Chapter 1

Assessment of In-Place Oil Shale Resources of the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah



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Volume Title Page

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Chapter 1 of 6

Oil Shale Resources of the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah

By U.S. Geological Survey Oil Shale Assessment Team

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Assessment of In-Place Oil Shale Resources in the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah

By Ronald C. Johnson, Tracey J. Mercier, Robert T. Ryder, Michael E. Brownfield, and Jesse G. Self

Abstract

An assessment of in-place oil shale resources of the Eocene Green River Formation, regardless of grade, was conducted in the Greater Green River Basin of Wyoming, Colorado, and Utah. However, no attempt was made to estimate the amount of oil that is economically recoverable, largely because there has not yet been an economic method developed to recover the oil. The Radial Basis Function method was used to generate the isopach maps, resource maps, and resource estimates. The three units assessed here are, in ascending order, the Tipton Shale Member, the Wilkins Peak Member, and the LaClede Bed of the Laney Member. Four maps were generated for each zone: (1) isopach map, (2) isoresource map showing variations in gallons per ton, (3) isoresource map showing variations in barrels per acre, and (4) isoresource map showing total amount of in-place oil in each 6-mile by 6-mile township. Total in-place resources for the three assessed units are: (1) Tipton Shale Member, 362,816 million barrels of oil (MMBO), (2) Wilkins Peak Member, 704,991 MMBO, and (3) LaClede Bed of the Laney Member, 377,184 MMBO, for a total of 1.44 trillion barrels of oil in place. This compares with estimated in-place resources for the Piceance Basin of Colorado of 1.53 trillion barrels and estimated in-place resources for the Uinta Basin of Utah and Colorado of 1.32 trillion barrels. The assessed area of the Greater Green River Basin–about 5,500 mi^2, however, is about 1.4 times larger than the assessed area of the Uinta Basin (3,834 mi^2) and more than four times larger than the assessed area of the Piceance Basin (1,335 mi^2).

Introduction

This report presents an assessment of all in-place oil shale resources of the Eocene Green River Formation, regardless of grade, in the Greater Green River Basin of southwestern Wyoming, northwestern Colorado, and northeastern Utah (figs. 1 and 2). Green River oil shale is also present in the Piceance Basin of western Colorado and the Uinta Basin of eastern Utah and western Colorado (fig. 1), and the results of these assessments are published separately (Johnson and others, 2010a, b).

A considerable amount of oil-yield data was collected subsequent to the previous assessments, making it possible to better assess in-place resources. Furthermore, there have been major advances in computational power and computer programming since the last assessments were published, and these were used to the extent possible for our assessment. All of the Fischer assay data, location data, and tops file were assembled into one Access database (Mercier and others, this report, chapter 6) similar to the one recently published for the Piceance Basin (Mercier, 2010). Due to the number of data records and the complexity of the spatial data involved in the assessment, Microsoft Access database management software and ESRI's ArcGIS software were used to combine, store, and analyze the raw data. The ability to create custom forms in Access was a crucial element in the assessment methodology, as it allowed us to write Visual Basic scripts and SQL statements to filter subsets of the data and perform the necessary calculations using Access form controls. The public benefits from this process, as the original forms used to calculate resources also serve as the end-user interface to view the raw data in a more simplified and meaningful manner. After resources were calculated for each core hole, the resultant Access tables were linked seamlessly with ESRI's ArcGIS software to model, extrapolate, and quantify the data spatially. The end product is a large database of tables (spreadsheets), forms to view the data, and a series of maps quantifying the results of those calculations. For a complete description of the process used for our resource assessment, see Mercier and others (chapter 6, this report).

In our assessment, we tried two extrapolation methods for spatial interpolation that are easier for a non-statistician to apply: the Radial Basis Function (RBF) method, and the Inverse Distance Weighted (IDW) method. Both methods gave similar results and we ultimately decided on the RBF method, which was recently demonstrated to give comparable results to those obtained from kriging (Rusu and Rusu, 2006).

