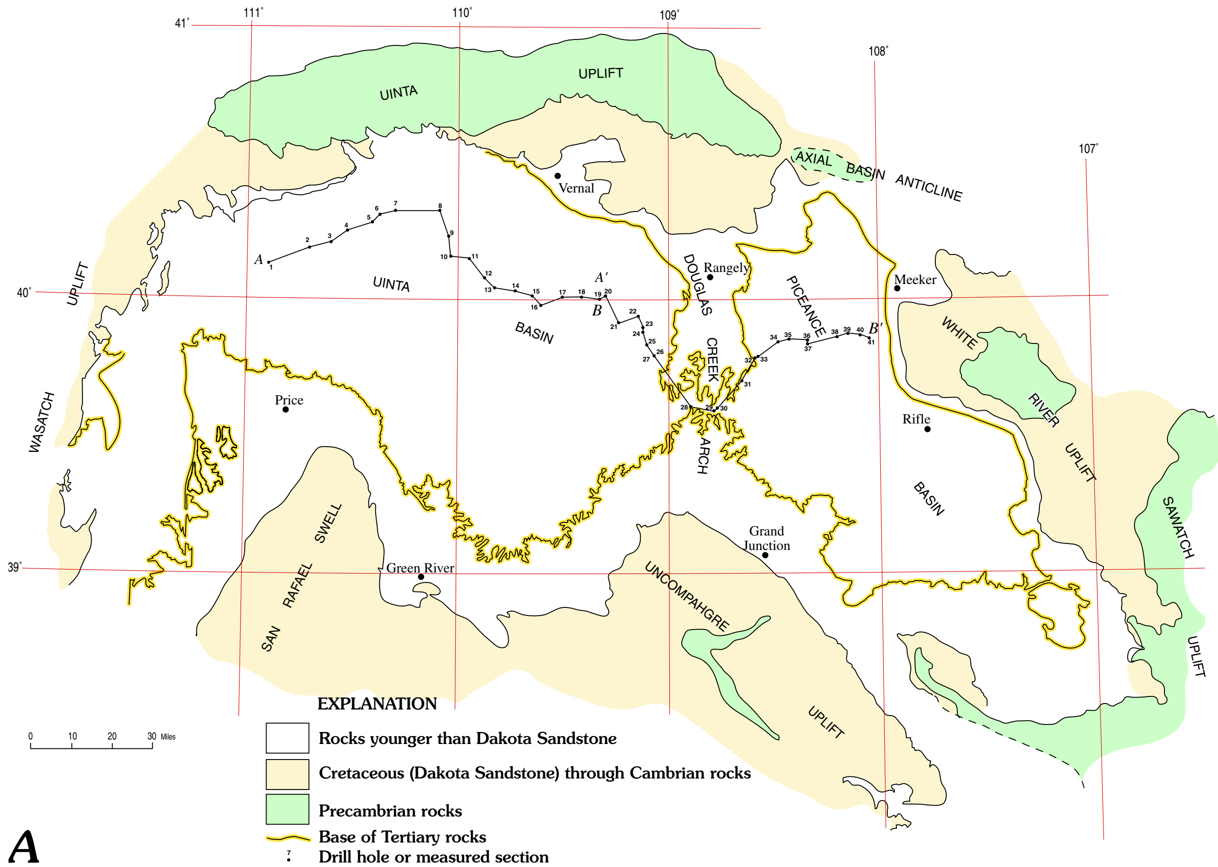


Figure 6*A*. Location of generalized east-west cross section of Tertiary units within the Uinta-Piceance Basin (modified from Johnson, 1989).

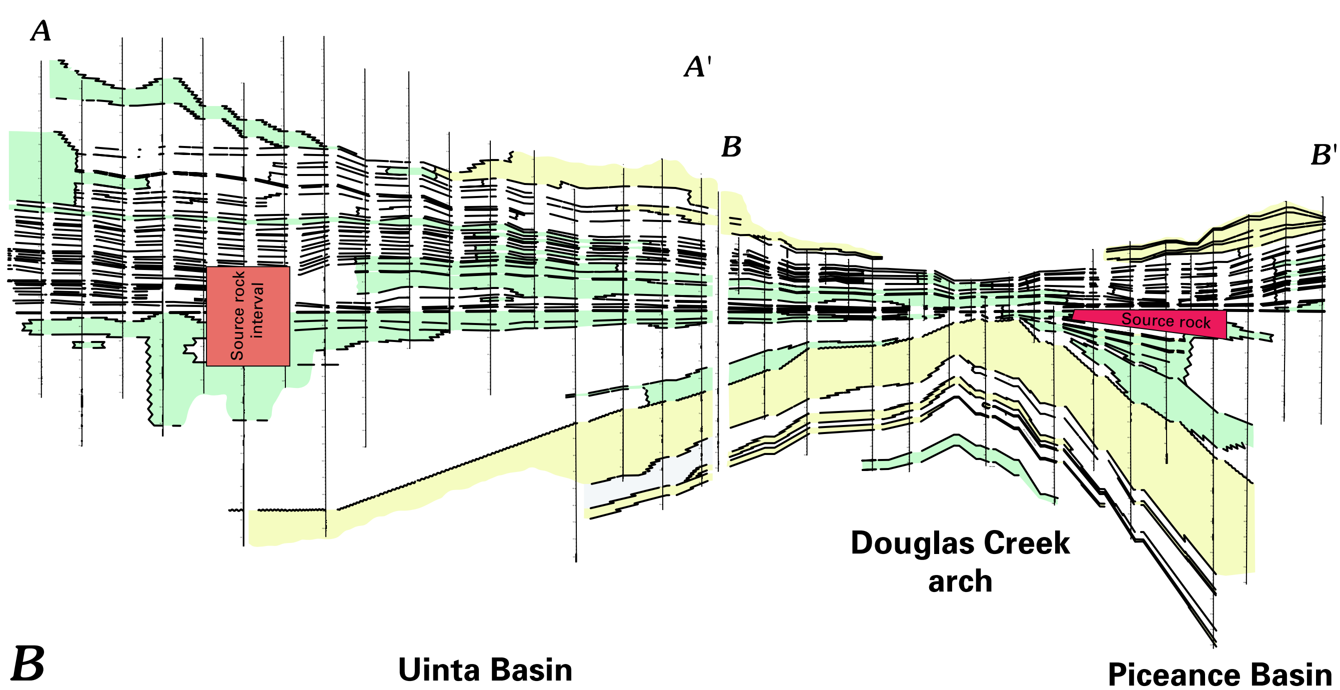


Figure 6*B*. Generalized east-west cross section of Tertiary units within the Uinta-Piceance Basin showing well logs, measured sections, depositional facies, and source-rock interval (modified from Johnson, 1989).

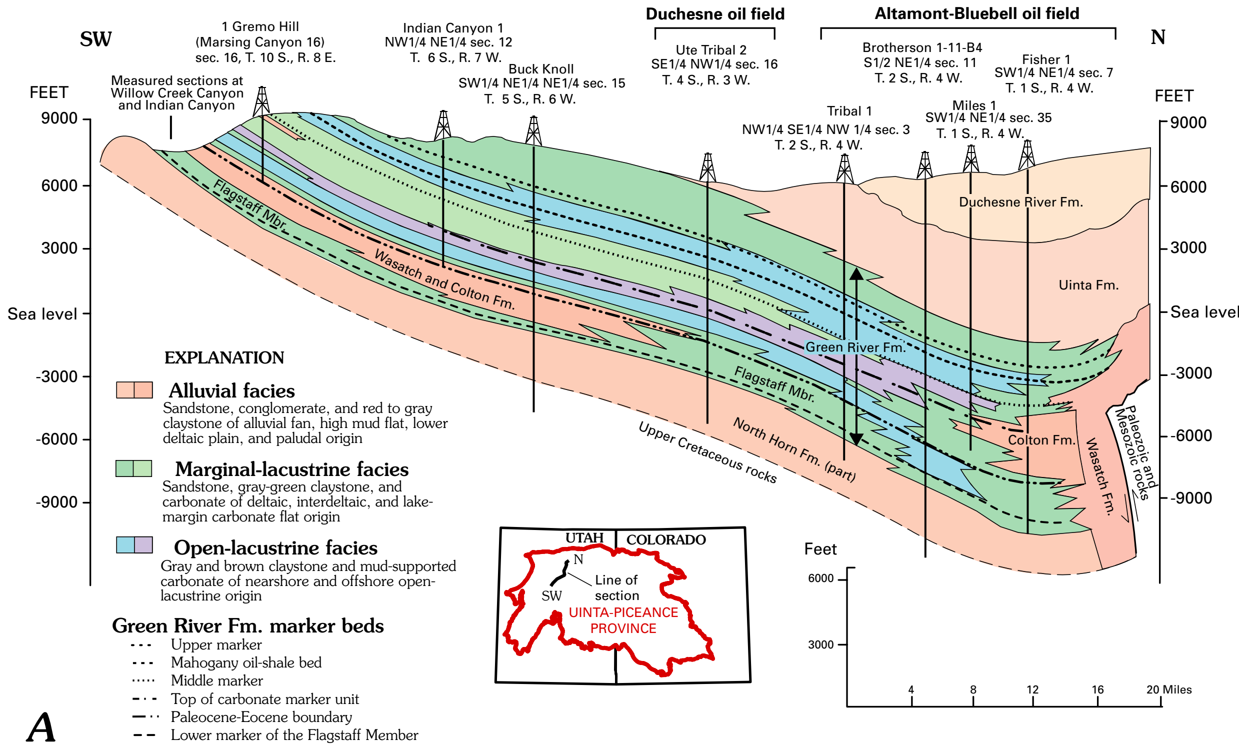


Figure 7*A*. North-south cross section showing location of wells and distribution of facies in the Green River Formation and related rocks in the Uinta-Piceance Basin (modified from Fouch, 1975, and Franczyk and others, 1989).

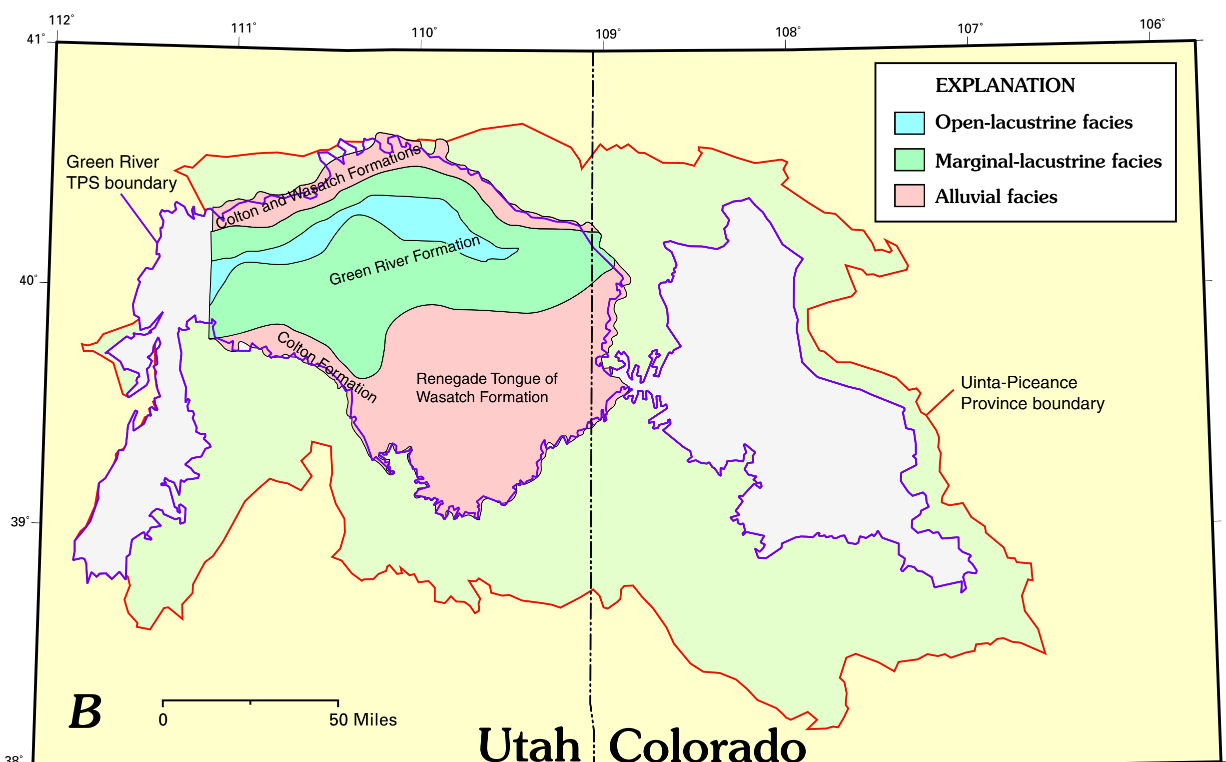


Figure 7*B*. Distribution of depositional facies in the Green River Formation superimposed on the outline of the Green River Total Petroleum System (modified from Fouch and others, 1992).

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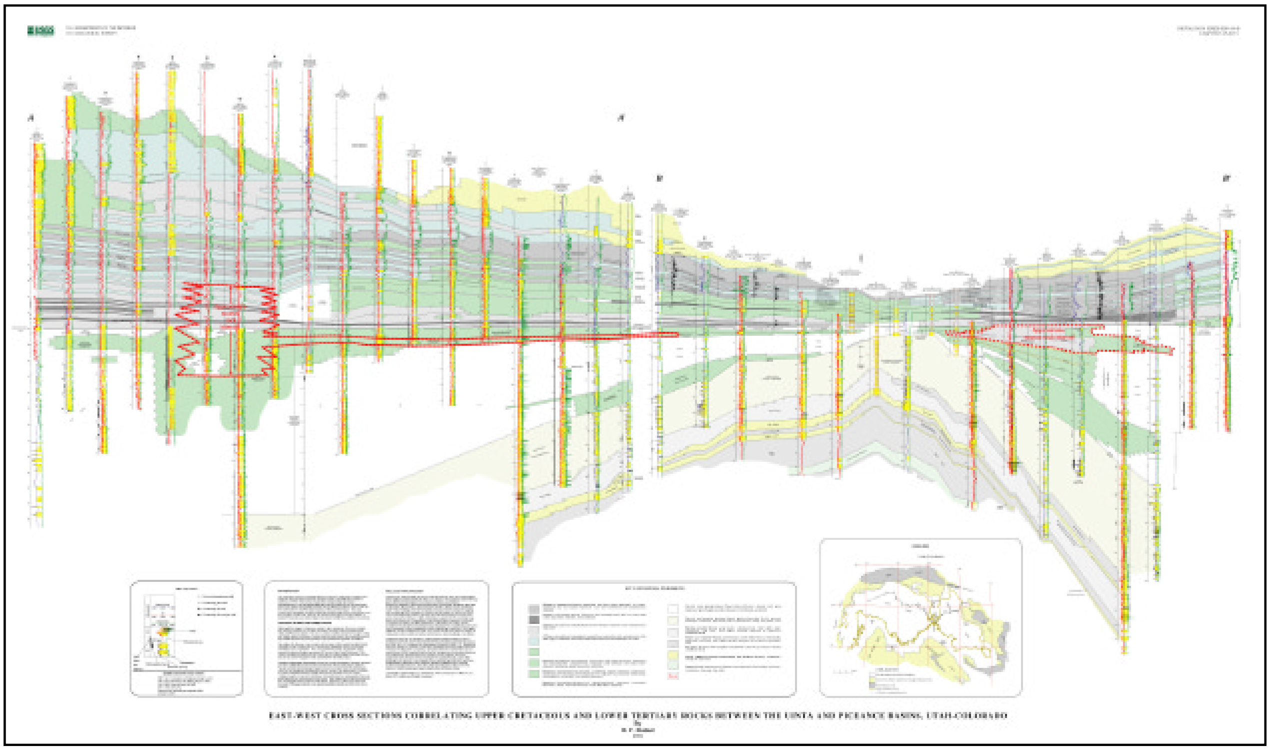


Plate 1. East-west cross sections correlating Upper Creratceous and Lower Tertiary rocks between the Uinta and Piceance Basins, Utah-Colorado.

pathways by which hydrocarbons moved within the Green River TPS. Laterally extensive open-lacustrine units, such as those of the middle marker and carbonate marker zones (Ryder and others, 1976) and the Mahogany oil-shale zone and Long Point Bed of the Green River Formation (Johnson, 1985), reflect significant rises of lake level and regional expansions of the lake facies (fig. 7). These laterally extensive beds can be correlated for long distances throughout the Uinta-Piceance Province and serve as important stratigraphic markers for outcrop and well-log correlation.

Green River Total Petroleum System

The Green River Total Petroleum System includes all major outcrops and subsurface deposits of the North Horn Formation, Flagstaff Limestone (and Flagstaff Member of the Green River Formation), Colton Formation, Wasatch Formation, Uinta Formation, and Duchesne River Formation (figs. 5, 6; pl. 1). The Green River TPS boundary was drawn to include the contiguous outcrops of these Maastrichtian and Tertiary rocks in the Uinta-Piceance Province that may have generated hydrocarbons or served as either migration pathways or reservoirs for those hydrocarbons. The boundary does not include small, isolated Tertiary outcrops outside the main contiguous outcrop area in the Piceance Basin and on the Douglas Creek arch (fig. 5). The Green River TPS also does not include Tertiary outcrops west of the Wasatch Plateau, which are considered here to be part of the Basin and Range Province.

The southern boundary of the Green River TPS is defined by the lower stratigraphic limit of Maastrichtian and Tertiary sedimentary rocks within the San Rafael Swell, Book Cliffs, Roan Cliffs, and Uncompahgre uplift in both the Uinta and Piceance Basins (see Fouch and others, 1994). The western boundary of the Green River TPS is drawn on the western limit of outcrops of Maastrichtian and Tertiary rocks within the Wasatch Plateau. In the northwest, the Green River TPS boundary extends slightly farther west than the Uinta-Piceance Province boundary to include contiguous outcrops of Maastrichtian and Tertiary rocks that extend west of the Nebo-Charleston thrust fault, which forms the Uinta-Piceance Province boundary. The Tertiary rocks overlie and are not cut by this fault, thus forming a contiguous petroleum system that extends just west of the mapped fault. On the north, the Green River TPS boundary follows the limits of the Tertiary outcrops along the northern margin of the Uinta Basin, through the Douglas Creek arch, and around the significant contiguous outcrops of Tertiary rocks in the Piceance Basin, excluding isolated outliers. The Green River TPS does not include any Maastrichtian-age rocks in the Piceance Basin.