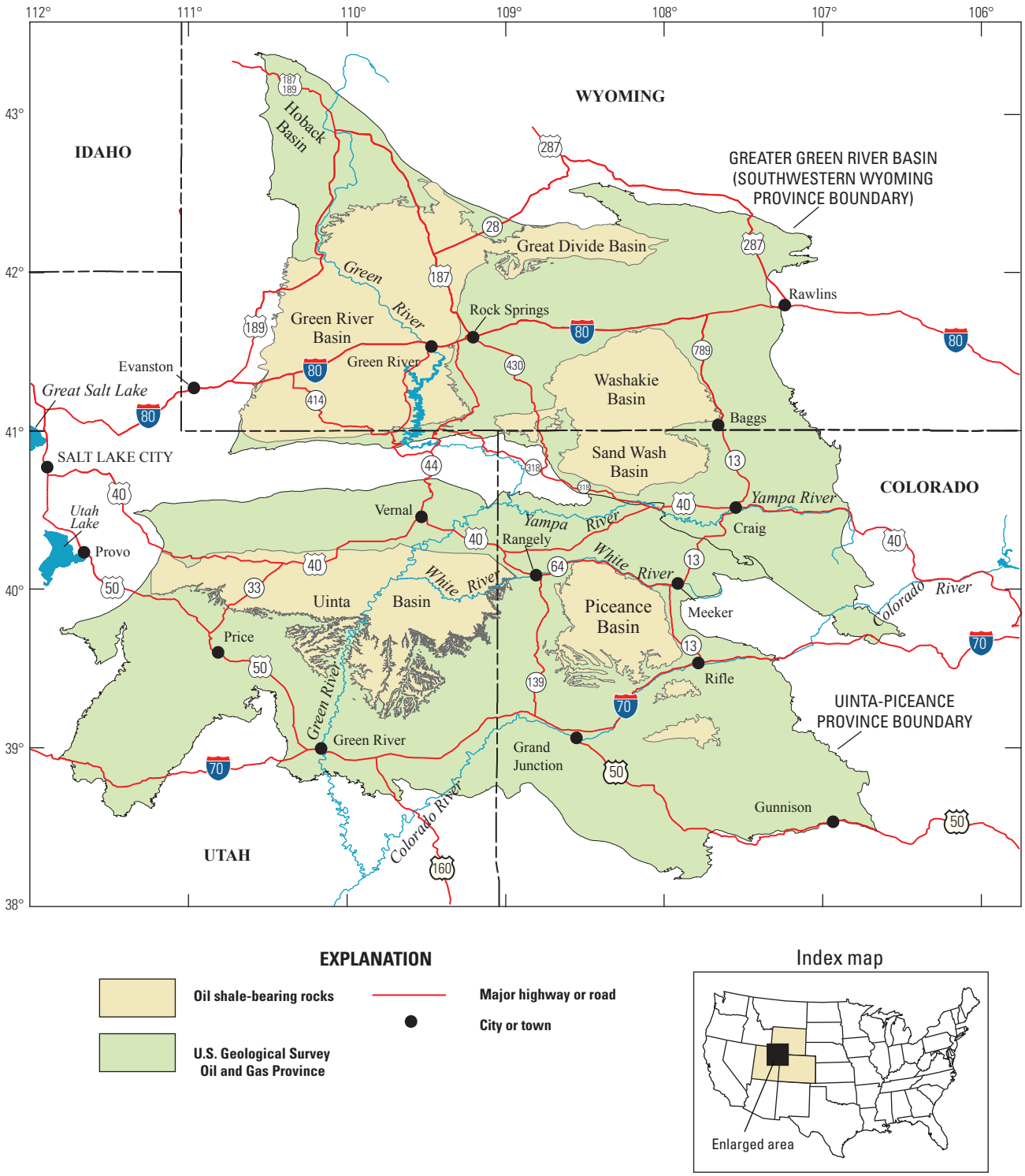
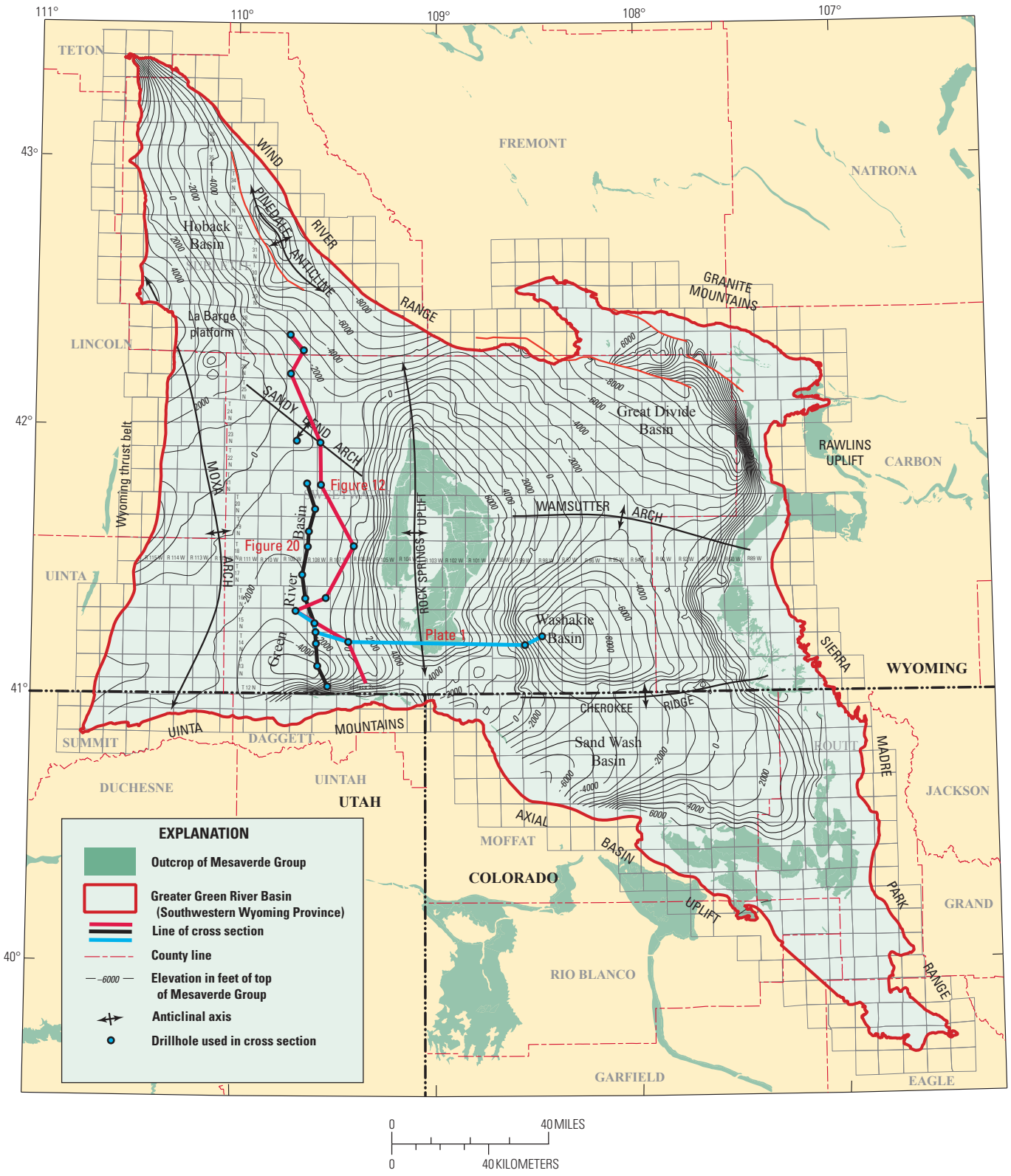


Figure 1. Extent of Uinta-Piceance and Greater Green River structural and sedimentary basin.


111°
110°
109°
108°
107°
43°
42°
41°
40°
TETON
FREMONT
NATRONA
LINCOLN
UINTA
SUMMIT
DAGGETT
DUCHESNE
UINTAH
UTAH
COLORADO
MOFFAT
RIO BLANCO
GARFIELD
EAGLE
CARBON
SWEETWATER
SUBLETTE
SUBLETTE
SUBLETTE

This overall effort has been hampered by difficulties in recovering the digital files that were used in the previous assessments both by the U.S. Geological Survey (USGS) and the former U.S. Bureau of Mines (USBM). The USBM was disbanded in 1996, and the considerable amount of oil shale data stored on its computers is, at present, not accessible. From the late 1940s to the early 1980s, the former USBM analyzed many cores and cuttings from holes drilled in Green River oil shale deposits in the three-state area using the Fischer assay method, a standardized laboratory test for determining oil yield from oil shale. During the 1970s and 1980s, the USBM and USGS each prepared digital databases of Fischer assays of the Green River oil shale deposits, and these data were made available to the public through the National Technical Information Service (NTIS) (Pitman, 1982; Pitman and Van Trump, 1974, 1975). However, it was later discovered that these tapes had degraded in storage and could no longer be read.

In the early 1990s, the U.S. Department of Energy (DOE) and the USGS initiated a cooperative project to create a digital National Oil Shale Database (NOSDB) that would combine all available Fischer assay information in the possession of the USBM and the USGS and prepare it for publication. The original assay data sheets were scanned and saved as Adobe PDF files. As a result of this effort, Fischer assay data for boreholes in all three basins–Piceance, Uinta, and Greater Green River–have now been published (Dyni, 1998; Dyni and others, 2006, 2008). Oil-yield histograms that plot variations in oil yield with depth have also been published for the Greater Green River Basin (Brownfield and others, 2008).

The reconstructed Fischer assay files constitute the foundation of this present assessment. In order to assess individual oil shale units in the basin, however, a file listing the tops and bases of the various oil shale units in all the drill holes used in the assessment was also needed. Such a file for the Green River Basin was not known to exist, so a new digital tops file was generated. A series of cross sections constructed to aid in this effort are published as chapter 5 of this report (Ryder and others, 2010).

The Fischer assay method is a standardized laboratory test that has been almost universally used to determine oil yields from oil shale, including the Green River Formation oil shales (Stanfield and Frost, 1949; American Society for Testing Materials, 1984). The Fischer assay standard method consists of heating a crushed and screened (-8 mesh (2.38-mm mesh))100-gram sample in a small aluminum retort to 500°C at a rate of 12°C per min and then holding it at that temperature for 40 min. The volatile vapors of shale oil, gas, and water pass through a condenser cooled with ice water (about 5°C) and collected in a graduated centrifuge tube. The oil and water are then separated by centrifuging and weighed. The quantities reported in the original sample are the weight percentages of shale oil, water, shale residue (contains carbon char), and "gas plus loss" (noncondensable gas yield) by difference. The specific gravity of the shale oil is measured and used to calculate the oil yield in gallons per ton (GPT).

The Fischer assay method does not determine the total amount of hydrocarbons in an oil shale sample, and the method does not measure the amount or composition of the gases released during the heating of the sample. These gases—chiefly light hydrocarbons, hydrogen, and carbon dioxide—are reported as the "gas plus loss."

Fischer assay does not necessarily measure the maximum amount of oil that an oil shale can produce, and there are retorting methods that yield more than the Fischer assay yield (see Dyni, 2003, p. 196–196 for a discussion of methods to determine oil yields). However, the oil yields achieved by other technologies are typically reported as a percentage of the Fischer assay oil yield, and thus Fischer assay is still considered the standard by which other methods are compared.

Much of the Fischer assay data for the Greater Green River Basin is not from core holes drilled to evaluate oil shale resources but rather from cuttings collected from oil and gas tests. The cuttings analyses are quite old, mainly from the 1950s and 1960s, and were done to supplement the limited core data available at the time. Although a significant number of oil shale core holes were drilled subsequent to the previous assessments of the Greater Green River Basin, there are still large areas where only cuttings data are available and in which resources could not be estimated using core data alone. There are, however, significant problems with cuttings data. Oil shale core is generally sampled every foot or so for Fischer assay. The sampling interval for rotary drill hole cuttings, in contrast, varies from about 5 ft to possibly as much as 50 ft, thus much of the detail of oil yield variation is lost. Up-hole cavings also pose a problem; average oil yield for rich zones is greater than the overlying strata, thus cavings from overlying leaner zones could dilute the samples resulting in a lowering of the average GPT. In like manner, cuttings from lean zones would be contaminated by cuttings from richer zones above resulting in an increase in oil yield as observed. This was recently demonstrated for cuttings data in the Uinta Basin of Wyoming and Colorado (Johnson and others, 2010 b). When a rotary hole is drilled, there is always a delay between the time the drill bit produces the cuttings and when the cuttings reach the surface. Drillers try to compensate for this delay, but they are not always entirely successful. A comparison between the geophysical logs and plots of the Fischer assay results revealed many relatively minor discrepancies in log depths and cuttings depths for oil shale zones. To minimize this problem, the depths at which oil shale zones appear in the cuttings based on Fischer assay were used in this assessment rather than the log depths.

Previous Assessments of the Greater Green River Basin

Trudell and others (1973) reported that several members of the Green River Formation along the west flank of the Washakie Basin contained significant oil shale resources but

did not attempt to estimate resources in the entire Washakie Basin due to a lack of subsurface control. Culbertson and others (1980) assessed only the Green River Basin (figs. 1 and 2) and only those resources that averaged at least 15 ft thick and 15 GPT. Culbertson and others (1980) separately assessed the oil shale resources of the three oil shale-bearing members of the Green River Formation**:** Tipton Shale Member, Wilkins Peak Member, and Laney Member (fig. 3), using oil-yield data from 32 cores, 40 rotary holes, and results from two channels cut in outcrops. Intervals thinner than 15 ft were included if they were sufficiently rich as to yield at least the same amount of oil as 15 ft of 15 GPT shale (about 17,300 barrels per acre). In some cases, the method resulted in the inclusion of significantly thick intervals of very low grade oil shale that would probably be discarded during the mining operation. As a result Culbertson and others (1980) eliminated lean intervals that were generally more than 10 ft thick.

Culbertson and others (1980) had to contend with a sparse data set that included many drill holes in which only part of an oil shale zone had been recovered or only part of a core had been assayed. They filled in the missing data by "extrapolation of nearby core data or from the lithologic description of the unassayed core, or by using geophysical logs (sonic, neutron, density), where available." In areas where no assay data were available, both geophysical logs and outcrop measurements were used. Based on these kinds of data, estimated in-place oil was estimated at 123 billion barrels in the Tipton Shale Member, 100.5 billion barrels in the Wilkins Peak Member, and 20.5 billion barrels in the Laney Member. Culbertson and others (1980, p. 14) also divided the resource into "demonstrated" which included resources near closely spaced cores and "inferred."

Culbertson and others (1980) manually calculated their resource numbers. Pitman and others (1989), in their assessment of the in-place oil shale resources of the Piceance Basin in western Colorado, used geostatisticial interpolation by kriging to generate resource maps and resource numbers. However, kriging requires an understanding of advanced statistical concepts and tools, and completely false results can be obtained if not done correctly. Pitman and others (1989) found that the method gave good results in areas with large numbers of control points, but that it produced unrealistic resource numbers with unreasonably large error limits in areas with little control. They resorted to manual contouring and calculation of resources in these problem areas.

Geology of the Eocene Green River Formation and Related Strata, Greater Green River Basin

The Greater Green River Basin is a structural and sedimentary basin formed during the Laramide orogeny (Late Cretaceous through Eocene). It is bounded on the north by the Wind River Range and Granite Mountains; on the east by the Rawlins uplift, Sierra Madre, and Park Range; on the south by the Axial Basin uplift and Uinta Mountains; and on the west by the Wyoming and Utah portions of the Wyoming thrust belt. (fig. 2). The basin is subdivided by broad structural arches into five sub-basins, the Green River, Great Divide, Sand Wash, Washakie, and Hoback Basins (fig. 2). Arches include the Rock Springs uplift, the Cherokee ridge, Moxa arch (and La Barge platform), Wamsutter arch, and Sandy Bench arch (fig. 2). The term "Bridger Basin" is commonly applied to the Green River Basin (for example, Surdam and Stanley, 1979). The term Hoback Basin is not always used and is generally confined to a limited area in the extreme northwestern part of the Greater Green River Basin (fig. 2). As used here, the Green River Basin is applied to that part of the Greater Green River Basin lying west of the Rock Springs uplift and south of the Hoback Basin (fig. 2). It includes all the oil shale deposits of the Green River Formation west of the Rock Springs uplift.

The stratigraphy of the Green River Formation and associated rocks in the Greater Green River Basin is highly variable and complex (fig. 3). Only a brief discussion is included here, but detailed descriptions are given in many of the references that are cited herein (for example, Smith and others, 2008). There are many excellent recent studies covering various aspects of the Green River Formation in the Greater Green River Basin (for example, Smith and others, 2008). For our purpose, we used the work of Roehler (1992a; 1992b; 1993) as a primary source of data, as it represents the latest comprehensive synthesis of the stratigraphic framework of the entire Green River Formation in the Greater Green River Basin including detailed measured sections and cross sections, paleogeographic maps, and isopach maps.