A somewhat similar Green River petroleum system, confined solely to the Uinta Basin, was defined and described by Fouch and others (1994; their fig. 25.3) based on known oil and gas accumulations, hydrocarbon production, and outcrops

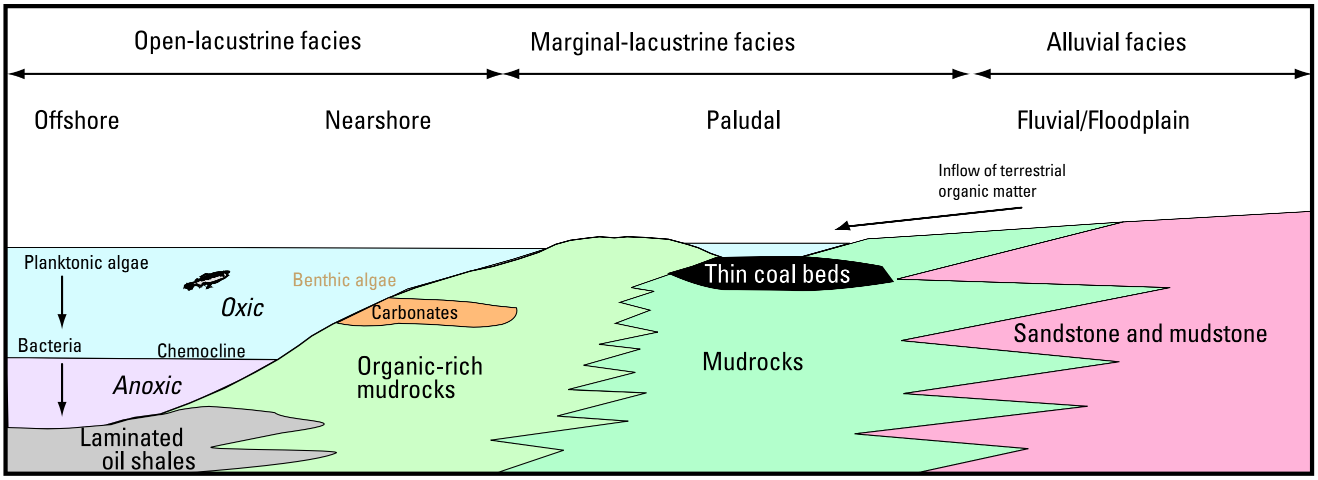


Figure 8. Schematic diagram of lacustrine and alluvial depositional environments of the Green River Formation (modified from Ruble and others, 2001).

of solid hydrocarbon-bearing Tertiary rocks within the Uinta Basin. They excluded, as does the present report, equivalent rocks of the Tertiary Green River Formation to the north in the Greater Green River Basin of Wyoming. Fouch and others (1994) did not extend their petroleum system of the Uinta Basin into the Piceance Basin. Because of the production of minor amounts of oil and gas from lower tertiary rocks in the Piceance Basin that is apparently derived from Green River source rocks, the Green River Total Petroleum System herein is defined to encompass both basins in the Uinta-Piceance Province. In several areas, such as the Greater Natural Buttes field, isotopic analyses of hydrocarbons indicate that gas produced from basal Tertiary Green River Formation and Wasatch Formation reservoirs has migrated from deeper Cretaceous or older source rocks (Johnson and Roberts, Chapter 7, this CD-ROM; Johnson and others, 1994). To avoid double counting of assessment cells and resources, Tertiary rocks and the oil and gas resources within them that can be demonstrated to have originated in Cretaceous or older rocks were assigned to the older Mesaverde TPS and not included in the Green River TPS. By this definition, the majority of subsurface units and outcrops of the Green River Formation and equivalent units within both the Uinta and Piceance Basins are included within the Green River TPS. Notable exceptions are those fluvial reservoirs of the Wasatch Formation in the Greater Natural Buttes field that are thought to primarily produce gas generated within the underlying Cretaceous section (see Johnson and Roberts, Chapter 7, this CD-ROM). The vertical migration of gas from the Mesaverde TPS appears to be largely inhibited by the first thick lacustrine shale (Johnson and others, 1994). Throughout much of the Uinta and Piceance Basins, the first thick lacustrine shale occurs just above the Long Point Bed (pl. 1), and the base of this shale is used as a general marker to delineate the two petroleum systems. Locally in the Uinta and Piceance Basins, lacustrine shales occur below the Long Point Bed, and the base of the Green River TPS is adjusted to include these shales and adjacent rocks.

Key Elements of the Green River Total Petroleum System

The total petroleum system approach defines a mappable area that includes a pod of active source rock, all known and undiscovered oil and gas reservoirs, and the processes and mechanisms (generation, trap, and seal) required for the oil and gas accumulations to exist. The essential physical elements are the source, reservoir, seal, and overburden rocks. Essential processes include trap formation, thermal maturation, and the generation, migration, and accumulation of petroleum. The total petroleum system can be used as a model to investigate known hydrocarbon accumulations and, as in this project, to assess the undiscovered resources in a region. The Green River Total Petroleum System contains all the essential physical elements and processes to define and assess hydrocarbon resources in that part of the Uinta-Piceance Province.

Numerous prolific oil and gas fields are developed within and produce from a variety of reservoirs in the Green River TPS (fig. 9) (see, for example, Lucas and Drexler, 1975; Fouch, 1975; Utah Geological and Mineral Survey, 1983; Fouch and others, 1992, 1994). The Paleocene and Eocene Green River Formation and laterally equivalent rocks in the Uinta-Piceance Province have long been recognized for their extensive deposits of oil shales, gilsonite, and other solid hydrocarbon species, along with numerous prolific oil and gas fields (see, for example, Fouch 1975; Fouch and others, 1994, and references therein). In addition, a variety of geochemical studies on source rocks within the Green River Formation provide additional evidence for lacustrine-basin source-rock maturity and migration of hydrocarbons within Tertiary rocks of the Uinta-Piceance Province (Tissot and others, 1978; Anders and Gerrild, 1984; Rice and others, 1992; Ruble and Philp, 1998; Ruble and others, 2001; Lillis and others, Chapter 3, this CD-ROM).

The principal hydrocarbon source rocks and reservoir rocks within Tertiary strata of the Green River TPS were

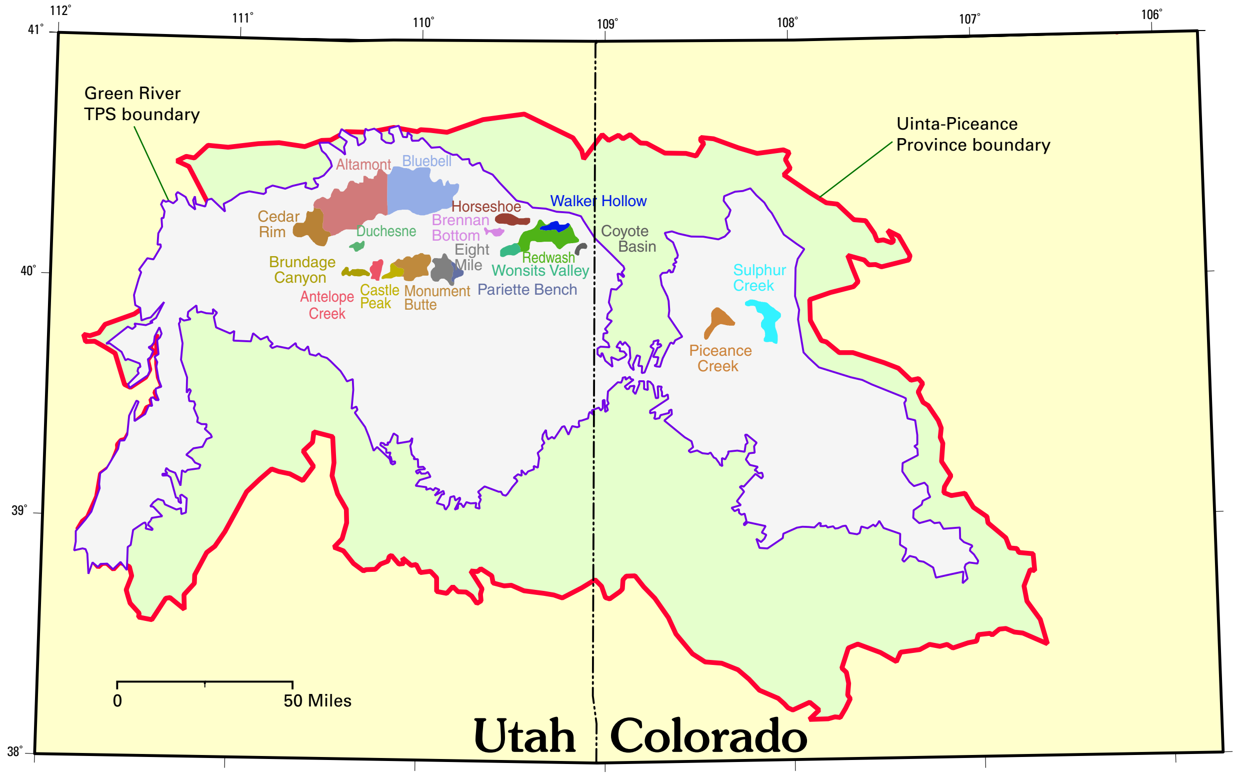


Figure 9. Location of producing oil fields in the Green River Total Petroleum System in the Uinta-Piceance Province (modified from Fouch and others, 1994, and Utah Geological and Mineral Survey, 1983).

controlled by the geometry (both thickness and aerial extent) of the geochemical and sedimentary cycles within the closed lacustrine basin of Lake Uinta (Fouch and others 1992). In the Uinta-Piceance Province, oil and associated gas are produced in the Green River TPS primarily from diagenetically enhanced, lenticular fluvial and lacustrine sandstone and carbonate reservoirs. Alluvial rocks, which are the most peripheral facies of the Lake Uinta depositional system, serve primarily as impermeable or nontransmissive complexes that stratigraphically trap most oil accumulations in down-dip open-lacustrine and marginal-lacustrine reservoirs (Fouch and others, 1994).

Oil and associated gas are produced from two distinct accumulations in the Green River TPS. In the deepest part of the Uinta Basin, the major oil accumulations are typified by the reservoirs in the Altamont-Bluebell and Cedar Rim fields (fig. 9). Hydrocarbons form a continuous oil and minor associated gas accumulation that was generated within adjacent lacustrine-basin shales (Fouch and others, 1994). Oil and associated gas are recovered from deeply buried and overpressured strata adjacent to the synclinal axis of the basin where pods of open fractures provide permeable fracture networks that drain “tight” oil reservoirs characterized by low matrix porosity and permeability (Fouch and others, 1994). Overpressuring resulting from inferred active hydrocarbon generation is thought to contribute to the fracturing of the reservoirs (Spencer, 1987; Fouch, 1975, 1981; Fouch and others, 1994).

The second major group of reservoirs includes normally pressured conventional accumulations of oil and minor associated gas in marginal-lacustrine and fluvial rocks, characteristic of the fields that extend from Brundage Canyon field on the west to Redwash and Walker Hollow fields on the east (fig. 9). These reservoirs are similar in facies and distribution to oil-bearing rocks (tar sands or natural bitumen on outcrops) that crop out at the southern rim, the center, and the northern rim of the Green River TPS (fig. 10; Ritzma, 1973; Utah Geological and Mineral Survey, 1983; Fouch and others, 1992). These represent the degraded surface expression of oil that has migrated up dip from the basin center to rocks exposed at the surface through marginal-lacustrine strata that are stratigraphically continuous with rocks that host the more deeply buried conventional oil fields (Anders and others, 1992). These conventional oil and gas fields in the Uinta Basin and similar isolated occurrences in the Piceance Basin represent hydrocarbon accumulations that were sourced from the Green River Formation lacustrine shales in the central parts of the basins.

Source Rocks

The primary source rocks for hydrocarbons in the Green River Total Petroleum System are the organic-rich Paleocene and Eocene shales and carbonate marlstones (oil shales) of

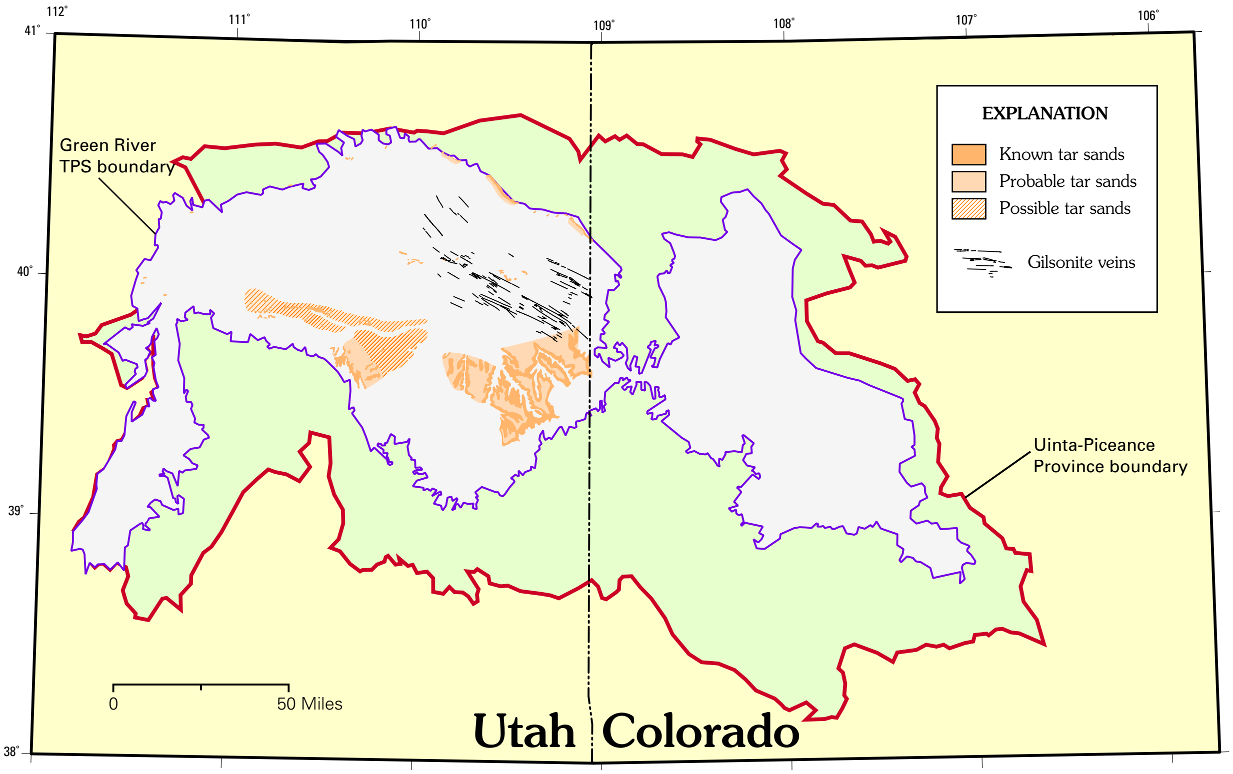


Figure 10. Location of tar sands and gilsonite veins in the Green River Total Petroleum System (modified from Utah Geological and Mineral Survey, 1983).

the lacustrine Green River Formation (Tissot and others, 1978; Anders and Gerrild, 1984). The offshore open-lacustrine facies was originally interpreted to have been deposited in a large, deep, perennial, meromictic, alkaline lake (Bradley, 1931). Despite an alternative "playa-lake model" proposed for oil-shale deposition in the Green River Formation of Wyoming (Eugster and Surdam, 1973; Eugster and Hardie, 1975), overwhelming sedimentological and geochemical evidence supports the deep lake interpretation of the Green River Formation in the Uinta and Piceance Basins (Cole, 1984; Johnson, 1981). According to the deep-water, meromictic model, the lake's water column was separated by a chemocline into two distinct water masses (fig. 8): (1) an upper mixolimnion that had relatively fresh to slightly alkaline chemistry, ample nutrients, and sufficient sunlight to support high biologic activity (blue-green algae), and (2) a lower monimolimnion that had dense, anoxic, saline, high-pH, low-Eh chemistry water in which biologic productivity was limited to anaerobic bacteria (Cole, 1984). The organic-rich laminated oil shales were deposited in open-lacustrine settings as alternating layers of bacterial-algal ooze and algae-generated, low-magnesium calcite in very quiet waters ranging in depth from 20 to 100 ft (Ryder and others, 1976). For an extended discussion of the several types of open-lacustrine facies and oil shales and their organic geochemistry, the reader is referred to Ruble and Philp (1998) and Ruble and others (2001). Repeated expansions and contractions of Lake Uinta in response to tectonic and climatic variation resulted in major transgressions and regressions of the lake environments, which controlled the spatial distribution of the open-lacustrine deposits that are the source rocks for Green River TPS hydrocarbon generation (figs. 6, 7*B*; pl. 1). Fouch (1975), Johnson (1985), and Fouch and others (1992, 1994) discussed the complex interfingering of facies and their paleogeographic distribution.

Fouch and others (1994) reported on the kerogen types and organic content of Green River TPS kerogenous calcareous mudrocks, carbonates, and algal coals. Type III kerogen is dominant in alluvial rocks of the Wasatch, North Horn, and Colton Formations, which were deposited peripheral to the lacustrine system. Marginal-lacustrine clastic and carbonate rocks of the Green River Formation contain Types I, II, and III kerogen. Open-lacustrine calcareous shales and carbonates contain abundant Type I kerogen and local accumulations of Type II kerogen. Lacustrine algal coals associated with shoreline deposits of Lake Uinta contain both Type II and Type III kerogen. These coals are particularly well preserved in upper Paleocene and upper lower Eocene to lower middle Eocene beds in the western part of the Uinta Basin, occupying the same stratigraphic interval that produces hydrocarbons from overpressured reservoirs in the Altamont-Bluebell field (Fouch and others, 1994).

Organically rich but thermally immature middle Eocene lacustrine rocks occur from about 500 ft above the Mahogany oil-shale bed down to the middle marker bed in the Uinta Basin (fig. 7*A*). They have TOC (total organic carbon) contents as high as 21 weight percent and an average of about

6 weight percent; a few samples attain 60 weight percent (Fouch and others, 1994). Upper Paleocene to middle Eocene lacustrine lithofacies beneath the middle marker bed exhibit significantly lower TOC values; thermally immature (Rm < 0.5 %) rocks average 1.8 weight percent TOC and thermally mature rocks (Rm > 0.5 %) average 1.6 weight percent TOC (Fouch and others, 1994).