The Green River Formation in the Greater Green River Basin was deposited in Eocene Lake Gosiute, a long-lived lake that occupied varying parts of the Greater Green River Basin from about 52.5 to 47.5 Ma (Smith and others, 2008). Paleogeographic maps presented here, representing various time periods in the development of Lake Gosiute, are from Roehler (1993), and isopach maps included with these reconstructions are from Roehler (1992b). The reconstructions and isopach maps were originally published separately, but are combined here. Isopach maps were also constructed for assessment purposes using the tops file that we assembled supplemented by surface sections measured by Roehher (1989a–e). These isopach maps are of different stratigraphic intervals than those constructed by Roehler (1992b).

Lake Gosiute underwent two expansive periods, one early and one late in its history, during which the lake expanded to cover much of the Greater Green River Basin. A prolonged period, during which the lake contracted to a comparatively small area, separated these two expansive periods. The early expansion is represented by the Tipton Shale Member, the contracted period is represented by the Wilkins Peak Member, and the later expansion is represented by the Laney Member (fig. 3; pl. 1). Significant oil shale was deposited during all three periods. However, oil shales in the Tipton Shale and

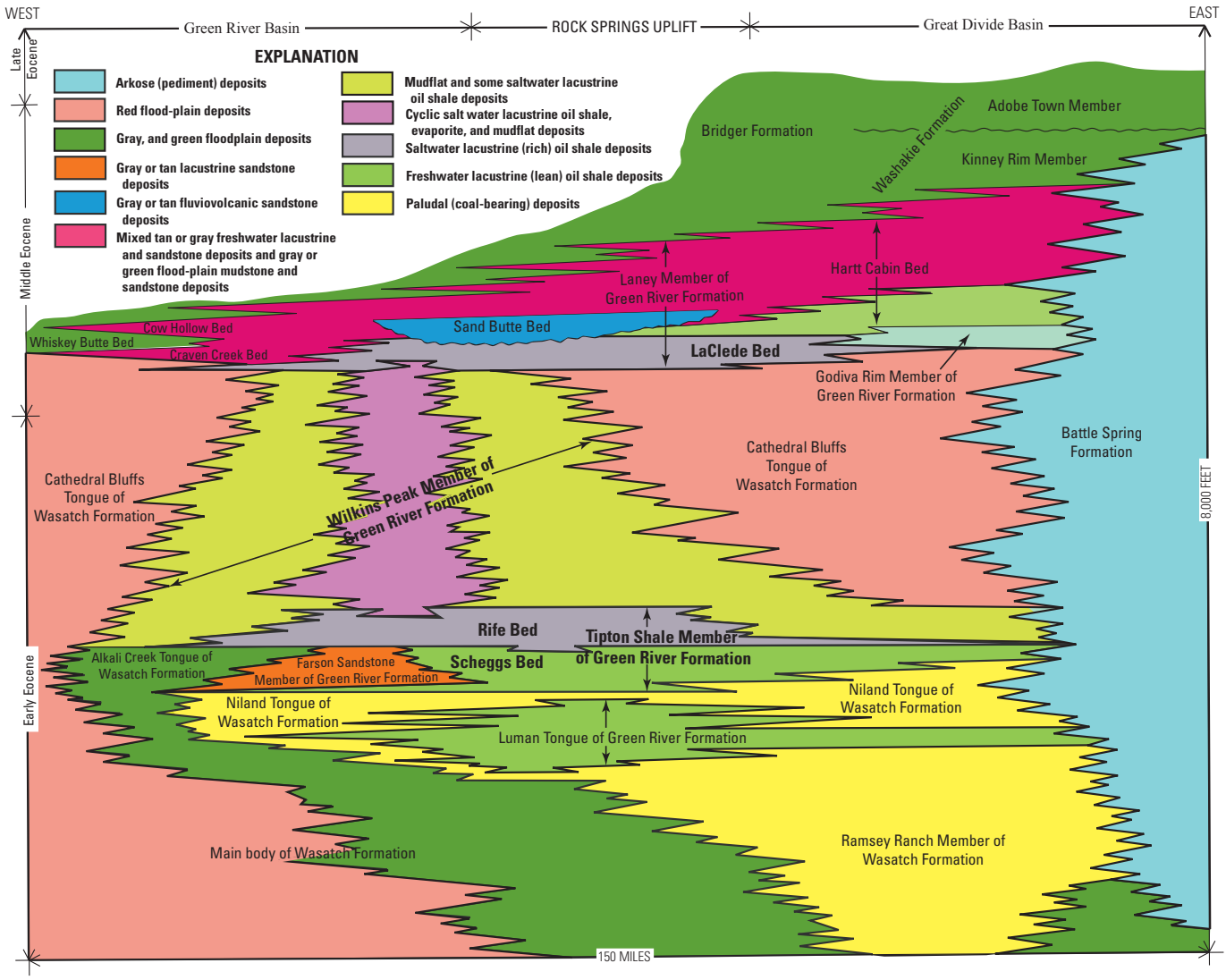


Figure 3. Generalized east-west cross section of Eocene rocks in the Greater Green River Basin.

Laney Members are in thick continuous intervals over large areas of the basin, whereas oil shales in the Wilkins Peak Member are restricted to a much smaller area and are, for the most part, interbedded with sandstone, mudstone, and the saline minerals trona (a sodium bicarbonate mineral), shortite (sodium calcium carbonate), and halite (pl. 1). Although most of the oil shale in the Greater Green River Basin is in the Tipton Shale, Wilkins Peak, and Laney Members, low-grade oil shale is also present in the freshwater Lumen Tongue of the Green River Formation below the Tipton (fig. 3). Oil shale resources in these rocks are not assessed here due to a lack of data, but these rocks will be described briefly. Units of the Green River Formation and intertonguing strata of the Wasatch Formation will be described from oldest to youngest.

Ramsey Ranch Member of the Wasatch Formation

Widespread lacustrine conditions first developed in the Greater Green River Basin during deposition of the Ramsey Ranch Member of the Wasatch Formation (figs. 3 and 4). Swamps, small shallow freshwater lakes and numerous ponds developed in the southernmost part of the basin north of the Uinta Mountains and into the central parts of the Washakie and Great Divide Basins (fig. 4). Carbonaceous shale, coal, freshwater limestone, and oil shale were deposited in these fresh-water lakes and ponds (Roehler, 1993). The Ramsey Ranch Member is more than 600 ft thick in the trough north of the Uinta Mountains and more than 800 ft in the center of