Oil Shale and Source Rock Location

The Green River Formation contains the world's largest oil-shale deposit (fig. 11*A*) with about 1.2 trillion barrels of oil in place in shale and marlstone at a richness of 15 gal/ton or greater (National Petroleum Council, 1973). Most of this vast deposit, however, has not been buried deeply enough to have generated significant amounts of hydrocarbons (see discussion of Thermal Maturity below, and Nuccio and Roberts, Chapter 4, this CD-ROM). The Cow Ridge Member (fig. 11*B*) of the Green River Formation in the Piceance Basin (located just below the Long Point Bed; pl. 1) includes an illitic oil-shale lacustrine facies with high TOC values. The minor Green River oil and gas produced from wells in that area was probably sourced by these oil shales. This minor hydrocarbon generation apparently took place despite lower thermal maturity values than those commonly associated with active hydrocarbon generation (see Thermal Maturity discussion below, and Nuccio and Roberts, Chapter 4, this CD-ROM). Lacustrine rocks of the overlying Garden Gulch and Parachute Creek Members, including the well-known Mahogany oil-shale zone (fig. 11*C*), and the "Big 3" oil-shale beds (fig. 11*D*) (Johnson, 1985), were not buried deeply enough in the Piceance Basin to achieve the necessary thermal maturity to have generated abundant hydrocarbons.

In the Uinta Basin (fig. 11), the greater accommodation space and thickness of rocks, and thus the greater depth of burial of the Garden Gulch, Parachute Creek, and rocks equivalent to the Cow Ridge Members (some formal nomenclature is not extended from the Piceance Basin into the Uinta Basin), produced sufficient thermal maturity in lacustrine oil-shale source rocks to generate abundant hydrocarbons. The inferred source rocks in the Uinta Basin extend upward from the Paleocene-Eocene boundary to about 1,500 ft (Anders and Gerrild, 1984) above the Long Point Bed (pl. 1). The east-west cross section in the Uinta Basin on plate 1 lies south of the depocenter, and thus the thickest section, of lacustrine source rocks in the interval equivalent to the Cow Ridge Member in the Piceance Basin. Thus, the source-rock interval shown on plate 1 is not present on the actual line of cross section. Lacustrine source rocks in this interval do appear on both the north-south cross section (fig. 7*A*) and the source-rock maps (fig. 11). Despite the statement in Fouch and others (1994, p. 415) that the Mahogany zone in the Uinta Basin generated oil from about 30 Ma to the present, more recent work (Ruble and Philp, 1998; Ruble and others, 2001; Nuccio and Roberts, Chapter 4, this CD-ROM) indicates that the Mahogany zone was not buried deeply enough to achieve thermal maturity and generate hydrocarbons. Thus, this report adopts a source-rock interval in the Uinta Basin similar to that suggested by Anders and Gerrild (1984).

Thermal Maturity

Vitrinite reflectance values at the top of the Mesaverde Group (Nuccio and others, 1992) and in the lower part of the Green River Formation (Nuccio and Roberts, Chapter 4, this CD-ROM) show increasing thermal maturity toward the northern, deep part of the Uinta Basin (fig. 12). The thermal maturity contours (fig. 12) generally follow the structural configuration of the basin (Johnson and Roberts, Chapter 7, this CD-ROM; Fouch and others, 1992). Both the thermal maturity and structural patterns are controlled by the maximum depth of burial and the thermal gradients of the rocks (Anders and others, 1992; Nuccio and others, 1992). In general, the thickness of the Tertiary units in the Uinta Basin increases to the north. The geothermal gradient is lower to the north due to the inferred increase in incursion of cooler meteoric waters along the Uinta Mountain fault zone (Fouch and others, 1992). In the Piceance Basin, limited samples indicate a more uniform and lower level of thermal maturity than in the Uinta Basin (fig. 12). Plotting vitrinite reflectance data from well samples onto the north-south cross section in the Uinta Basin (fig. 13; Fouch and others, 1992, 1994) demonstrates that the lacustrine source rocks are well below the 0.6 percent Ro maturation line for oil generation throughout the deepest parts of the Uinta Basin. Tertiary lacustrine rocks approach and are just below the 1.35 percent Ro line for cracking of oil to gas near the base of the interval. Moderate- and high-temperature oil and gas were generated from Green River lacustrine source rocks that achieved a level of Ro > 0.6 percent (Nuccio and Roberts, Chapter 4, this CD-ROM; Fouch and others, 1994). Lacustrine source rocks in the deepest part of the Tertiary Unita Basin section are presently at or near their maximum burial depth, although earlier workers had suggested that many thousands of feet of overburden had been removed from the area (see, for example, Johnson and Nuccio, 1993). Oil and gas are likely currently being generated below about 10,000 ft. This active hydrocarbon generation from Green River source rocks is probably significantly contributing to the overpressuring of reservoirs in that area (see discussion below in section on Reservoir Rocks, and in Nelson, Chapter 14, this CD-ROM).

A burial history curve and petroleum-generation model constructed for the Shell Brotherson 1-11-B4 well in the Altamont-Bluebell field indicates that oil and gas generation began near the base of the Green River Formation around 40 Ma (million years ago) at a depth of about 11,000 ft (figs. 14, 15). Peak oil generation probably occurred during rapid burial between 30 and 40 Ma. Rates of hydrocarbon generation slowed during the period from maximum burial at 30 Ma to the present. The zone of hydrocarbon generation has

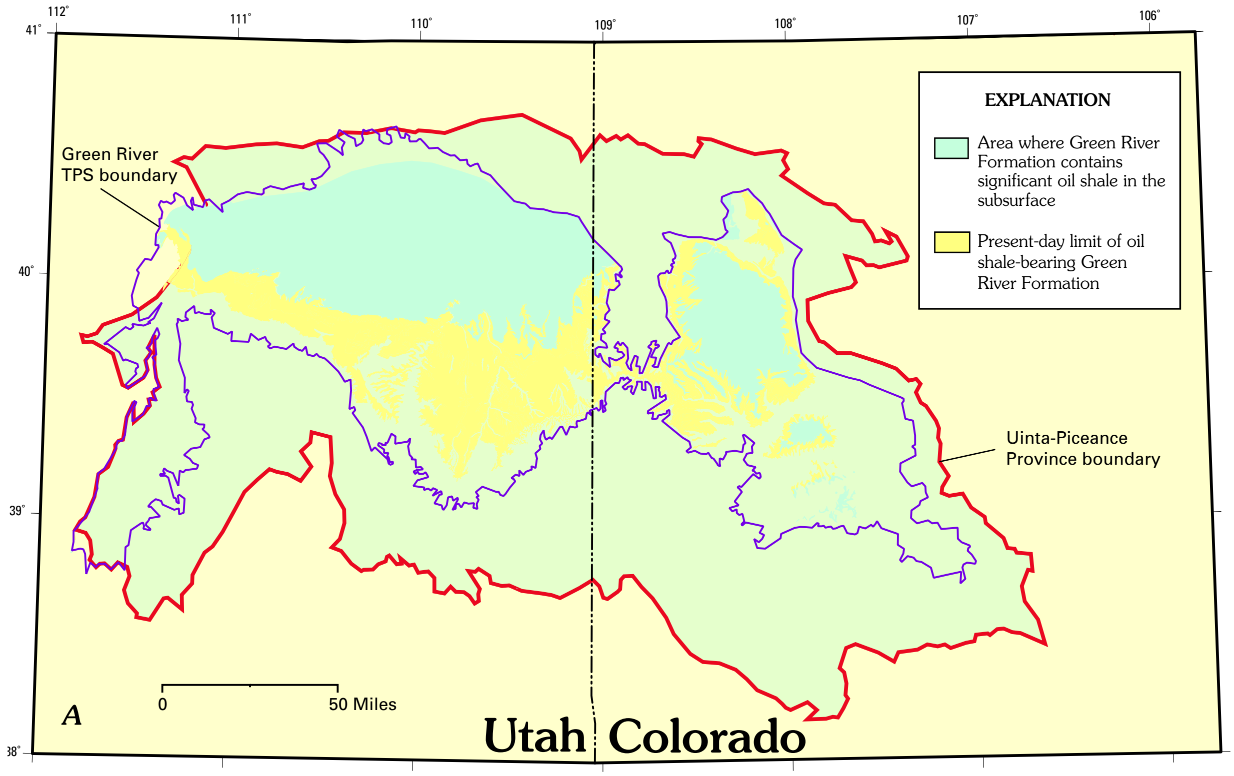


Figure 11*A*. Distribution of oil shale in the Green River Formation of the Green River Total Petroelum System (modified from Donnell, 1961, and Cashion, 1964).

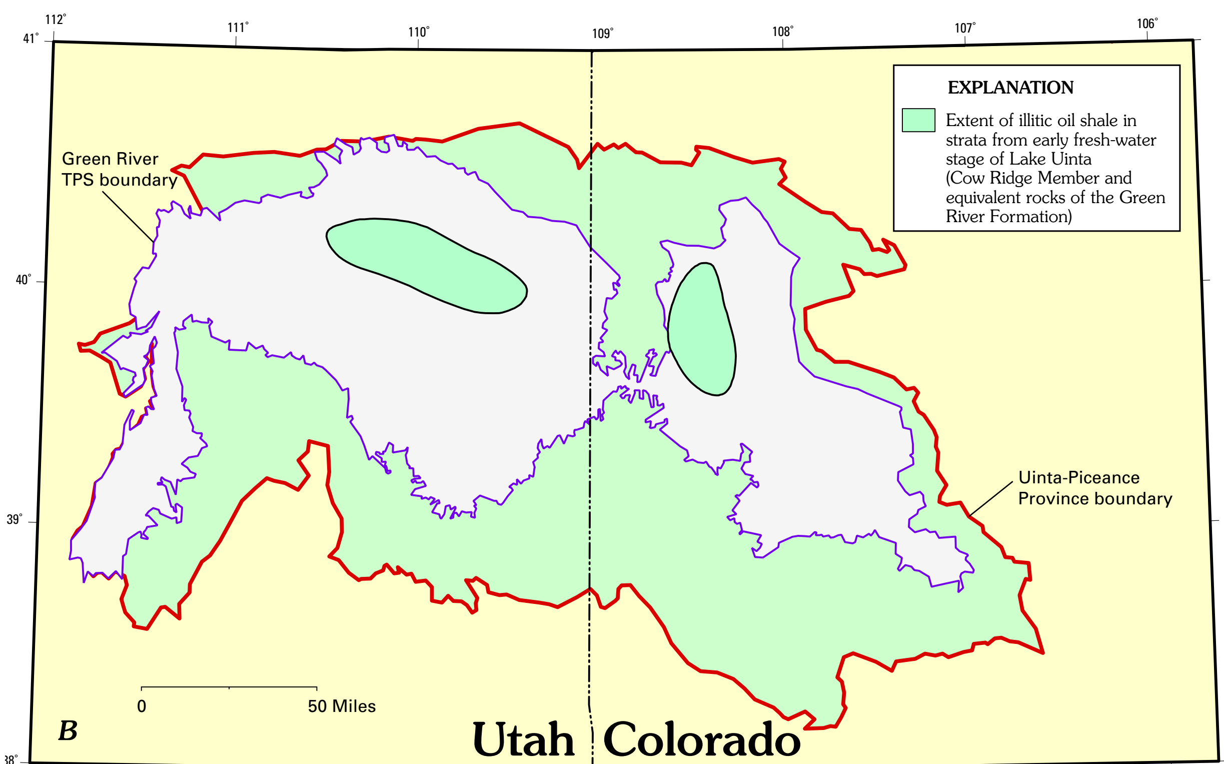


Figure 11*B*. Distribution of lacustrine source rocks in the Cow Ridge Member and equivalent strata of the Green River Formation (modified from Johnson, 1985, fig. 6).

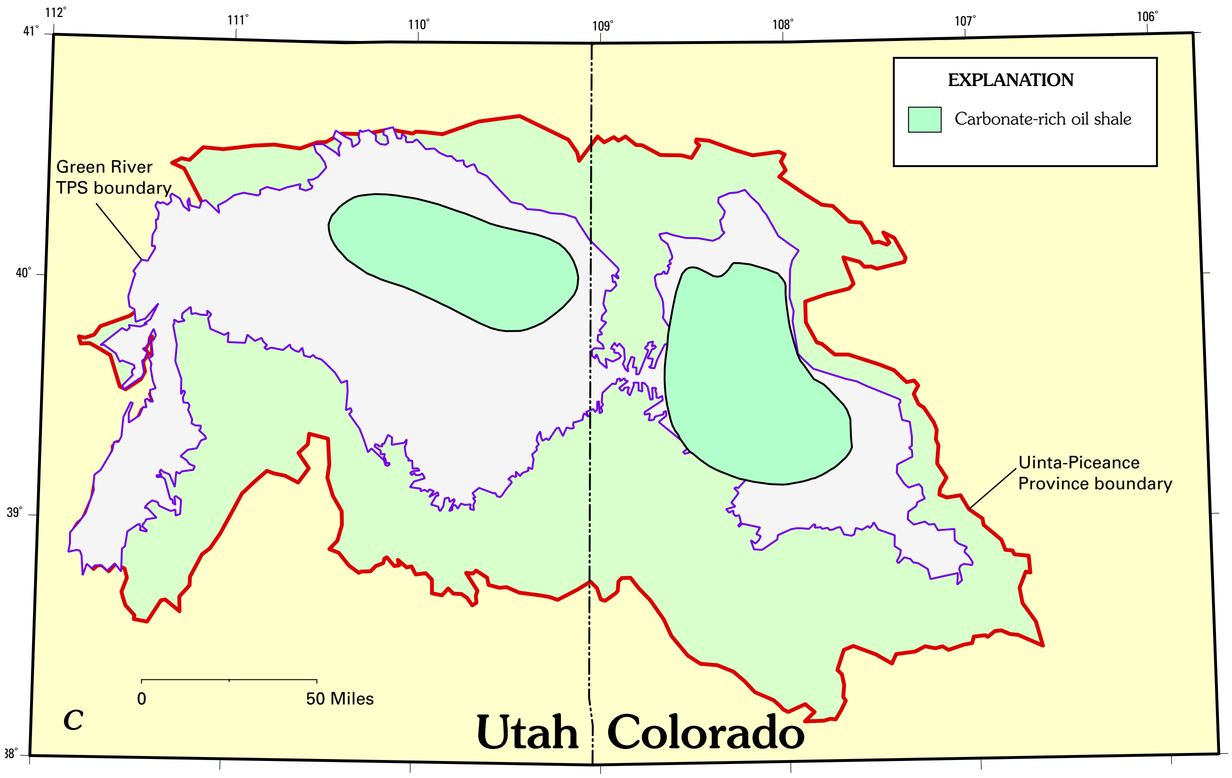


Figure 11*C*. Distribution of lacustrine oil source rocks at the top of the Mahogany oil-shale zone of the Green River Formation (modified from Johnson, 1985, fig. 12).

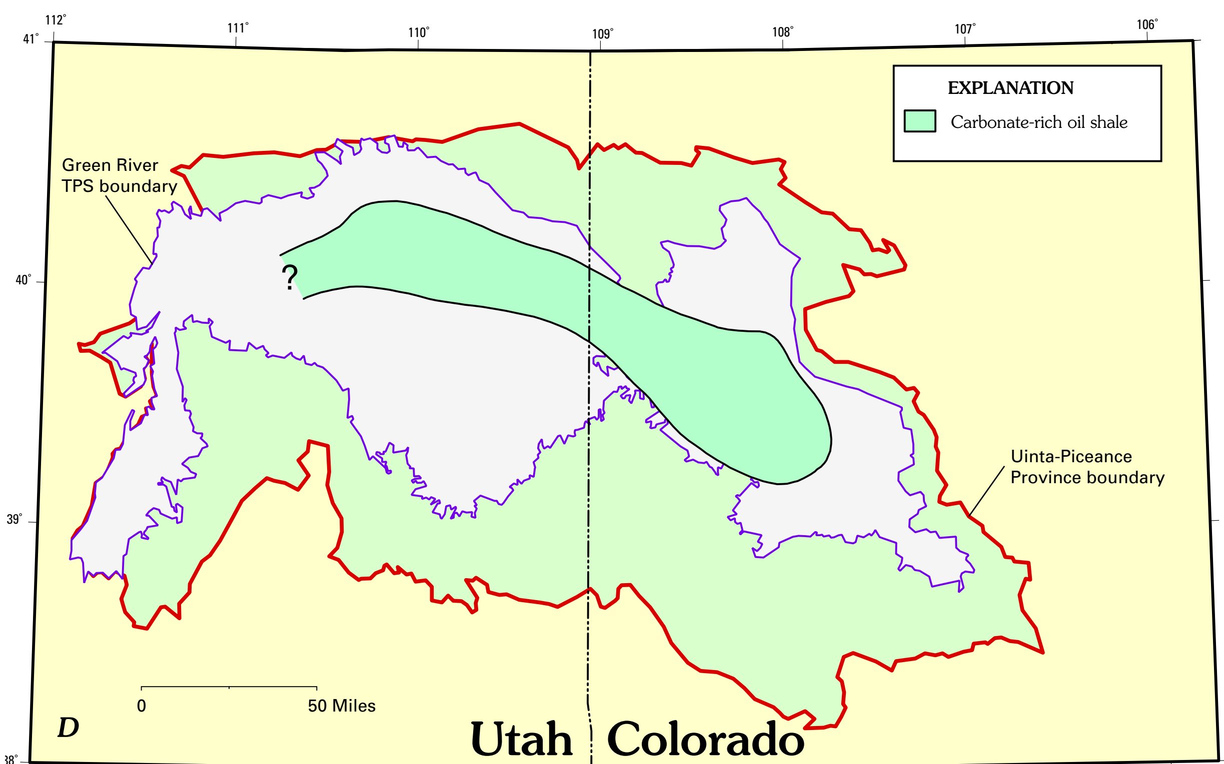


Figure 11*D*. Distribution of lacustrine oil source rocks in the “Big 3” oil-shale beds of the Green River Formation (modified from Johnson, 1985, fig. 11). Pattern queried where uncertain.

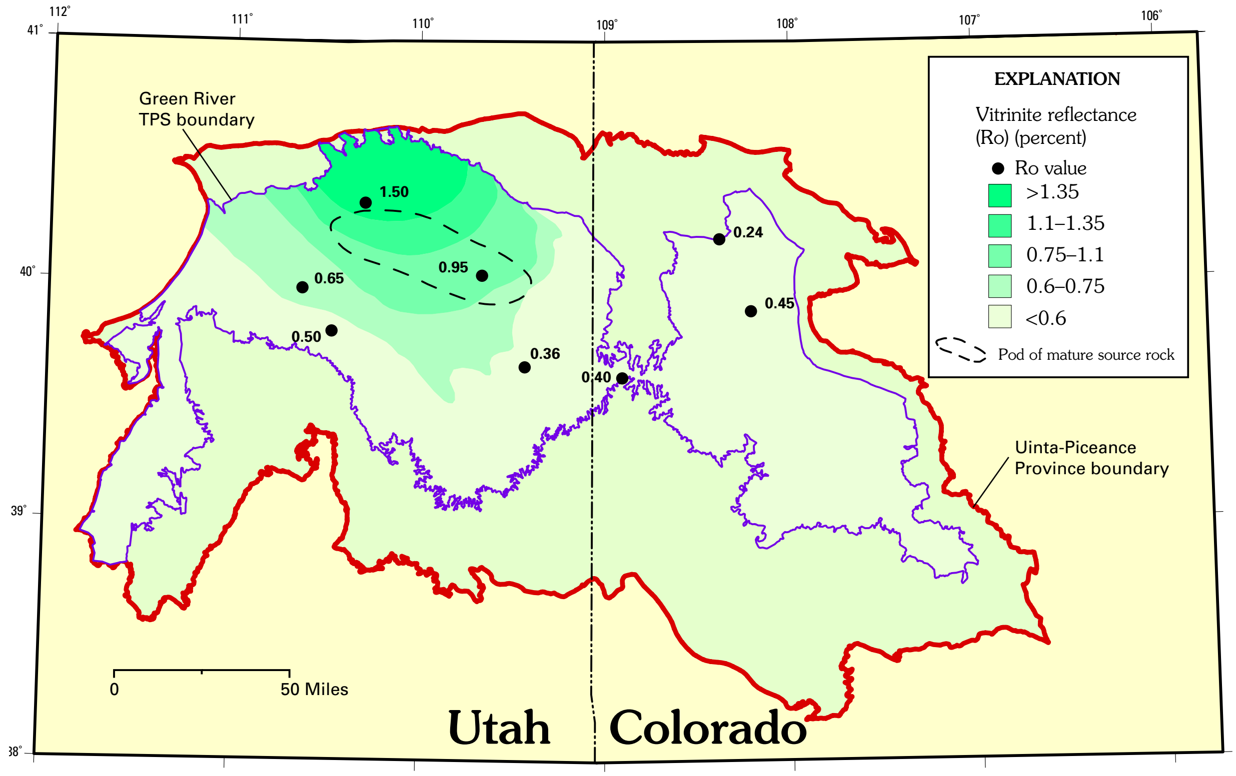


Figure 12. Distribution of vitrinite reflectance values (Ro) in the Green River Total Petroleum System and pod of mature source rock (modified from Nuccio and Roberts , Chapter 4, this CD-ROM).

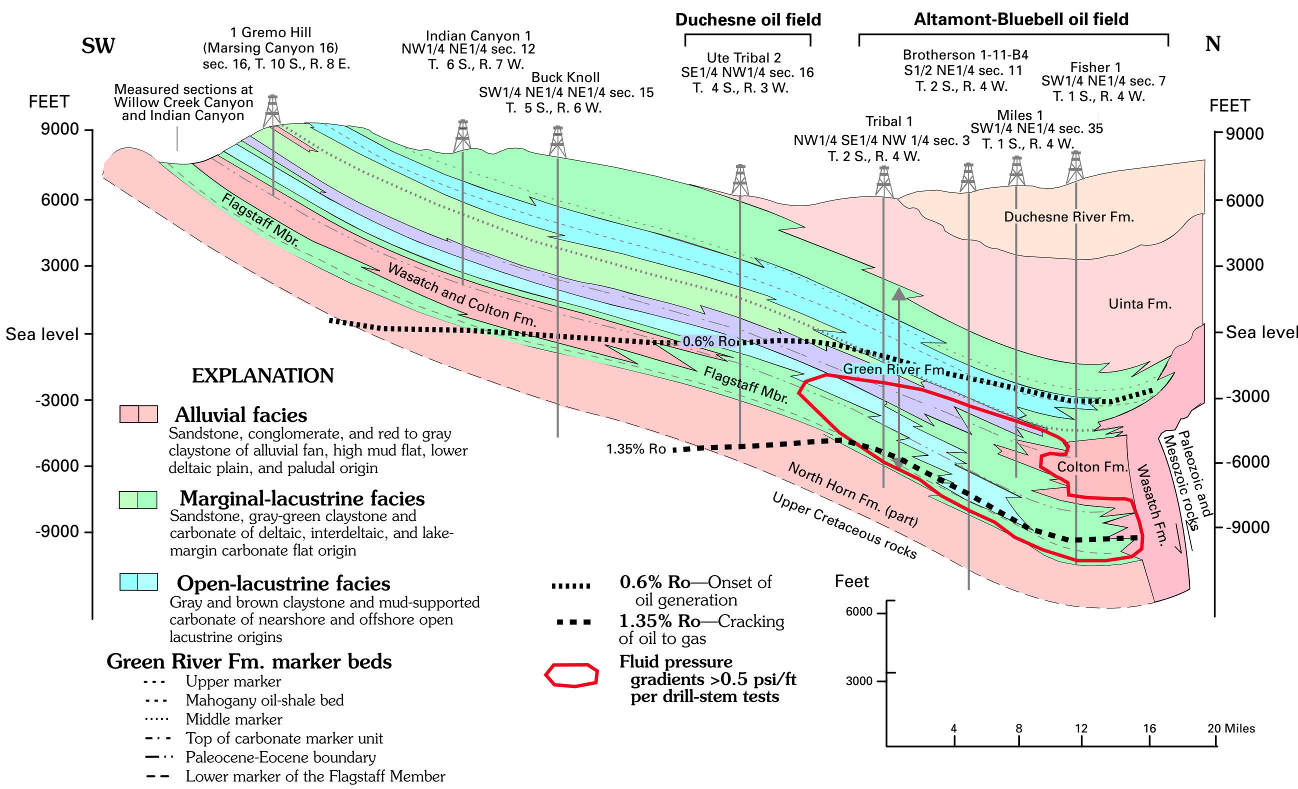


Figure 13. North-south cross section of well logs and depositional facies of the Green River Formation showing vitrinite reflectance lines (Ro) and area of overpressured strata. See figure 7*A* for location of cross section (modified from Fouch and others, 1992).

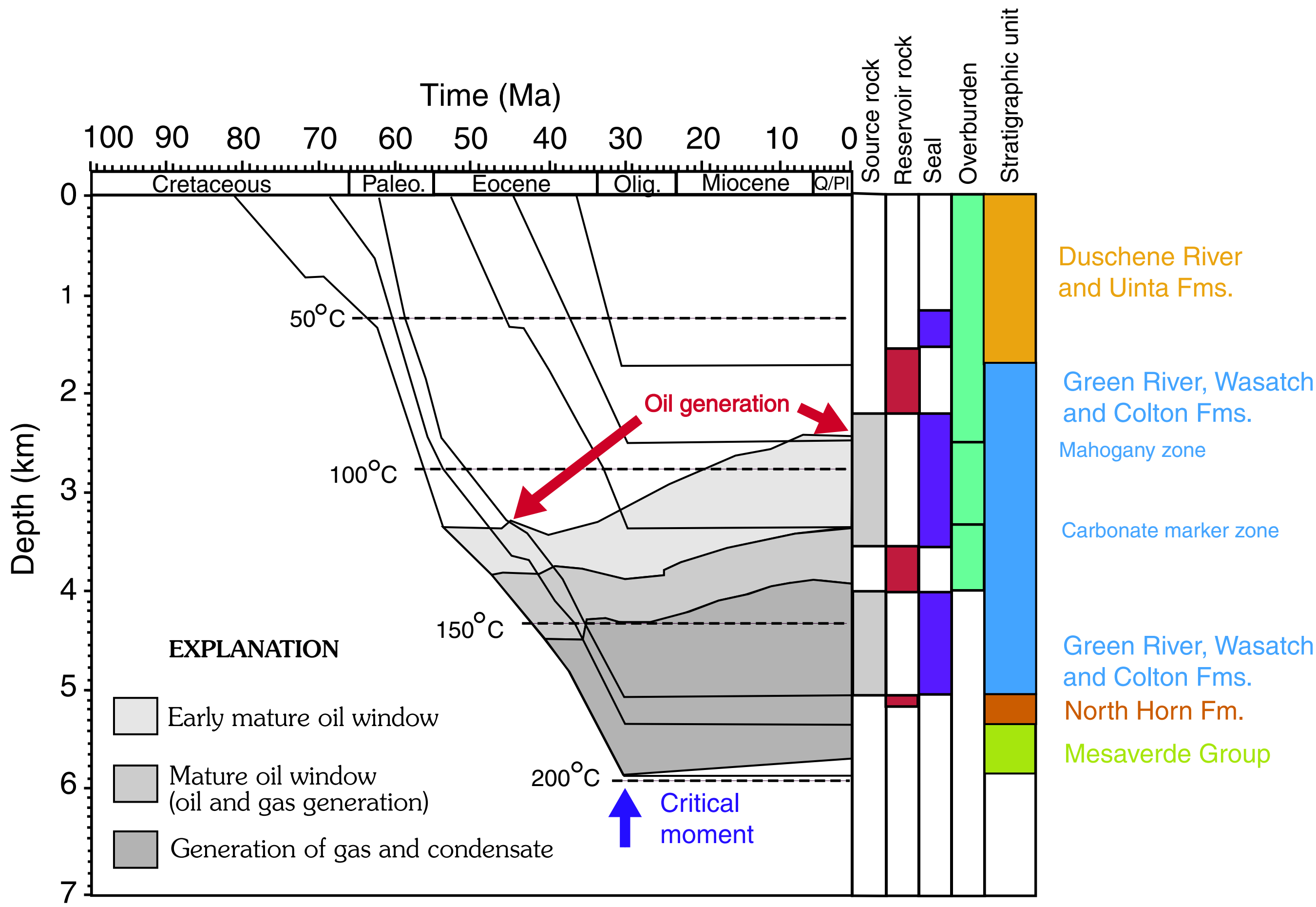


Figure 14. Burial history curve for the Green River Total Petroleum System in the Uinta-Piceance Province (modified from Fouch and others, 1994).

risen stratigraphically through time (fig. 14; Fouch and others, 1994). Oil in the lower part of the Green River Formation in the Uinta Basin has likely been undergoing thermal cracking to gas and condensate since about 35 Ma. Because gas generation from oil cracking can continue to Ro values as high as 3.0 percent, it is possible that some gas generation is ongoing for the source rocks near the base of the Green River Formation in the Uinta Basin, contributing to the overpressuring of the reservoirs in that area (Fouch and others, 1994; Nuccio and Roberts, Chapter 4, this CD-ROM). Oil and gas generation for the units stratigraphically above the carbonate marker bed (see fig. 13 and pl. 1) did not begin until about 25–30 Ma, and it appears likely that this zone is still within the oil-generation window.

Migration of Hydrocarbons

The majority of the oil and gas fields and production from the Green River Total Petroleum System is within Tertiary rocks in the Uinta Basin, with only minor production from the Piceance Basin. Gilsonite veins in the central part of the Uinta Basin and tar sand deposits in the central, southern, and northern parts (fig. 10) all indicate that hydrocarbons have migrated vertically and laterally from their original site of generation in lacustrine source rocks in the deeper parts of the basin. Oils of the Altamont-Bluebell field (fig. 9) are produced at depths less than about 8,400 ft from middle to upper Eocene reservoir rocks of the Green River Formation that have vitrinite reflectance values < 0.7 percent Rm (Fouch and others, 1994). This would suggest slight vertical migration from underlying lacustrine source rocks (fig. 13). In contrast, Altamont-Bluebell oils in fractured reservoirs at depths of about 8,400–14,000 ft appear to have been derived from upper Paleocene to lower Eocene rocks of the Flagstaff Member of the Green River Formation with vitrinite reflectance values of 0.7–1.3 percent Rm (Fouch and others, 1994). These oils appear to have been generated in lacustrine source rocks adjacent to their marginal-lacustrine reservoir rocks, indicating only slight lateral migration from adjacent facies (fig. 13).

In comparison, oil in Redwash, Duchesne, and adjacent fields to the south (fig. 9) is hosted by middle Eocene beds of the Green River Formation at depths ranging from 5,000 to

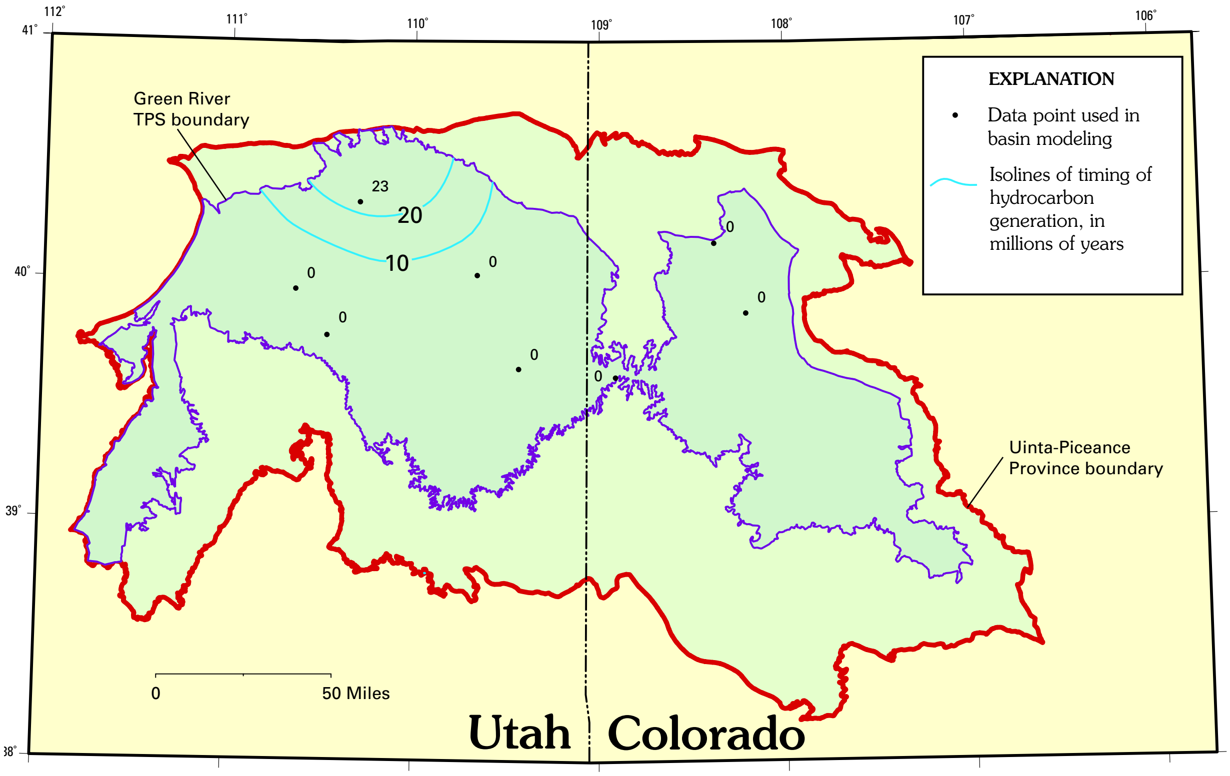


Figure 15. Timing of generation of hydrocarbons in the Green River Total Petroleum System.

9,000 ft (fig. 13). Green River Formation rocks at these depths have vitrinite reflectance values in the range of 0.40–0.55 percent Rm, yet those oils have thermal maturity geochemical indices equivalent to values of 0.7–0.8 percent Rm. These thermal maturity discrepancies suggest that hydrocarbons in Redwash and other fields have migrated up dip from more deeply buried, higher temperature upper Paleocene to middle Eocene Green River source rocks (Anders and others, 1992). The eastward and southward migration of this oil to the Redwash field is along a migration pathway for fluids and gas that can be predicted by fluid-pressure gradients, the composition of the gases, and the formation waters. The flow pattern also follows an anticlinal structure that extends from the north-central part of the Uinta Basin as far east as Redwash field (Fouch and others, 1994).

Gases generated and produced from the Green River TPS are mainly associated with oil (Fouch and others, 1994). Based on composition, stratigraphic position, and association with a distinct type of oil, the gas is interpreted to have been sourced primarily from Type I kerogen in the open-lacustrine facies of the Green River Formation during catagenesis (oil window) when both oil and associated gas were generated (Rice and others, 1992). The thermogenic oil and gas were probably generated in the deep part of the Uinta Basin near the Altamont-Bluebell field and then migrated out from that area. Much of the gas production is from fields developed along the surface trace of faults and fractures in the eastern part of the Uinta Basin. The trend of the gilsonite veins and several of the fault zones in the southern and eastern parts of the Uinta Basin appear to coincide with and overlie the Douglas Creek, Seep Ridge, and Garmesa faults (Stone, 1977; Fouch and others, 1992). Stone (1977) demonstrated that these faults developed along the north and northeast flanks of the Uncompahgre uplift in the region of the Uinta Basin during the late Paleozoic and Mesozoic. Fouch and others (1992) suggested that the faults that cut the Cretaceous and Tertiary units of the Uinta Basin represent reactivation of buried faults associated with the ancestral Uncompahgre uplift.

Tar Sands

Additional evidence for migration of hydrocarbons in the Green River Total Petroleum System is provided by the extensive occurrence of natural solid bitumen (tar sands, gilsonite veins) in outcrops around and in the center of the Uinta Basin. The tar sands in Tertiary outcrops of the Uinta Basin are the degraded surface expression of hydrocarbons that have migrated up dip from deep Green River lacustrine source rocks (Fouch and others, 1994). Bituminous sandstones (tar sands or natural bitumen) are exposed in four areas: (1) extensive outcrops of Tertiary rocks along the southern margin of the Uinta Basin; (2) isolated outcrops of Tertiary rocks near the western margin of the basin; (3) scattered outcrops of Upper Cretaceous and Tertiary rocks along the northern and northeastern basin margins; and (4) a belt of outcrops associated with a fracture system and gilsonite veins in Tertiary rocks in the east-central part of the basin (fig. 10; Ritzma, 1973, 1974; Utah Geological and Mineral Survey, 1983).

The tar sand deposits represent the degraded surface expression of oil that has migrated up dip from the basin center through marginal-lacustrine strata that are stratigraphically continuous with rocks that host the more deeply buried conventional oil fields (Anders and others, 1992). Small outcrops of tar sands on the western part of the Uinta Basin occur near Soldier Summit and Thistle, Utah (Peterson and Ritzma, 1972) and at the Chinese Wax mine (Ritzma, 1975). At the Chinese Wax mine, hydrocarbons occur in the Pennsylvanian-Permian Oquirrh Formation. These rocks are part of the Charleston-Nebo thrust sheet, which has overridden Tertiary rocks, allowing Tertiary-sourced oils to migrate up fractures from the Green River Formation below.

Gilsonite Veins

Additional evidence for the generation and migration of hydrocarbons is indicated by the unusual occurrence of hydrocarbon-filled fractures, commonly referred to as gilsonite veins, in the central Uinta Basin. These solid hydrocarbon-filled fractures, which generally parallel the trends of major structural uplifts (fig. 10), are significant not only from the standpoint of hydrocarbon generation, but also are important for evaluation of the subsurface stress fields (Verbeek and Grout, 1992, 1993). These veins or dikes are nearly vertical and are filled with ozocerite, gilsonite, and wurtzilite that originated from organic-rich layers generally less deeply buried and less chemically and thermally mature than the organic-rich lacustrine source rocks related to the Altamont-Bluebell producing trend (Verbeek and Grout, 1992).