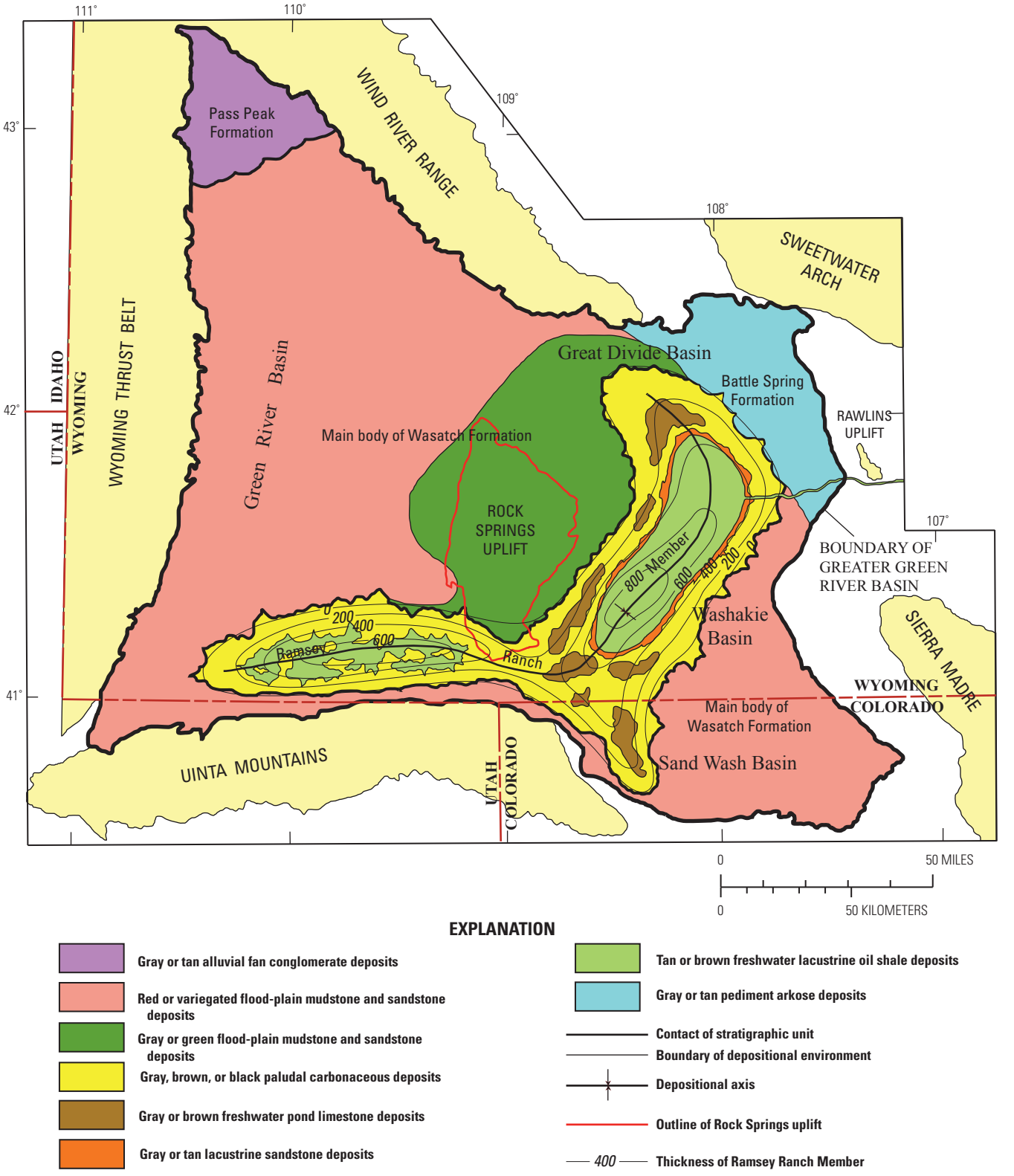


Figure 4. Paleogeographic map of the Ramsey Ranch Member of the Wasatch Formation.

the Washakie Basin. It thins to less than 400 ft across the south part of the Rock Springs uplift (fig. 4).

Lumen Tongue of Green River Formation

The freshwater lakes and ponds expanded and coalesced during deposition of the Lumen Tongue of the Green River Formation (figs. 3 and 5) (Roehler 1993). The Lumen stage of Lake Gosiute, at its maximum extent, covered about 6,650 mi^2 of the Washakie and Great Divide Basins, the western part of the Sand Wash Basin and the southern part of the Green River Basin (fig. 5, Roehler, 1993). The freshwater Lumen Tongue varies from about 200 to 400 ft thick along the trough, north of the Uinta Mountains and in the Washakie Basin (fig. 5). It consists of clay-rich oil shale, mollusk-bearing sandstone and limestone, carbonaceous shale with thin coal beds, and siltstone deposited mainly in lacustrine environments (Pipiringos, 1961; Roehler, 1993). Molluscs are freshwater types, consisting mainly of the gastropods *Goniobasis terera* and *Viviparus* sp., and the pelecypod *Lampsilis* sp. Roehler (1993, p. F38) believed that Lake Gosiute during the Lumen stage drained southward near the east end of the Uinta Mountains and into the Piceance Basin to the south. Johnson (1985) noted similarities between the Lumen Tongue of the Green River Formation and the Cow Ridge Member of the Green River Formation, a roughly contemporaneous freshwater lake phase in the Piceance and Uinta Basins.

Low-grade oil shales were deposited throughout much of the lake during Lumen time (fig. 5). There has been little Fischer assay data collected for the Lumen Tongue and it has not been the target of an oil shale project. The unit was assayed in the Farmers Union Twin Buttes Unit 1 well in sec. 33, T. 14 N., R. 106 W., in the trough of the Green River Basin north of the Uinta Mountains where it is 380 ft thick and averaged 9.2 GPT. One 30-ft-thick interval in the lower part of the Lumen averaged 26.7 GPT, with a maximum reading of 31.6 GPT. It appears that the tongue includes significant oil shale in the subsurface north of the Uinta Mountains, but at present there is too little information to assess it.

Niland Tongue of Wasatch Formation

The Niland Tongue of the Wasatch Formation lies between the Lumen Tongue and the Tipton Shale Member of the Green River Formation and represents a contraction of lacustrine deposition from the preceeding Lumen phase into a comparatively small area north of the Uinta Mountains and in the trough of the Washakie and Great Divide Basins (figs. 3 and 6). Maximum thickness is about 400 ft along the trough north of the Uinta Mountains and in the Washakie Basin (fig. 6). In the Great Divide Basin, the Niland Tongue consists of coal beds, clay shale, siltstone, sandstone, and low-grade oil shale (Pipiringos, 1961). It grades laterally into variegated mudstones and sandstones of the main body of the Wasatch Formation. Samples were assayed in the Farmers Union Twin Buttes Unit 1 well mentioned above, where the unit is 170 ft thick and averages 7.3 GPT; it does not appear to contain oil shale of high enough grade to be considered a resource.

Tipton Shale Member of the Green River Formation

The Tipton Shale Member is the oldest member of the Green River Formation in the Greater Green River Basin that contains widespread oil shale of sufficient grade to have been considered for oil shale development. The member has been subdivided into the lower Scheggs Bed and the upper Rife Bed (Roehler, 1991a), which are separated by the Farson Sandstone Member of the Green River Formation (fig. 3). Maximum expansion during Tipton time was during deposition of the Scheggs Bed, when Lake Gosiute expanded to cover most of the Greater Green River structural and sedimentary basin (fig. 7). Lake Gosiute was freshwater during deposition of the Scheggs Bed, as freshwater mollusks are present in lake-margin deposits. Roehler (1993, his fig. 50) believed that Lake Gosiute drained southward into Lake Uinta during deposition of the Scheggs Bed, keeping the lake's waters fresh. By the beginning of deposition of the Rife Bed, Lake Gosiute had significantly shrunk in size, the outlet had been lost, and the lake waters evolved from fresh to saline (Roehler, 1993, p. F43).