The gilsonite dikes of the eastern Uinta Basin originated as large hydraulic fractures from overpressured, hydrocarbon-rich source beds in the Green River Formation during early stages of post-Laramide regional tectonic extension (Verbeek and Grout, 1993). The formation and filling of the dikes suggest that significant hydraulic pressures were generated in the source-rock beds so that extensive vertical fractures as much as 10 ft wide were opened and subsequently filled by solid hydrocarbons. Emplacement depths are estimated at 2,300–8,200 ft. The widespread occurrence of gilsonite sills that were injected along bedding planes indicates that fluid pressures at the time of injection frequently exceeded lithostatic load. The deformation proceeded with time from local hydraulic extension fracture (gilsonite dikes) through regional nonhydraulic extension fractures (joints) to minor shear failure (normal faults at depth, reactivated joints nearer the surface) of the basin strata (Verbeek and Grout, 1993).

Reservoir Rocks, Traps, and Seals

Oil and associated gas are produced from two distinct types of accumulations in the Green River Total Petroleum

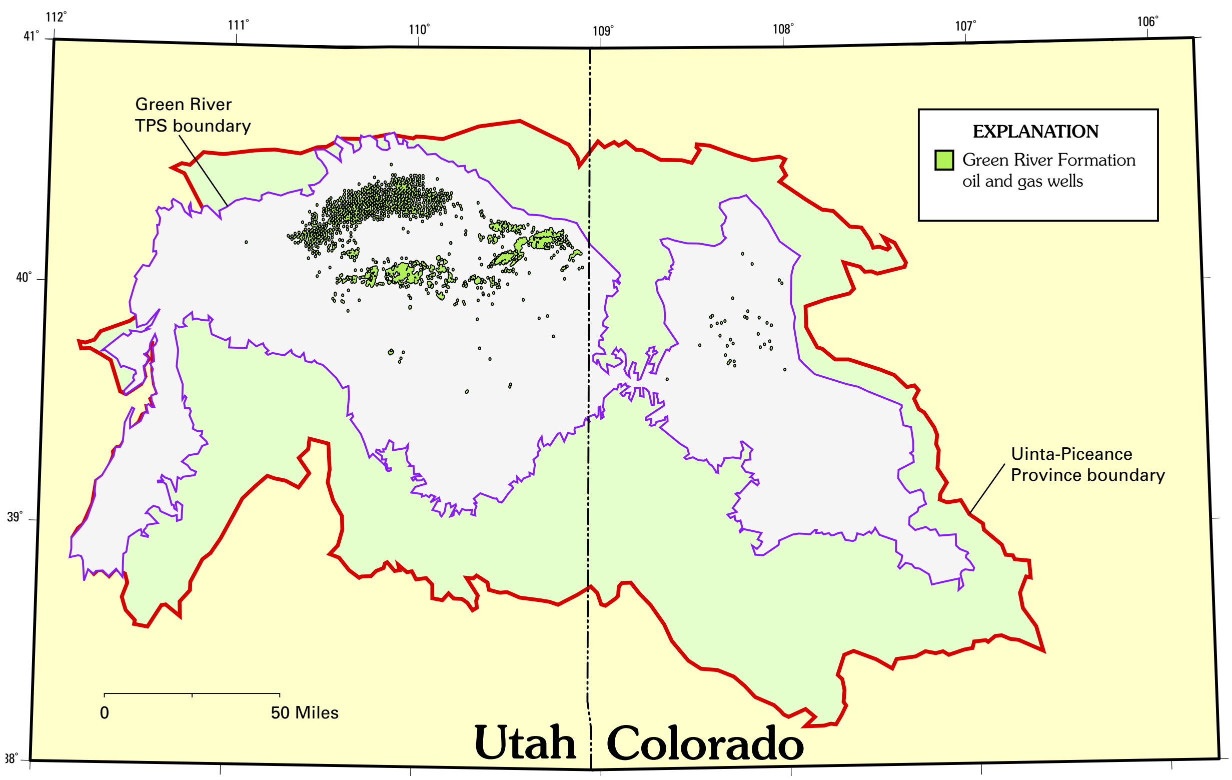


Figure 16. Distribution of hydrocarbon-producing wells in the Green River Total Petroleum System.

System. In the deepest part of the Uinta Basin, the major oil accumulations are typified by the reservoirs in the Altamont-Bluebell and Cedar Rim fields (fig. 9). The uniform distribution and close spacing of producing wells (fig. 16), drill-stem-test data characteristic of overpressured and fractured reservoirs (see discussion of Fluid-Pressure Gradients), and the fact that oil-water contacts are rare to absent indicate that this is a continuous oil accumulation (Fouch and others, 1994; HIS Energy group, 2000a). Hydrocarbons in marginal-lacustrine strata form a continuous oil and minor associated-gas accumulation that was generated within adjacent lacustrine-basin shales (Fouch and others, 1994). In the Uinta Basin, oil and associated gas are recovered from secondary pores in the basal parts of marginal-lacustrine channel sandstones that are interbedded with carbonate and gray to green mudstones (Fouch, 1975, 1985). The sequence contains units that have contrasting ductility, and the reservoir rocks were fractured by brittle failure due to changes in stress caused by overpressuring and (or) tectonic tilting and basin subsidence. Core, drill-stem tests, and production data (Narr and Currie, 1980; Fouch and others, 1994; Petroleum Information/Dwights LLC, 1999a, b) all indicate that production of hydrocarbons is controlled by fracture distribution and fracture-enhanced porosity in the unconventional accumulations. Fluvial-channel sandstones that developed at the margins of Lake Uinta are interbedded with, and encased within, ductile marginal-marine and fluvial claystones. Brittle lacustrine carbonates are rare to absent in this facies association. Thus, oil apparently has not been able to migrate laterally through fractures from lacustrine source rocks into the fluvial channel sandstones, such as along the northern margin of the lake facies (fig. 13). Therefore, in the northern part of the petroleum system, the fluvial rocks serve as an impermeable barrier (seal) to oil migration in the overpressured reservoirs (Fouch and others, 1994).

The second major group of reservoirs in the Green River TPS occurs south of the first grouping in marginal-lacustrine and fluvial rocks in the Uinta Basin, characterized by the fields that extend from Brundage Canyon on the west to Redwash and Walker Hollow on the east (figs. 9, 16). These fields host discrete, conventional accumulations of oil and minor associated gas. The pod-like distribution of the producing areas (fig. 16), the production data (Petroleum Information/Dwights LLC, 1999a, b), and the presence of oil-water contacts in many wells (HIS Energy Group, 2000b) indicate that these are normally pressured conventional oil and gas fields in which hydrocarbons are trapped by stratigraphic and facies-change traps. Seals are formed by encasing mudstones that were deposited as lower energy, fine-grained facies. These reservoirs are similar in facies and distribution to oil-bearing rocks (tar sands or natural bitumen on outcrops) that crop out at the southern rim, the center, and the northern rim of the Green River TPS (fig. 10; Ritzma, 1973; Utah Geological and Mineral Survey, 1983; Fouch and others, 1992). These oil and gas fields in the Uinta Basin represent conventional hydrocarbon accumulations that were sourced from the Green River Formation lacustrine shales in the central parts of the two basins. In the Piceance Basin, oil and gas sourced by the Green River Formation is produced from marginal-lacustrine rocks.

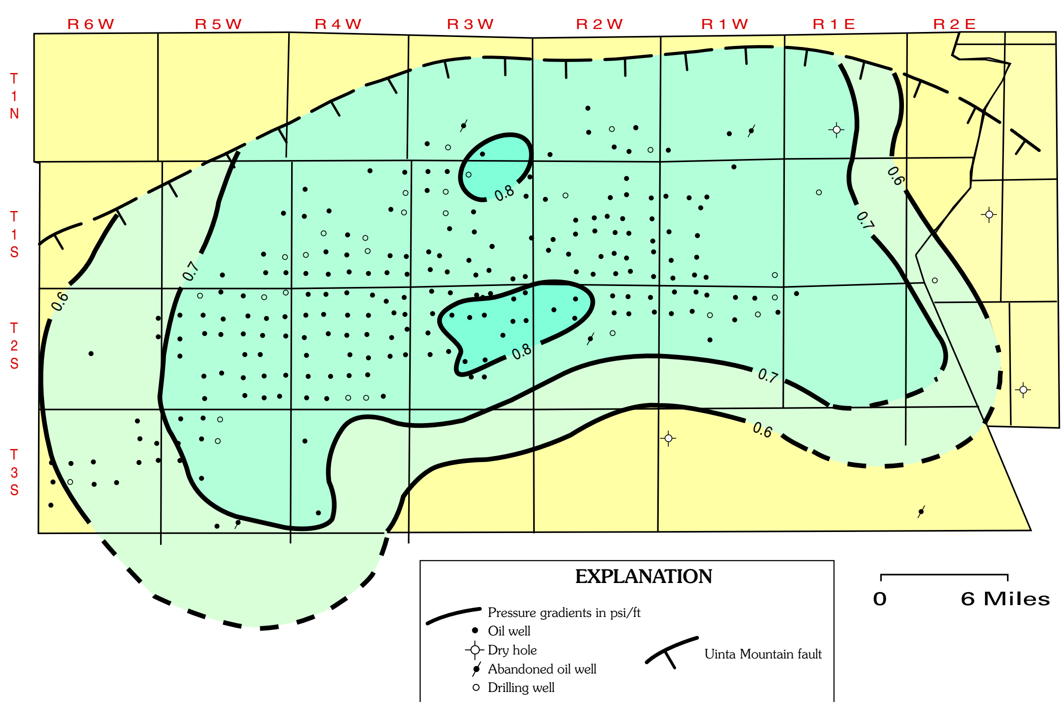


Figure 17. Distribution of wells and contours of pressure-gradient data in the Altamont-Bluebell field (modified from Lucas and Drexler, 1975).

Fluid-Pressure Gradients

Oil and associated gas in the Altamont-Bluebell field are recovered from deeply buried and overpressured strata adjacent to the synclinal axis of the Uinta Basin (fig. 17; Lucas and Drexler, 1975). Sets of open fractures provide permeable fracture networks that drain “tight” oil reservoirs characterized by low matrix porosity and permeability (Fouch and others, 1994; Nelson, Chapter 14, this CD-ROM). Overpressuring caused by hydrocarbon generation may cause natural fracturing (Chaney, 1949; Law and others, 1979; Spencer, 1987; Sweeny and others, 1987). In the deep Uinta Basin, overpressuring results from inferred active hydrocarbon generation and is thought to contribute to the fracturing of the reservoirs (Spencer, 1987; Fouch, 1975, 1981; Fouch and others, 1994).

Fluid-pressure gradients were estimated by Fouch and others (1994) using a variety of techniques. The regional distribution of drill-stem-test-derived fluid-pressure gradients plotted on the north-south cross section (fig. 13) demonstrates the locations in the subsurface where the fluid-pressure gradient exceeds 0.5 psi/ft (Fouch and others, 1994). The depth and geometry of the pod of overpressured strata coincide with the producing interval of the Altamont-Bluebell field (fig. 9). The highest fluid-pressure gradients are where rocks with abundant Type I hydrogen-rich kerogen are subjected to sufficient heat to thermochemically generate hydrocarbons and produce the observed overpressuring of strata and reservoirs (Fouch and others, 1994). A compilation of down-hole drill-stem pressure-gradient data (see Nelson, Chapter 14, this CD-ROM for plots of individual well data) indicates an increase in the slope of the pressure-gradient curves and the onset of overpressuring at about 8,500 or 9,000 ft (fig. 18*A*), The fluid-pressure gradients decrease slightly at about 13,000 ft, approximately at the stratigraphic interval of the top of the underlying Cretaceous rocks (see Nelson, Chapter 14, this CD-ROM). Extrapolating the pressure-gradient data from the drill-stem tests and plotting it next to the data from Lucas and Drexler (1975) indicates that the overpressured rocks define a pod of rocks deeper than about 8,500 ft and coincident with the Altamont-Bluebell field (figs. 9, 18*B*). The association of abnormally high fluid-pressure gradients, source rocks, high maturation temperatures, and open-fracture reservoirs surrounded by strata with few interconnected fractures indicates that much of the hydrocarbon-producing fracture porosity may be the result of active generation of hydrocarbons within the largely impermeable rock strata (Fouch and others, 1994). The deeply buried overpressured reservoirs have core-derived matrix permeability values near, and commonly below, 0.1 millidarcies. Porosity values average 5 percent and range from 3 to 10 percent (Fouch and others, 1992).

Assessment of Oil and Gas Resources

The events chart (fig. 19) summarizes the important elements and timing of processes that contributed to generation and accumulation of hydrocarbons in the Green River Total Petroleum System. Deposition of the Green River Formation and related rocks during Paleocene to Oligocene time (64–30 Ma) formed the source rocks, reservoir rocks, and seals for the hydrocarbons. The overburden rock required to thermally mature the Green River lacustrine source rocks includes the upper part of the Green River Formation and the overlying Uinta and Duchesne River Formations. Many of the traps are stratigraphic in nature; thus, trap formation primarily occurred during deposition of the Green River Formation itself. Regional uplift in the Uinta and Piceance Basins area during the last 10 m.y. enhanced the structural component of the traps. Based on the burial history curve (fig. 14), petroleum generation occurred approximately 35–20 Ma, with peak generation (Critical Moment) at about 30 Ma. However, the high fluid-pressure gradients and thermal maturation values recorded for the Altamont-Bluebell field suggest that hydrocarbon generation is presently ongoing in the deeper parts of the Uinta Basin (Fouch and others, 1994; Bredehoeft and others, 1994). During the last 20 m.y., hydrocarbons either were preserved in their original state in reservoirs, were migrated, or were biodegraded and partially eroded on outcrop (tar sand deposits).

Key geologic elements and processes combined to form distinct types of hydrocarbon accumulations that are known from producing fields in the Uinta-Piceance Province (figs. 9, 16). Based on the distributions of producing fields, producing oil and gas wells, and dry holes (Petroleum Information/Dwights LLC, 1999a), and the source rock–reservoir rock–trap relations, three distinct assessment units were defined, mapped, and assessed for undiscovered hydrocarbon resources in the Green River Total Petroleum System of the Uinta-Piceance Province (fig. 20). In the eight chapters of this CD-ROM on methodology (Chapters 17–23), various authors (Charpentier, Cook, Crovelli, Klett, and Schmoker) discuss methodology, forms, and tables employed herein to assess the undiscovered hydrocarbon resources in unconventional and conventional reservoirs.

Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561)

The Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561) in the Green River Total Petroleum System is defined primarily by the occurrence of known overpressured source and reservoir rocks in the Green River Formation in the deepest part of the Uinta Basin (fig. 20). A map of the overpressured data in drill-stem tests from the Altamont-Bluebell field (Lucas and Drexler, 1975) shows a distribution of pressure gradients from greater than 0.8 psi/ft to 0.6 psi/ft. An extrapolation of data out to a pressure gradient of 0.5 psi/ft based on the geographic and stratigraphic distribution of drill-stem-test data (Lucas and Drexler, 1975; Fouch and others, 1994) outlines the extent of strata in the assessment

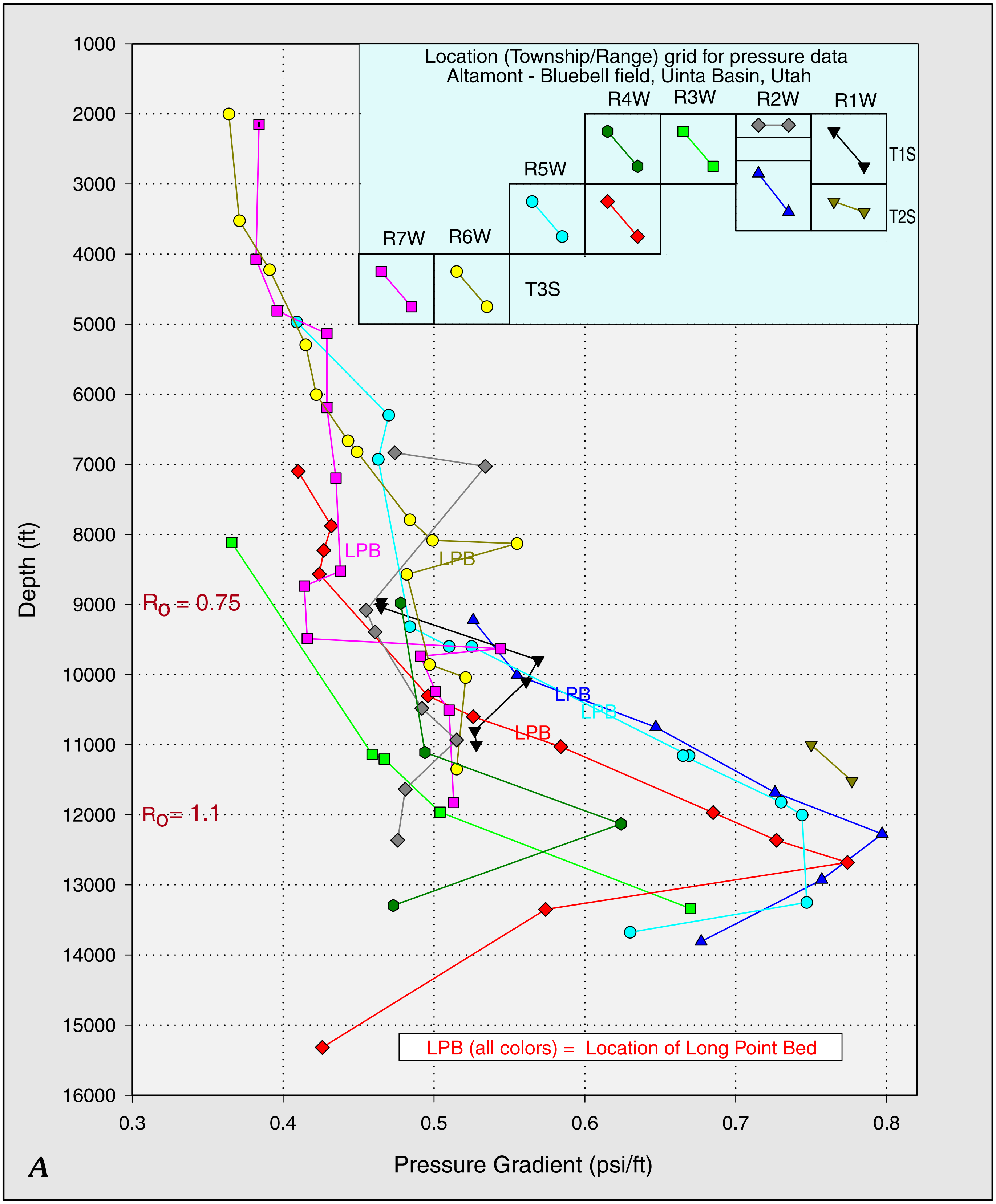


Figure 18*A*. Pressure-gradient data versus depth for wells in the Altamont-Bluebell field (see Nelson, Chapter 14, this CD-ROM for detailed explanation).

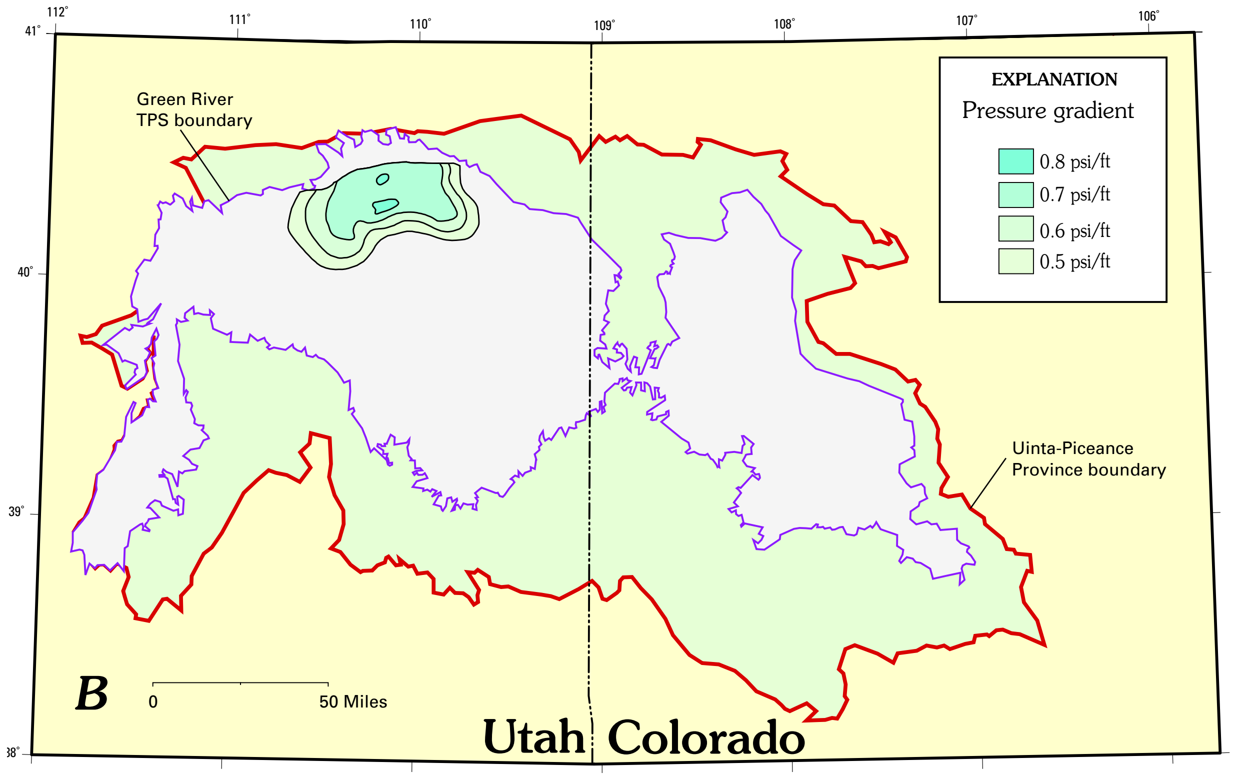
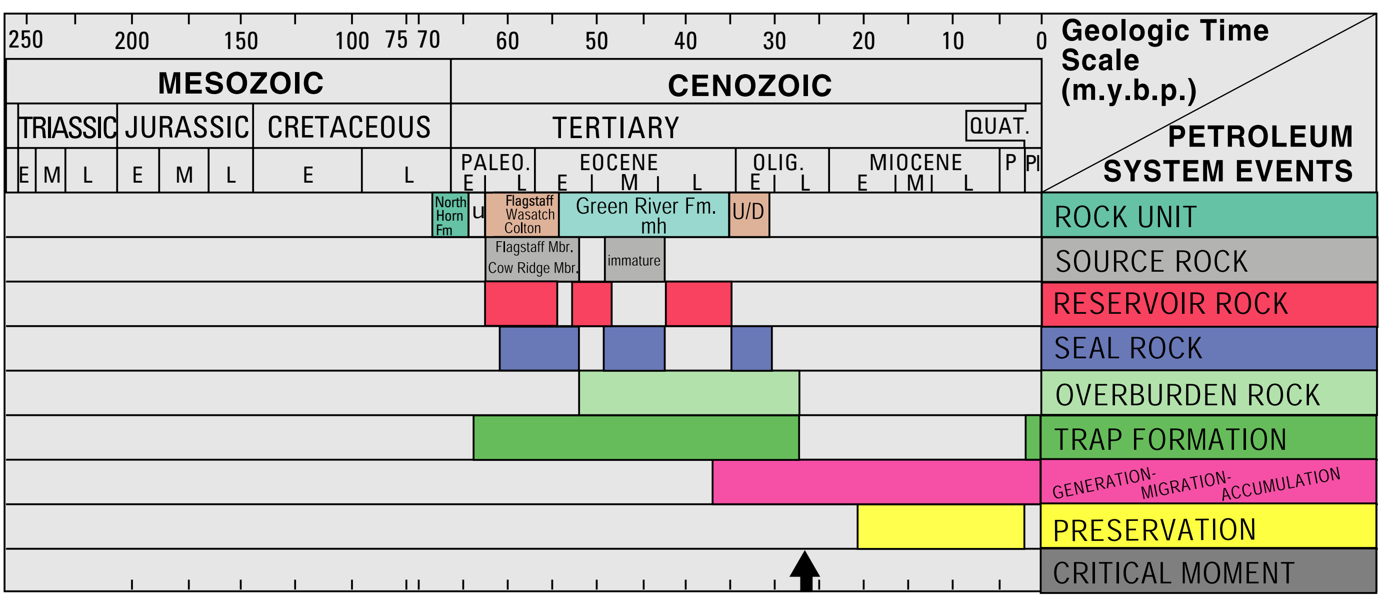


Figure 18*B*. Pressure-gradient contours in the Altamont-Bluebell field (modified from Lucas and Drexler, 1975).



u = unconformity mh = Mahogany oil-shale zone U/D = Uinta and Duchesne River Fms.

Figure 19. Petroleum system events chart for the Green River Total Petroleum System in the Uinta-Piceance Province (modified from Fouch and others, 1994).

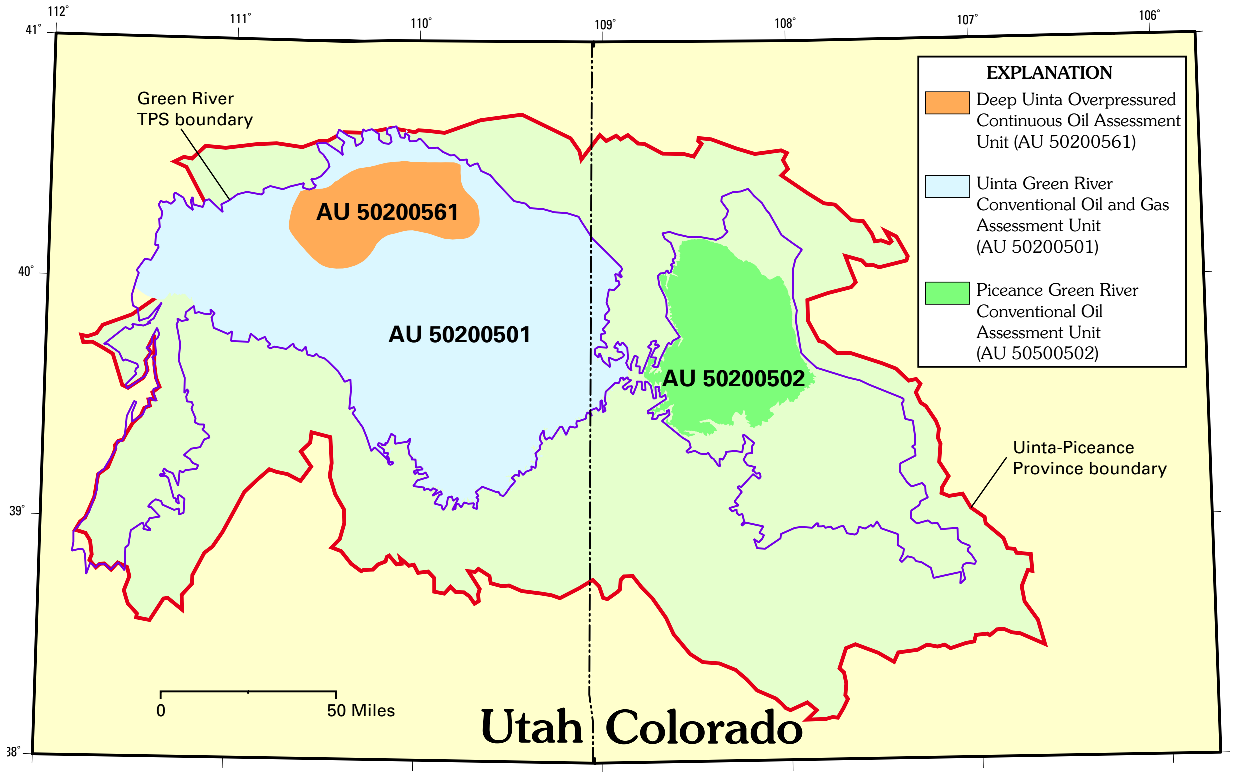


Figure 20. Location of the three assessment units defined in this report for the Green River Total Petroleum System—Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561); Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501); and Piceance Green River Conventional Oil Assessment Unit (AU 50500502).

unit thought to have a pressure gradient higher than hydrostatic pressure (compare figs. 18 and 20). In addition, the downhole distribution of drill-stem-test overpressure data (fig. 18*A*) indicates that overpressuring occurs deeper than about 8,500 ft. The well production data (Petroleum Information/Dwights LLC, 1999a) indicate that wells in the Altamont-Bluebell field are normally pressured at depths shallower than about 8,500 ft, similar to the concept shown by the north-south cross section (fig. 13; Fouch and others, 1994). For this assessment, wells that produce hydrocarbons from normally pressured reservoirs at depths shallower than 8,500 ft were attributed to the second conventional assessment unit defined for the Green River TPS, which is described in the next section of this report.

The Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561) includes strata of the Tertiary Green River Formation and laterally equivalent rocks that have a fluid-pressure gradient greater than 0.5 psi/ft and that are deeper than about 8,500 ft in the subsurface. A summary of the characteristics and evaluation of the assessment unit is presented in the Assessment Model for Continuous Accumulations (Appendix A). Only wells that produced oil and associated gas from the Green River Formation and equivalent rocks were included in this assessment unit (Petroleum Information/Dwights LLC, 1999a). Wells that produced only gas from the Wasatch Formation or its equivalents were assumed to have accumulated that gas from underlying Mesaverde rocks. Those wells and reservoirs were included in the assessment of the corresponding Cretaceous Mesaverde Total Petroleum System to avoid double counting of cells or resources (see Johnson and Roberts, Chapter 7, this CD-ROM).

Of the previously drilled wells in this assessment for the continuous overpressured hydrocarbons in the Green River Formation, 903 were producing wells and 39 were dry holes, for a total of 942 evaluated cells (Appendix A). Approximately 8 percent of the producing wells had an estimated ultimate recovery (EUR) less than 0.003 million barrels of oil (MMBO), the minimum value used with other assessment units in this province (fig. 21). There are 849 wells with the total recovery greater than the minimum EUR, indicating that this is an established assessment unit. The median EUR is 0.35 MMBO for the first third of the discovered wells, 0.18 MMBO for the second third, and 0.1 MMBO for the third third (fig. 22), indicating a steady decline in production over time as is expected from a mature field. There is adequate charge, reservoir, traps, seals, access, and timing of generation and migration of hydrocarbons, indicating a geologic probability of 1.0 for finding at least one additional untested cell with a total recovery greater than the stated minimum EUR of 0.003 MMBO.

To calculate the percentage of untested assessment-unit area and the total recovery for untested cells, GIS techniques were applied to geographic coverages in Arc/Info (ESRI: Environmental Systems Research Institute, Inc.) to estimate

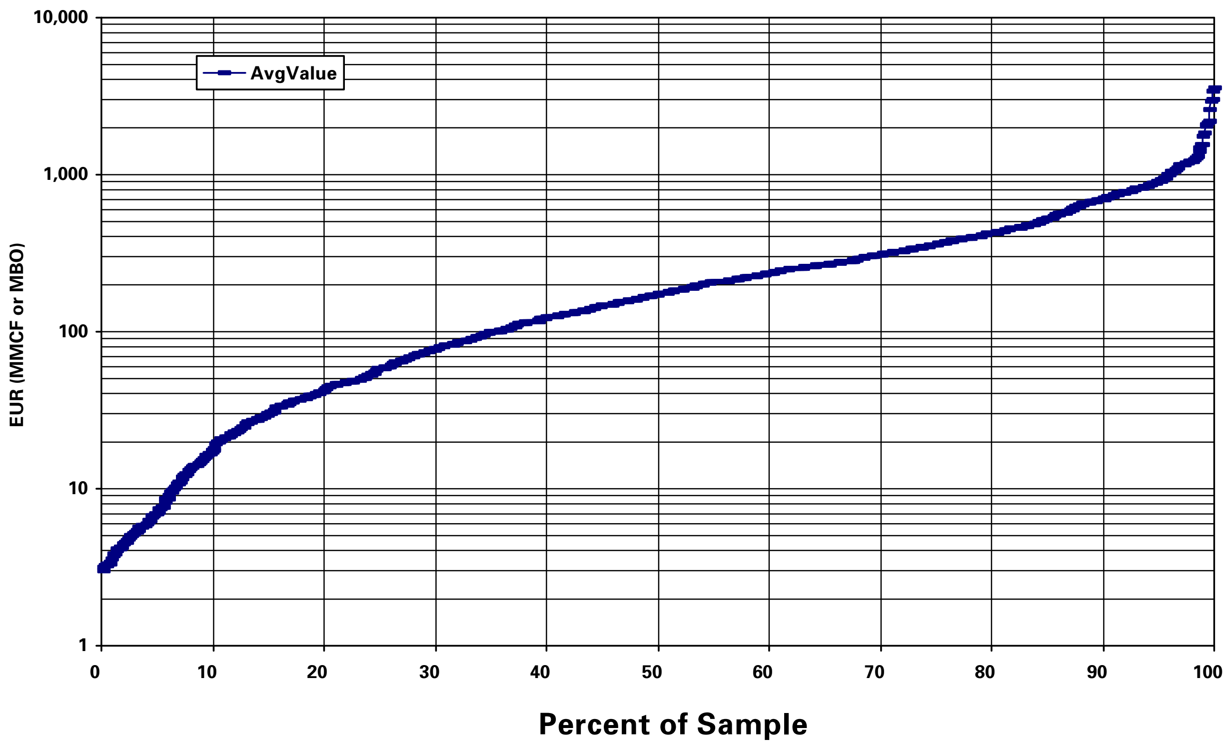


Figure 21. Distribution of average estimated ultimate recoveries (EURs) for wells in the Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561). Approximately 8 percent of the smallest wells were removed from the lower end of the graph.

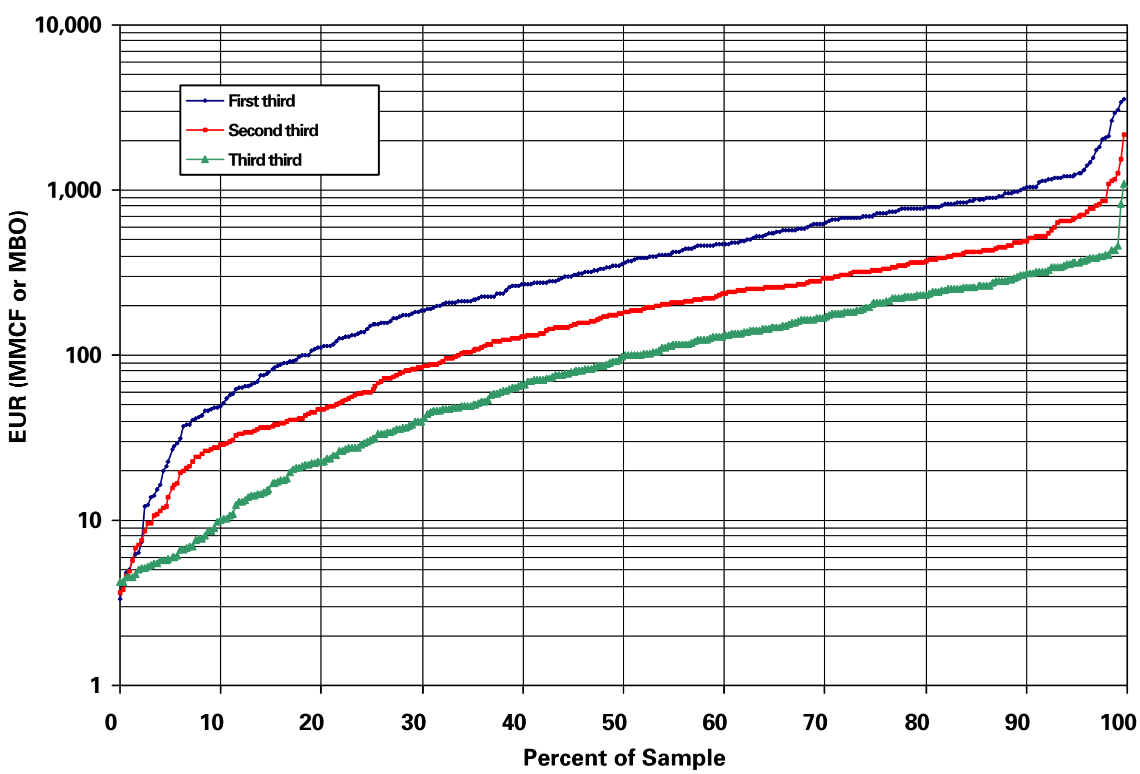


Figure 22. Distribution by thirds of the estimated ultimate recoveries (EURs) for the Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561).

the total assessment-unit area, the area per cell of untested cells, and the untested areas (Appendix A). The median map area of the overpressured assessment unit is 713,000 acres, based on the geographic area within the 0.5 psi/ft pressure-gradient contour. However, this area is not known with certainty because the location of the contour was extrapolated from published data (Lucas and Drexler, 1975), and it represents an approximation of the areal extent of the overpressured strata. The error in drawing the 0.5 psi/ft line was estimated to be ±10 percent, which leads to a maximum area of 784,000 acres and a minimum area of 641,000 acres.