The Scheggs Bed consists, in offshore areas, of mostly brown-weathering, clay-rich oil shale with a few beds of thin tuff (Roehler, 1991a) (fig. 7). In lake-margin areas, it includes limestone, dolomite, conglomerate, sandstone, siltstone, carbonaceous shale, and coal (Roehler, 1991a). The bed is more than 200 ft thick along the trough of the Green River Basin just north of the Uinta Mountains, exceeds 300 ft in the troughs of the Washakie and Sand Wash Basins (fig 7), and is less than 50 ft thick throughout the northern part of the Green River Basin and Great Divide Basin (fig 7). The upper part grades into the Farson Sandstone Member toward the north in the Green River Basin. Two stacked sandy shoreline sequences consisting of, in ascending order, nearshore, strandline, swamp, mudflat, and fluvial channel have been described in the upper part of the Scheggs Bed along the southeast margin of the Sand Wash Basin (Roehler, 1990a). Total thickness of the two shoreline sequences is about 200 ft. Late in the deposition of the Scheggs Bed, marginal lacustrine sandstone of the Farson Sandstone Member prograded from north to south across the northern part of the Green River Basin (fig. 8).

A generally northward-thickening wedge of sandy marginal lacustrine rocks, the Farson Sandstone Member of the Green River Formation, overlies the Scheggs Bed throughout the northwestern part of the Green River Basin (Roehler, 1992b) (figs. 3and 8) and is, in part, laterally equivalent to the upper part of that bed. The predominantly fluvial Alkali Creek Tongue of the Wasatch Formation overlies the Farson Sandstone in the northwest part of the Green River Basin (Roehler, 1991a) (fig. 8). Where the Rife Bed is absent the Wilkins Peak Member directly overlies the Farson Sandstone Member and

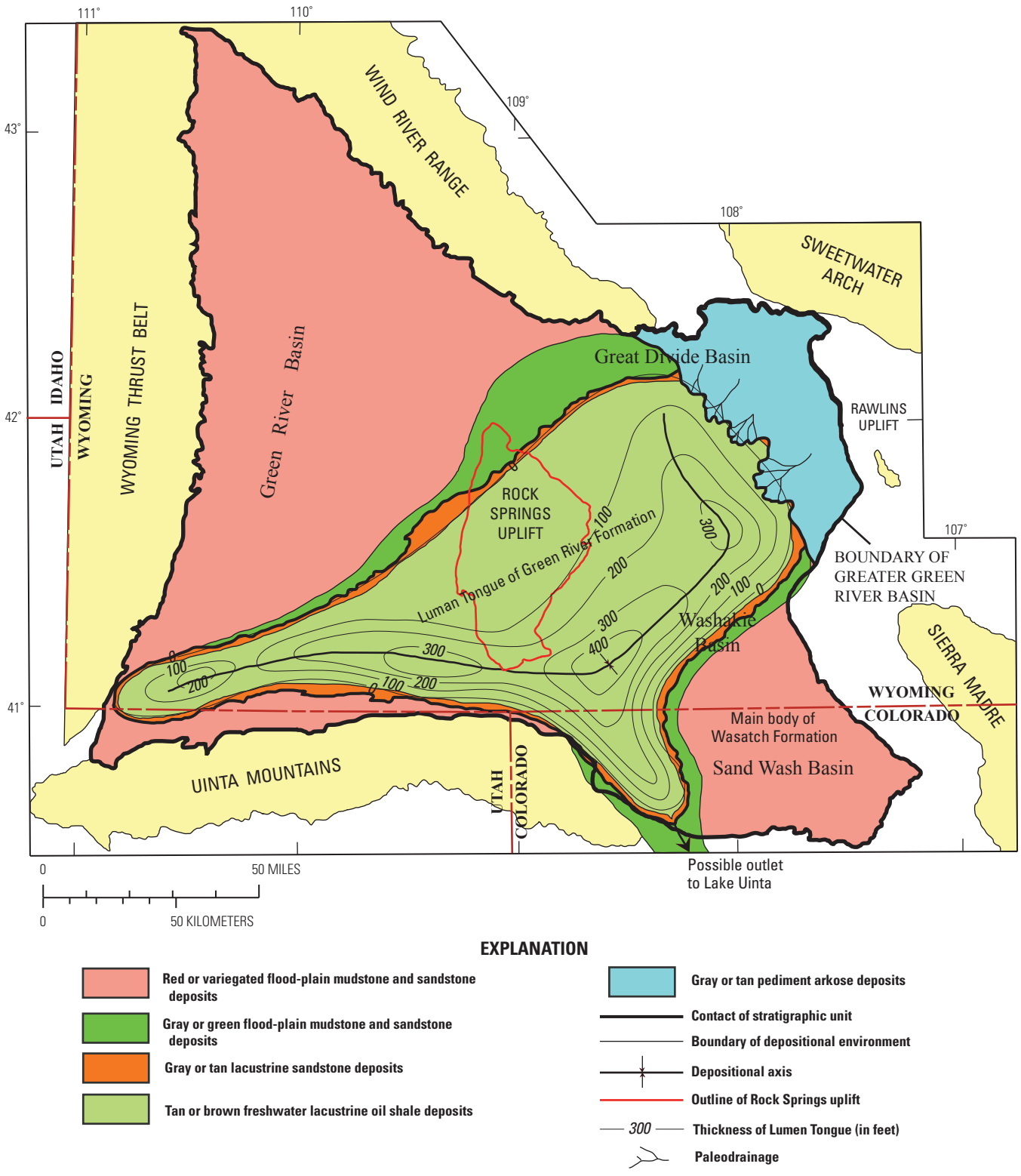


Figure 5. Paleogeographic map of the Lumen Tongue of the Green River Formation.