The area per cell of untested cells is related to the drainage area of a well. For known drilling in the area of the Altamont-Bluebell field, the maximum cell size for the assessment unit is 640 acres, and the minimum cell size is 80 acres, with a median cell size of 305 acres (Appendix A). The number of evaluated cells (942 producing wells plus dry holes) was multiplied by the median tested cell area (305 acres), then divided into the total median assessment area (713,000 acres), and then further modified because of other geologic factors to give a percent of the area tested for hydrocarbons. This led to a median value of 58 percent of the total assessment-unit area as presently untested for hydrocarbon resources. Similar calculations and areal considerations yield values of untested total assessment-unit area of 34 percent for the minimum and 77 percent for the maximum, using the corresponding minimum and maximum assessment-unit acreage. Of these values for the untested assessment-unit area, only a certain percentage of that area has the potential for additions to hydrocarbon reserves over the next 30 years, based on understanding of the geologic and petroleum system models for the Green River TPS. To calculate the size of these areas, one must apply an understanding of the geologic factors affecting the distribution of reservoirs and their included hydrocarbons to the known distribution of producing wells and their success ratio.

For this continuous oil assessment unit, 903 of the 942 wells drilled were producing wells, for a success ratio of 94 percent (or a dry-hole ratio of 6 percent). This high success ratio is an indication of exploration drilling for a continuous (overpressured) hydrocarbon accumulation in which active generation of hydrocarbons has both produced extensive fracture porosity and hydrocarbons in laterally extensive reservoirs. However, several geologic considerations suggest that the distribution and amount of future reserves may be limited by several factors.

An overlay of the area underlain by the lacustrine-shale source rocks of the Cow Ridge Member-equivalent stratigraphic interval of the Green River Formation with the

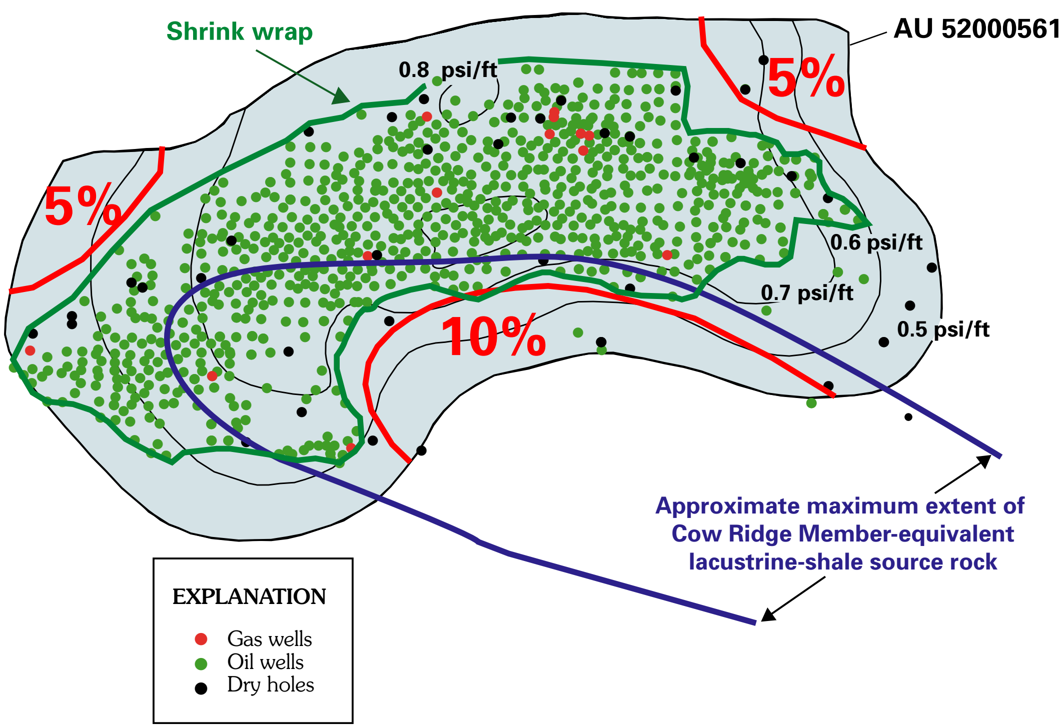


Figure 23. Approximate boundary of the Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561) and distribution of producing oil and gas wells and dry holes. Also shown are lines that delimit: (1) the most likely area for future hydrocarbon reserves ("shrink wrap" line), (2) the approximate area (labeled 10%) underlain by the lacustrine source rocks of the Cow Ridge Member of the Green River Formation, and (3) the two areas (labeled 5%) that each make up about 5 percent of the play area thought to be of limited potential for containing hydrocarbon resources in outlying areas of the 0.5 psi/ft pressure-gradient contour. Note that latitude and longitude are not shown and that the locations of the wells have been shifted slightly to alter their exact location due to the proprietary nature of the well-location database. Pressure gradients modified from Lucas and Drexler (1975).

distribution of the producing cells (fig. 23) indicates that the lacustrine shale overlaps a small part of the area of producing cells. There is a deflection of the pressure-gradient contours to the northwest that is interpreted to be related to the distribution of the lacustrine shale and the expulsion of hydrocarbons from this source rock. Because the lacustrine-shale source rock is ductile, it apparently has not sustained the fracturing due to hydrocarbon generation as have the adjacent marginal-lacustrine carbonate reservoir rocks; producing wells here are far less common than in areas with abundant carbonate reservoirs. Thus this area of lacustrine facies is unlikely to produce significant hydrocarbon reserves in the future. This small area represents about 10 percent of the assessment-unit area (fig. 23). Similarly, there are two areas at the northeast and northwest margins of the assessment unit in which geologic factors may also limit the occurrence of hydrocarbons. The lack of producing wells and the uncertainty in the location of the 0.5 psi/ft pressure-gradient contour suggest that there is a limited likelihood of resources in these two areas, each of which represents about 5 percent of the assessment-unit area. Adding these two 5 percent areas to the previous 10 percent area yields a total of 20 percent, indicating that the maximum of the untested assessment-unit area that has potential for additions to reserves in the next 30 years can only be as large as about 80 percent (Appendix A). A line drawn around the concentration of known producing cells in the assessment unit (“shrink wrap” line on fig. 23) covers an area that is most likely to produce hydrocarbons in the future, based on established historical producing trends. Part of this area has been “tested” by virtue of having already been drilled, and the minimum and median estimates of the remaining acreage within this “shrink wrap” area that has the potential for additions to reserves in the next 30 years is 35 percent and 50 percent, respectively.

Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501)

The Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501) in the Green River Total Petroleum System is defined by the distribution of normally pressured conventional oil and associated gas accumulations in reservoir rocks of the Green River Formation at depths less than about 8,500 ft in the Uinta Basin (fig. 20); it physically overlies the entire area of the Deep Uinta Overpressured Continuous Oil AU, which is at depths greater than about 8,500 ft. Examination of wells (Petroleum Information/Dwights LLC, 1999b) in the northern part of the Uinta Basin indicates that wells in the Altamont-Bluebell field produced hydrocarbons from a continuum of depths extending from shallow holes to the deepest holes in the basin. Based on examination of the distribution of pressure-gradient data compared to depth, a cutoff of 8,500 ft was chosen to assign wells to either the overpressured continuous assessment unit for wells greater than 8,500 ft or to the conventional assessment unit for wells shallower than that depth.

The Uinta Green River Conventional Oil and Gas Assessment Unit includes strata that produce oil and associated gas from normally pressured reservoirs in primarily marginal-lacustrine rocks of the Green River Formation and in alluvial rocks of the Wasatch Formation and correlative units. A summary of the characteristics and an evaluation of the assessment unit are presented in the data form (Appendix B), which in this case evaluates the size and distribution of producing fields in the area. Only wells that produced oil and associated gas from the Green River Formation and equivalent rocks were included in this assessment unit (Petroleum Information/Dwights LLC, 1999a). Wells that produced only gas from the Wasatch Formation or its equivalent units were assumed to have been sourced from underlying Mesaverde rocks, and those wells and reservoirs were included in the assessment of the corresponding Cretaceous resources (see Johnson and Roberts, Chapter 7, this CD-ROM). Of the Green River Formation conventional fields in this assessment unit, 15 fields exceeded the minimum field size of 0.5 MMBO that was established for this oil and gas assessment (fig. 24; Appendix A), indicating that it is an established assessment unit. The median size of discovered fields is 2.15 MMBO for the first third of the discovered wells, 2.19 MMBO for the second third, and 1.2 MMBO for the third third (fig. 24), indicating a moderate decline in the field size over time. There is adequate charge, reservoir, traps, seals, access, and timing of generation and migration of hydrocarbons, indicating a geologic probability of 1.0 for finding at least one additional field with a total recovery greater than the stated minimum of 0.5 MMBO (grown).

To estimate the number and size of undiscovered fields, one must examine the size of discovered fields as expressed by the relative geographic size of the reservoirs, their distribution among specific lacustrine facies, and the relative grown sizes of the fields. The distribution of the discovered fields is related to the distribution of the lacustrine facies (fig. 25). Examination of the well file (Petroleum Information/Dwights LLC, 1999a) indicated that for the prescribed parameters of producing oil and associated gas wells, or gas wells, there were 1,840 producing wells and 507 dry holes. This distribution indicates a success ratio of about 73 percent and a dry-hole ratio of about 27 percent, values characteristic of a maturely explored area with uncertainty in identifying stratigraphic traps. The distribution of the producing and dry wells (fig. 25) indicates a pattern in which the reservoirs occur largely in the marginal-lacustrine carbonates and sandstones of the Green River Formation and locally in alluvial sandstones of the Wasatch and Colton Formations. Exploration has extended to peripheral areas adjacent to known production in the marginal-lacustrine facies (fig. 25), but the distribution of dry wells indicates less success in areas distal to proven production. To estimate the number of undiscovered fields in the assessment unit, the general size of the producing fields was applied to untested areas within the marginal-lacustrine map pattern. Only small parts of the eastern and central

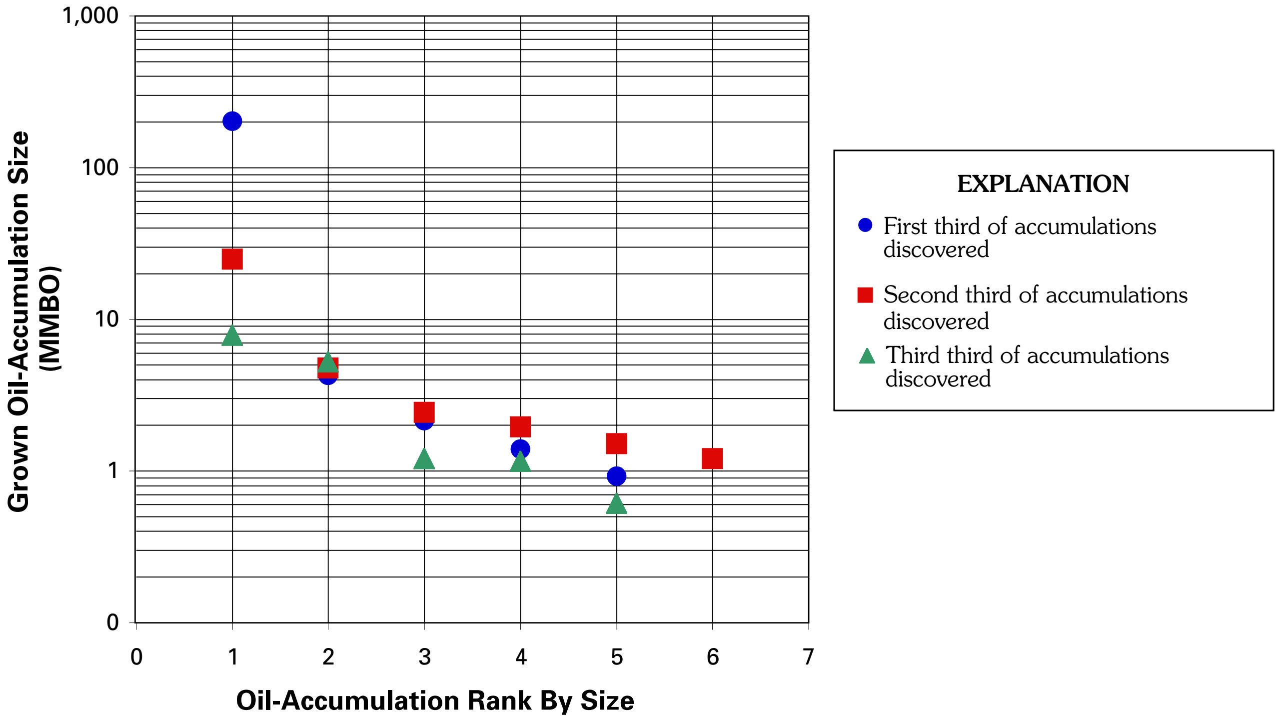


Figure 24. Distribution by thirds of grown oil accumulation size versus rank by size for the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501).

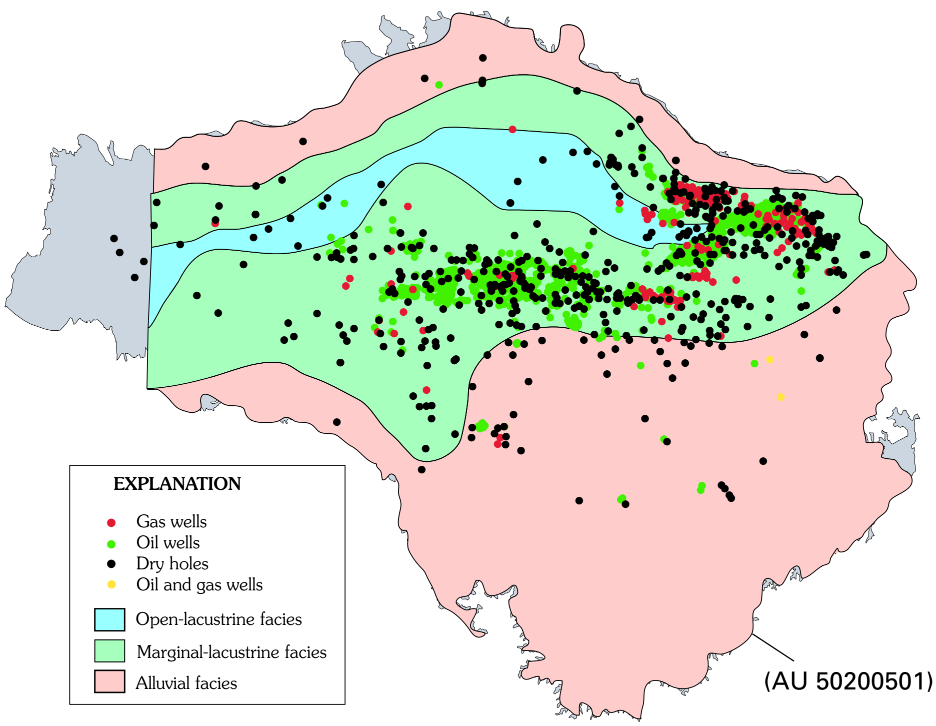


Figure 25. Approximate boundary of the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501) and distribution of lacustrine facies. The lacustrine facies are generalized, depicting the facies at only one point in time, whereas in reality the different facies migrated laterally and interfinger to a great extent. Note that latitude and longitude are not shown and that the locations of the wells have been shifted slightly to alter their exact location due to the proprietary nature of the well-location database. Facies distribution modified from Fouch and others (1992, fig. 25.11).

areas remain untested (fig. 25), leaving little area in which undiscovered fields may exist. Significant untested areas lie in the western and northern parts of the marginal-lacustrine map pattern. Considering the extent of these untested areas, the average spatial size of reservoirs, and the likely future success ratio, an estimate of the undiscovered fields indicates the maximum number of undiscovered fields to be 12, the median number is 6, and the minimum number is 1 (Appendix B).

The size of the undiscovered fields was estimated from the distribution of the discovered field sizes versus the discovery year (figs. 26*A*, *B*). The size of the largest field discovered has decreased steadily over the years. The maximum estimated size for undiscovered fields is 25 MMBO, the median size is 1 MMBO, and the minimum is the established value considered for the assessment of 0.5 MMBO (Appendix B).

Piceance Green River Conventional Oil Assessment Unit (AU 50200502)

The Green River Formation in the Piceance Basin interfingers with and overlies the Wasatch Formation and was deposited in lacustrine environments of Eocene Lake Uinta, similar to the rocks of the Green River Formation in the Uinta Basin. The Green River Formation in the Piceance Basin is more than 5,000 ft thick in the lacustrine depocenter, located a few miles west of the structural axis of the Piceance Basin. Almost all Green River gas produced as of 1990 had been from either marginal-lacustrine rocks deposited during the early freshwater stages or from the basal transgressive bed deposited during the Long Point transgression (Johnson and Rice, 1990). Most gas production in the Green River Total Petroleum System has been from the Piceance Creek Dome field (Johnson and Rice, 1990, figs. 4, 8) in the central part of the basin. This field has produced 133 billion cubic feet of gas (BCFG) through 1986 from basal sandstones in the Green River Formation, but this gas appears to be sourced from the underlying Mesaverde Group and is included in the Mesaverde TPS (see Johnson and Roberts, Chapter 7, this CD-ROM). Gas at the Piceance Creek Dome field is trapped in part by the up-dip pinch out of marginal-lacustrine sandstones into lacustrine shales on the east flank of the dome (Johnson and Rice, 1990, fig. 4). Less than 2.5 BCFG had been produced as of 1990 from the wells in the Green River Formation in other areas of the basin (fig. 27), where the gas appears to be sourced from lacustrine rocks in that formation. This discussion refers only to gas resource considered to be part of the Green River TPS. Gas produced from the Wasatch Formation, as in the previous assessment units, is considered to be sourced from the underlying Cretaceous Mesaverde strata and is included in the assessment of the Mesaverde TPS (see Johnson and Roberts, Chapter 7, this CD-ROM).