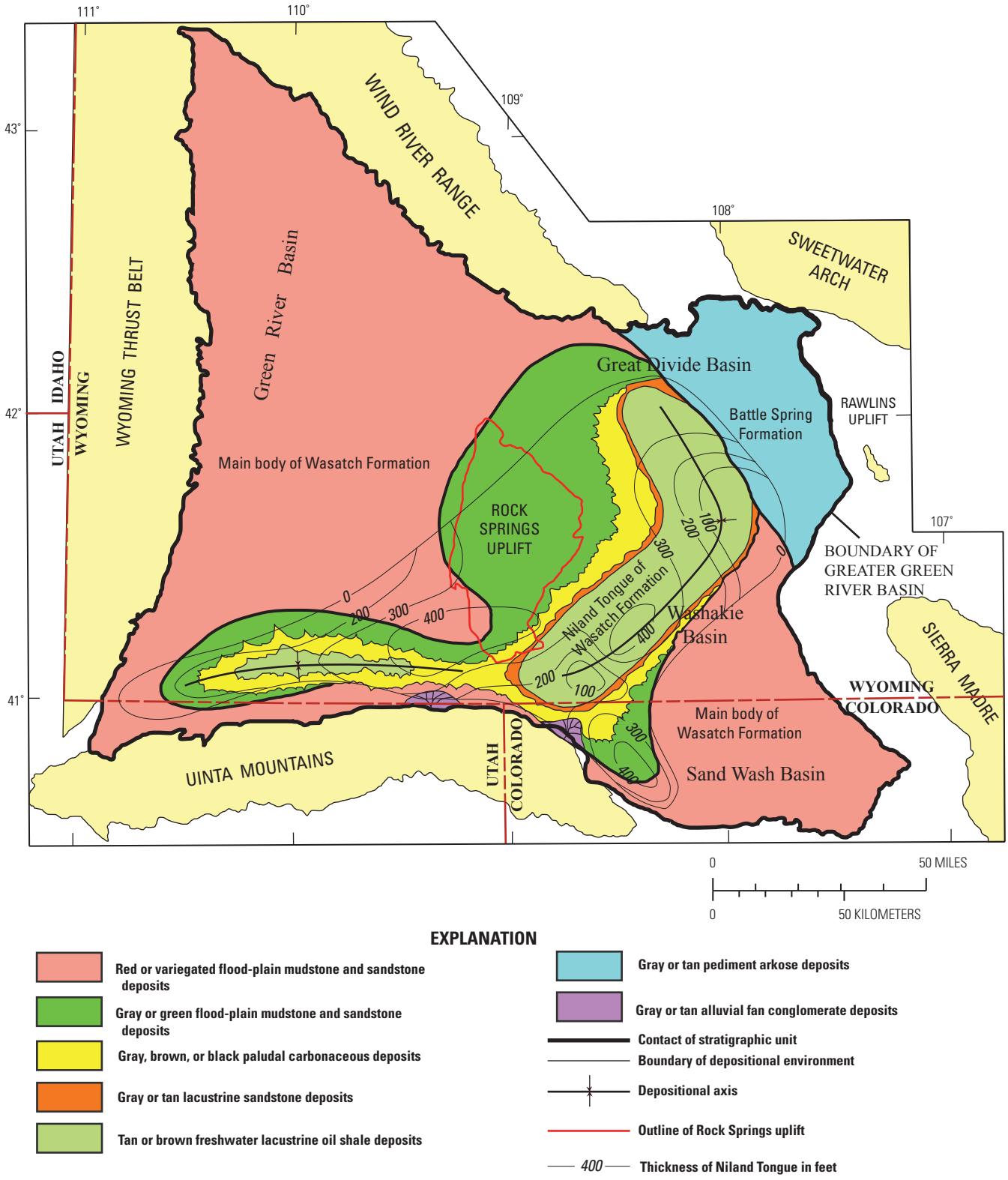


Figure 6. Paleogeographic map of the Niland Tongue of the Wasatch Formation.

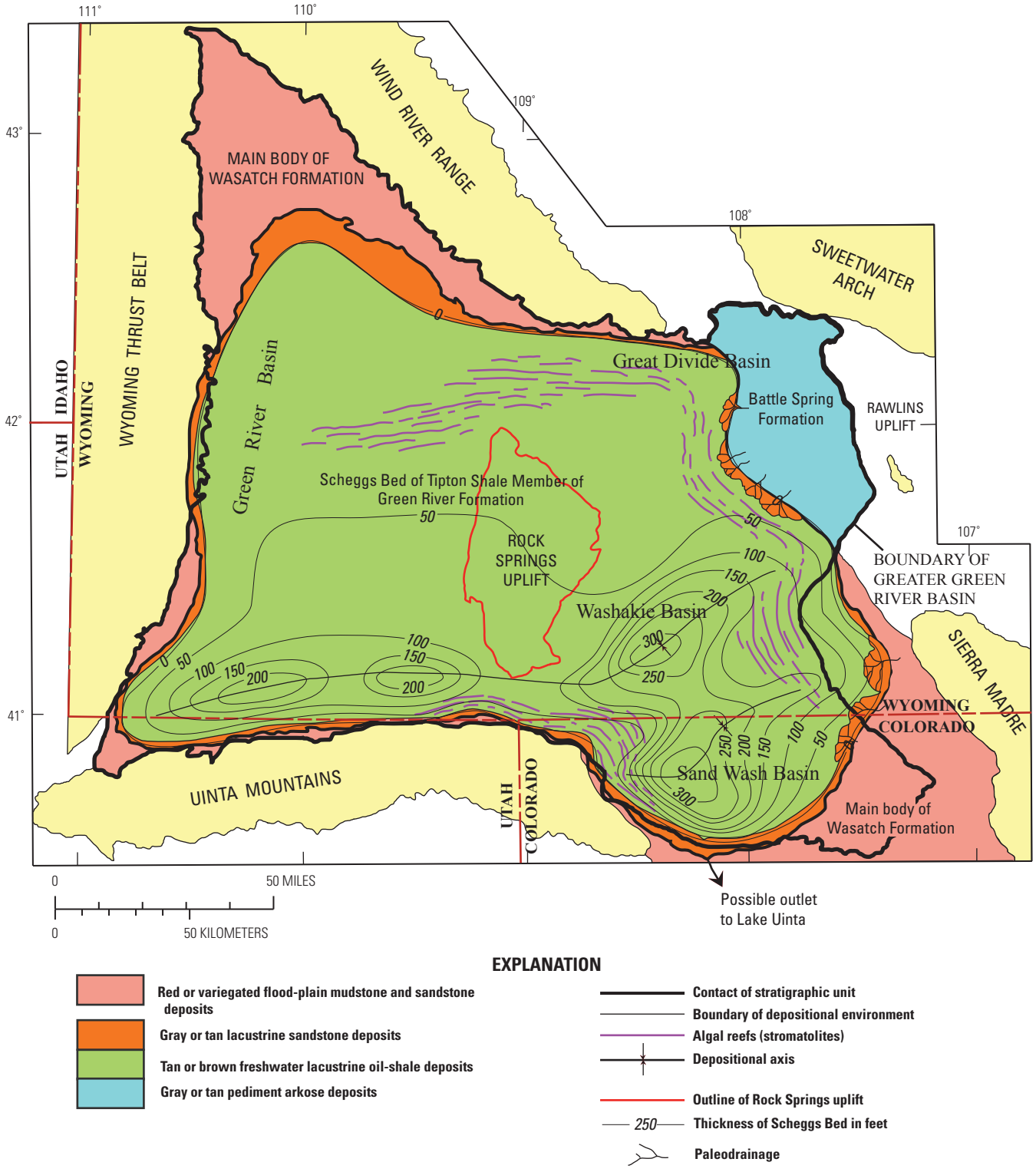


Figure 7. Paleogeographic map of the Scheggs Bed of the Tipton Shale Member of the Green Formation.