Three gas samples from the Green River Formation in the Sulphur Creek structural area of the Piceance Basin are compositionally different from gases analyzed from the Wasatch

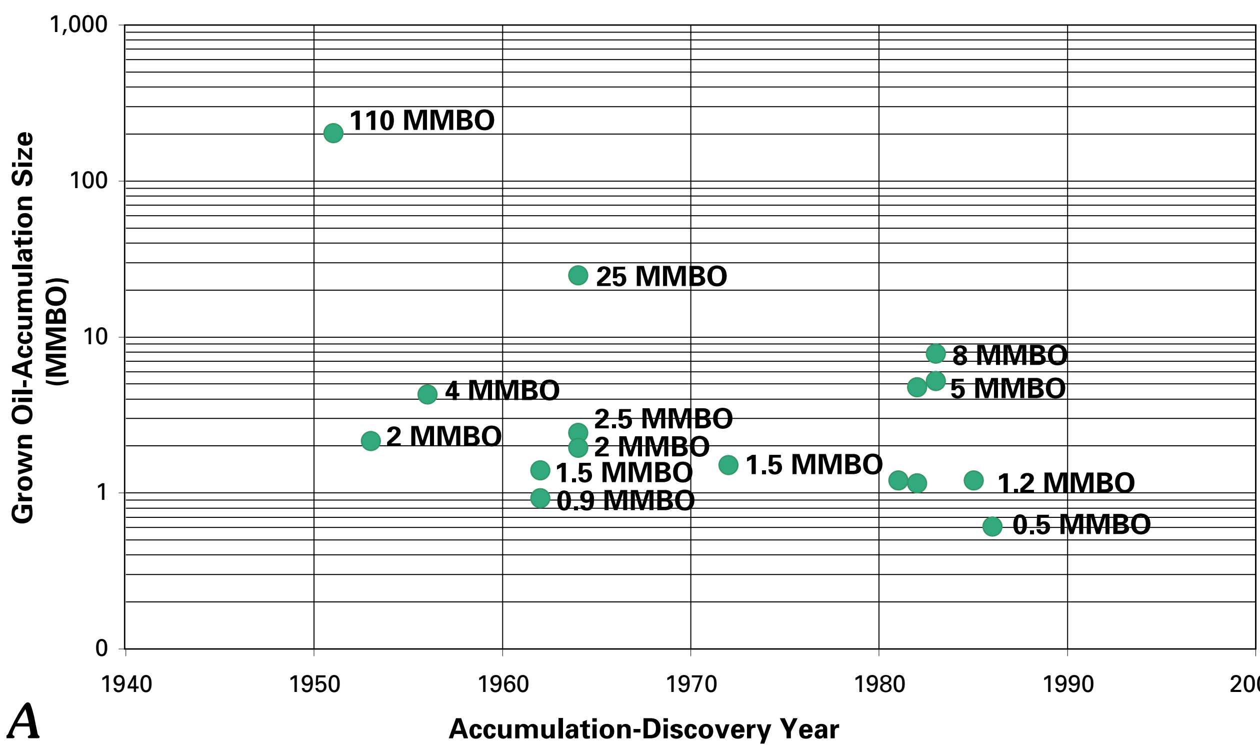


Figure 26*A*. Distribution of grown oil-accumulation size versus accumulation discovery year for the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501).

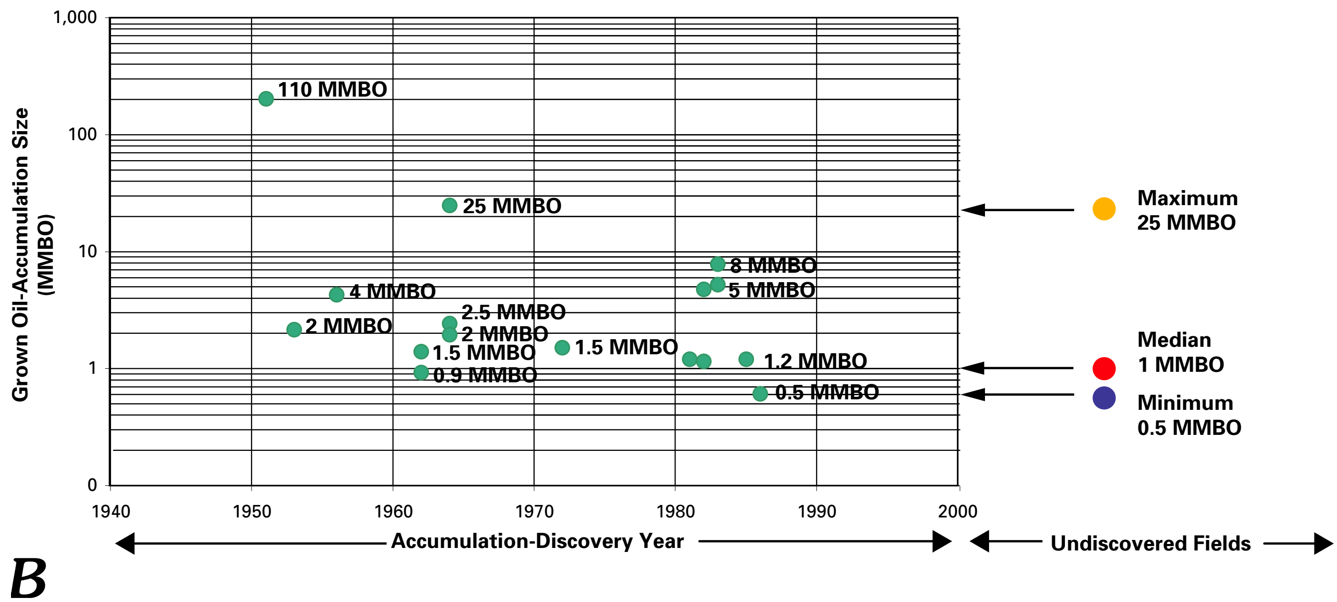


Figure 26*B*. Projections of the maximum, median, and minimum grown field size for undiscovered fields for the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501).

Formation ($\delta^{13}C_1$: -46.3 to –42.9 $^0/_{00}$; C_1/C_{1-5} : 0.95–0.96 (Johnson and Rice, 1990). These isotopic compositions suggest hydrocarbon generation at a mature stage; however, production is from immature to marginally mature reservoirs according to vitrinite reflectance values for the area (see fig. 12). Some oil production also occurs from the Green River Formation in the Piceance Basin, despite the low maturity of the lacustrine source rocks there (see Lillis, Chapter 3, this CD-ROM). This production is likely the result of minor generation of hydrocarbons from the marginally mature organic-rich lacustrine source rocks in the Cow Ridge Member of the Green River Formation.

The Piceance Green River Conventional Oil Assessment Unit includes Tertiary rocks of the Green River Formation in the Piceance Basin. Although there are producing wells (fig. 27), none of the fields exceed the 0.5 MMBO minimum established for this assessment, indicating that this is a hypothetical assessment unit (Appendix C). The requisite source rocks, traps, seals, and access are all present, but the low vitrinite reflectance values for the Green River Formation in the Piceance Basin indicate that charge or generation of hydrocarbons may be lacking; the value for charge is estimated to be a probability of 0.25. This leads to an assignment of geologic probability of 0.25 for at least one new undiscovered field in the Green River TPS in the Piceance Basin, and the assessment unit was not quantitatively assessed.

Assessment of Undiscovered Oil and Gas Resources

The results of the assessments of undiscovered oil and gas resources for conventional and continuous accumulations in the Green River Total Petroleum System are summarized in Appendix D. The Monte Carlo simulations (Charpentier and Klett, Chapter 21, this CD-ROM), verified by the analytical probability method (Crovelli, Chapter 22, this CD-ROM), provide the following results for the three assessment units and their respective types of undiscovered resources (Appendix D).

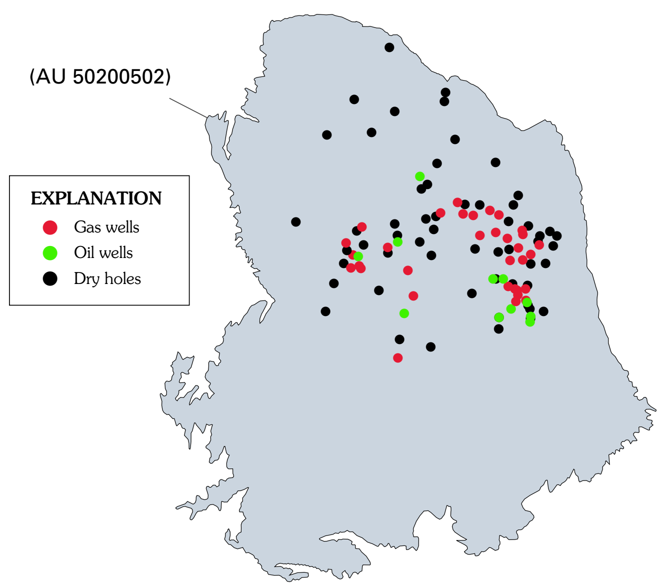


Figure 27. Distribution of the producing wells and dry holes in the Piceance Green River Conventional Oil Assessment Unit (AU 50200502). Note that latitude and longitude are not shown and that the locations of the wells have been shifted slightly to alter their exact location due to the proprietary nature of the well-location database.

Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501)—The estimate of oil in undiscovered conventional fields (all of which would be in this assessment unit) ranges from an F95 (95 percent chance) of 2.74 MMBO to an F5 (5 percent chance) of 20.52 MMBO, with a mean volume of undiscovered oil of 9.63 MMBO. For undiscovered gas resources in this same conventional assessment unit, there is an F95 of 7.59 BCFG and F5 of 63.73 BCFG, with a mean value of 28.88 BCFG.

Piceance Green River Conventional Oil (AU 50200502)—Since this is a hypothetical conventional unit, it was not quantitatively assessed.

Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561)—For continuous oil resources (all of which would be in this assessment unit), there is an F95 of 24.83 MMBO and an F5 of 56.84 MMBO, with a mean value of 38.78 MMBO. For undiscovered gas resources in this continuous assessment unit, there is an F95 of 35.72 BCFG and an F5 of 103.29 BCFG, with a mean value of 63.99 BCFG.

The total undiscovered oil resources for the Green River Total Petroleum System have an F95 of 27.57 MMBO and an F5 of 77.36 MMBO, with a mean value of 48.41 MMBO. The total undiscovered gas resources have an F95 of 43.31 BCFG and an F5 of 167.02 BCFG, with a mean value of 92.87 BCFG.

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Appendix A. Data form for the Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561).

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (Version 4, 10-5-00)

IDENTIFICATION INFORMATION

Assessment Geologist:…	R. F. Dubiel	Date:	10/16/00
Region:……….	North America	Number:	5
Province:……….	Uinta-Piceance	Number:	5020
Total Petroleum System:.	Green River	Number:	502005
Assessment Unit:……	Deep Uinta Overpressured Continuous Oil	Number:	50200561
Based on Data as of:….	PI production data current through third quarter 1999		
Notes from Assessor….			

CHARACTERISTICS OF ASSESSMENT UNIT (A.U.)

Assessment-Unit type: **Oil** (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Oil

What is the minimum total recovery per cell?… 0.003 (mmbo for oil A.U.; bcfg for gas A.U.)

Number of evaluated cells:……. 942

Number of evaluated cells with total recovery per cell ≥ minimum: ….. 849

Established (>24 cells ≥ min.) X Frontier (1-24 cells) ____ Hypothetical (no cells) ____

Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)

1st 3rd discovered 0.35 2nd 3rd 0.18 3rd 3rd 0.1

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum ….	1.0
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.0
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum……	1.0

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

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ………………………. . 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN NEXT 30 YEARS

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
minimum 641,000 median 713,000 maximum 784,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres):
(values are inherently variable) minimum 80 median 305 maximum 640

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 34 median 58 maximum 77

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
(uncertainty of a fixed value) minimum 35 median 50 maximum 80

Appendix A—Continued. Data form for the Deep Uinta Overpressured Continuous Oil Assessment Unit (AU 50200561).

Assessment Unit (name, no.) Deep Uinta Overpressured Continuous Oil, 50200561

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:
(values are inherently variable)
(mmbo for oil A.U.; bcfg for gas A.U.) minimum 0.003 median 0.045 maximum 0.45

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS

(uncertainty of a fixed value)

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)........	825	1650	2475
NGL/gas ratio (bngl/mmcfg)........	35	70	105
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)........			

SELECTED ANCILLARY DATA FOR UNTESTED CELLS

(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)........	31	37	42
Sulfur content of oil (%)........	0	0.1	0.2
Drilling depth (m)	2500	4000	6280
Depth (m) of water (if applicable)........			
Gas assessment unit:			
Inert-gas content (%)........			
CO_2 content (%)........			
Hydrogen-sulfide content (%)........			
Drilling depth (m)........			
Depth (m) of water (if applicable)........			

Appendix B. Data form for the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501).

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 2, 10-5-00)

IDENTIFICATION INFORMATION

Date:...........	10/16/00		
ssessment Geologist:.....	R.F. Dubiel		
Region:...........	North America	Number:	5
Province:...........	Uinta-Piceance	Number:	5020
Priority or Boutique.......			
Total Petroleum System:....	Green River	Number:	502005
ssessment Unit:.......	Uinta Green River Conventional Oil and Gas	Number:	50200501
Based on Data as of:.....	NRG Associates through 1998		
* Notes from Assessor	Function e2, U.S. Lower 48 States Conventional Growth Functior		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **o** Gas (≥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: 15 Gas: 0
Established (>13 fields) X Frontier (1-13 fields) ____ Hypothetical (no fields) ____

Median size (grown) of discovered oil fields (mmboe):
1st 3rd 2.15 2nd 3rd 2.19 3rd 3rd 1.2
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:** dequate petroleum charge for an undiscovered field ≥ minimum size........	1.0
2. **ROCKS:** dequate 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

ssessment-Unit GEOLOGIC Probabilit (Product of 1, 2, and 3):............... . 1.0

4. **ACCESSIBILITY:** dequate location to allow exploration for an undiscovered fielc ≥ 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)

	min. no. (>0)	median no.	max no.
Oil fields:............	1	6	12
Gas fields:............	0	0	0

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

	min. size	median size	max. size
Oil in oil fields (mmbo)..........	0.5	1	25
Gas in gas fields (bcfg):.........			

Appendix B—Continued. Data form for the Uinta Green River Conventional Oil and Gas Assessment Unit (AU 50200501).

Assessment Unit (name, no.)
Uinta Green River Conventional Oil and Gas, 50200501

AVERAGE RATIOS FOR UNDISCOVERED FIELDS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil Fields:	minimum	median	maximum
Gas/oil ratio (cfg/bo)........	1500	3000	4500
NGL/gas ratio (bngl/mmcfg)........	30	60	90

Gas fields:	minimum	median	maximum
Liquids/gas ratio (bngl/mmcfg)........			
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	35	40
Sulfur content of oil (%)........	0	0.1	0.31
Drilling Depth (m)	475	1500	2750
Depth (m) of water (if applicable)........			

Gas Fields:	minimum	median	maximum
Inert gas content (%)........			
CO_2 content (%)........			
Hydrogen-sulfide content (%)........			
Drilling Depth (m)........			
Depth (m) of water (if applicable)........			

Appendix C. Data form for the Piceance Green River Conventional Oil Assessment Unit (AU 50200502)

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 2, 10-5-00)

IDENTIFICATION INFORMATION

Date:..........	10/16/00		
Assessment Geologist:.....	R.F. Dubiel		
Region:..........	North America	Number:	5
Province:..........	Uinta-Piceance	Number:	5020
Priority or Boutique.......			
Total Petroleum System:....	Green River	Number:	502005
Assessment Unit:.......	Piceance Green River Conventional Oil	Number:	50200502
Based on Data as of:.....	NRG Associates through 1998		
* Notes from Assessor			

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥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: 0 Gas: 0
Established (>13 fields) ______ Frontier (1-13 fields) ______ Hypothetical (no fields) X

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........	0.25
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):............. 0.25

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) ______ median no. ______ max no. ______
Gas fields:.............min. no. (>0) ______ median no. ______ max no. ______

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 ______ median size ______ max. size ______
Gas in gas fields (bcfg):.........min. size ______ median size ______ max. size ______

Appendix C—Continued. Data form for the Piceance Green River Conventional Oil Assessment Unit (AU 50200502)

Assessment Unit (name, no.)
Piceance Green River Conventional Oil, 50200502

AVERAGE RATIOS FOR UNDISCOVERED FIELDS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil Fields:	minimum	median	maximum
Gas/oil ratio (cfg/bo)........			
NGL/gas ratio (bngl/mmcfg)........			

Gas fields:	minimum	median	maximum
Liquids/gas ratio (bngl/mmcfg)........			
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)........			
Sulfur content of oil (%)........			
Drilling Depth (m)			
Depth (m) of water (if applicable)........			

Gas Fields:	minimum	median	maximum
Inert gas content (%)........			
CO_2 content (%)........			
Hydrogen-sulfide content (%)........			
Drilling Depth (m)........			
Depth (m) of water (if applicable)........			

Appendix D. Summary of assessment results for conventional and continuous assessment units of the Green River Total Petroleum System.

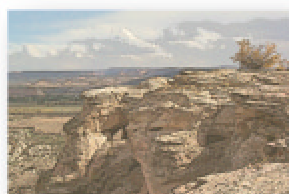
[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MAS, minimum accumulation size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one accumulation equal to or greater than the MAS or, for continuous-type resources, at least one additional cell equal to or greater than the minimum estimated ultimate recovery. Accum., accumulation. Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. A single major commodity and its coproducts were assessed for continuous-type assessment units. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable.]

Code Accumulation Type	MAS	Prob. (0-1)	Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
502005 Total: Conventional undiscovered resources in the Green River Total Petroleum System														
Oil Accums.	0.5	1.00	2.74	8.52	20.52	9.63	7.59	24.83	63.73	28.88	0.42	1.45	3.98	1.73
Gas Accums.	3.0						0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		1.00	2.74	8.52	20.52	9.63	7.59	24.83	63.73	28.88	0.42	1.45	3.98	1.73
502005 Total: Continuous-type (undrilled) resources in the Green River Total Petroleum System														
Oil Accums.		1.00	24.83	37.57	56.84	38.78	35.72	60.74	103.29	63.99	2.23	4.17	7.79	4.48
Gas Accums.							0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		1.00	24.83	37.57	56.84	38.78	35.72	60.74	103.29	63.99	2.23	4.17	7.79	4.48

Appendix D—Continued. Summary of assessment results for conventional and continuous assessment units of the Green River Total Petroleum System.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MAS, minimum accumulation size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one accumulation equal to or greater than the MAS or, for continuous-type resources, at least one additional cell equal to or greater than the minimum estimated ultimate recovery. Accum., accumulation. Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. A single major commodity and its coproducts were assessed for continuous-type assessment units. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable.]

Code Accumulation Type	MAS	Prob. (0-1)	Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
50200501	Uinta Green River Conventional Oil and Gas Assessment Unit													
Oil Accums.	0.5	1.00	2.74	8.52	20.52	9.63	7.59	24.83	63.73	28.88	0.42	1.45	3.98	1.73
Gas Accums.	3.0						0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		1.00	2.74	8.52	20.52	9.63	7.59	24.83	63.73	28.88	0.42	1.45	3.98	1.73
50200502	Piceance Green River Conventional Oil Assessment Unit													
	NOT QUANTITATIVELY ASSESSED													
50200561	Deep Uinta Overpressured Continuous Oil Assessment Unit													
Oil Accums.		1.00	24.83	37.57	56.84	38.78	35.72	60.74	103.29	63.99	2.23	4.17	7.79	4.48



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