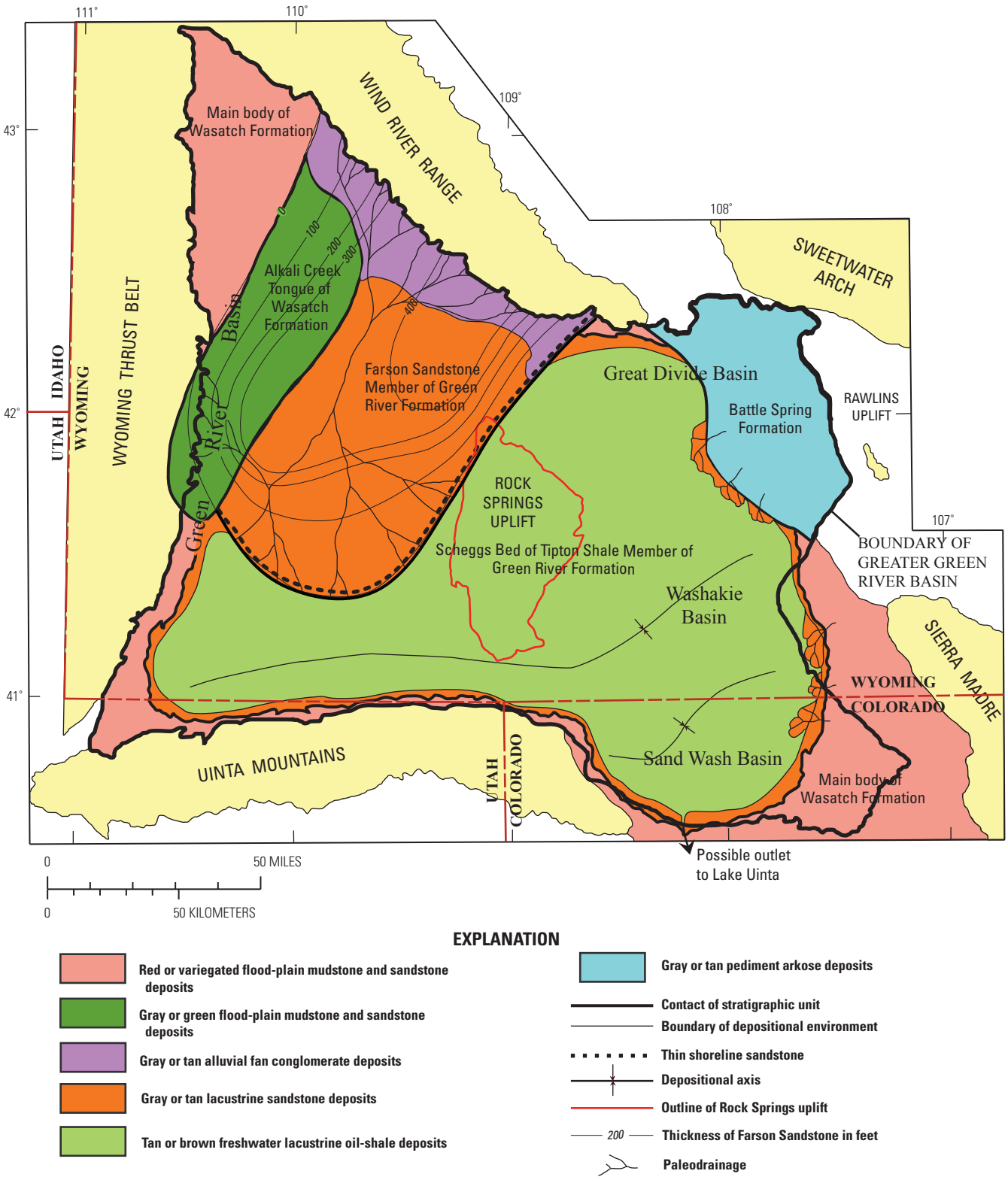


Figure 8. Paleographic map of the Farson Sandstone Member of the Green River Formation.

Alkali Creek Tongue (fig. 3). According to Roehler (1992b), the Farson Sandstone Member reaches a maximum thickness of over 400 ft in the northeastern part of the Hoback Basin and wedges out in the southern part of the Green River Basin (fig. 8). We combined the Farson Sandstone Member and the Alkali Butte Member in our study because the two cannot be distinguished using only geophysical logs and Fischer assay results. Using our tops file, the combined Farson Sandstone Member and Alkali Creek Tongue reaches a maximum thickness of 790 ft in the northern part of the Green River Basin (fig. 9). The Farson Sandstone Member is represented in the Washakie Basin by a thin interval of lean, silty oil shale that is generally less than 10 ft thick between the Scheggs and Rife Beds.

Roehler (1991a; 1992b) believed that the Farson Sandstone Member was deposited by drainages that originated in the Wind River Range, north of the Greater Green River Basin (fig. 8), and noted that the Farson contains pebbles of schist and gneiss sourced from the Precambrian core of that range as a result of a major tectonic uplift. More recently, Pietras and others (2003) and Smith and others (2008) suggested that (1) the Farson Sandstone Member was deposited by throughgoing drainage systems that originated north of, and flowed southward across the Wind River Range, which was characterized as being topographically subdued at the time; and (2) uplift of the range after deposition of the Farson Sandstone Member diverted these drainages to the north and away from the Greater Green River Basin, causing a retreat of Lake Gosiute during deposition of the overlying Wilkins Peak Member.

The Rife Bed (figs. 3 and10) overlies the Scheggs Bed or Farson Sandstone Member where present. It consists of (1) light-gray-weathering, brown to black dolomitic oil shale with scattered lenses of dolomite, and thin layers of siltstone and tuff in offshore areas; (2) largely gray and green mudstone, algal limestone, and siltstone in lake-margin areas, strata that Roehler (1991a) included in the lithologically similar Wilkins Peak Member (fig. 3); and (3) mainly sandstone and conglomerate along the north margin of the Uinta Mountains (Roehler, 1991a). According to Roehler (1992b), the Rife Bed attains a maximum thickness exceeding 200 ft along the trough north of the Uinta Mountains and in the Great Divide and Washakie Basins (fig. 10). The isopach map of the unit generated by the tops file compiled for this assessment indicates maximum thicknesses of 123 ft for the Rife Bed along the Uinta Mountain trough and 230 ft in the Washakie Basin (fig. 10). The area occupied by Lake Gosiute decreased throughout deposition of the Rife Bed with the lake retreating out of the northern part of the Green River Basin and most of the Sand Wash Basin (fig 10).

Figure 11 is a structure contour map on the top of the Tipton Shale Member. For most of the Greater Green River Basin the contour horizon is the top of the Rife Bed, but in the northern part of the Green River Basin, where the bed is missing, the contour horizon is the top of the Scheggs Bed. The map was constructed using subsurface data from core holes and oil and gas tests (Mercier and others, this report) and surface elevations and locations from published geologic maps. Published geologic maps used include Roehler (1972a, b; 1973b; 1974b, c, d, e; 1977; 1978a, b, c), Tweto (1976; 1979), and W. C. Culbertson (USGS, unpub. mapping).

Wilkins Peak Member of the Green River Formation

The Wilkins Peak Member, named by Bradley (1959), represents a major contraction of Lake Gosiute to mostly the central part of the Green River Basin and the western parts of the Great Divide and Washakie Basins (figs. 3 and 12). This contraction was attributed by Bradley (1963) to a shift to a hotter, drier climate. However, Wilf (2000), in his study of plant species in the Greater Green River Basin found little evidence that climate played the dominant role in the expansions and contractions of Lake Gosiute. Pietras and others (2003), as previously discussed, attributed the contraction of Lake Gosiute during Wilkins Peak time to a loss of water supply due to the diversion of major drainages entering the basin from the north due to uplift of the Wind River Range.

Unlike the underlying Tipton Shale Member and overlying Laney Member the Wilkins Peak Member generally does not include thick intervals of continuous oil shale, but rather the oil shale beds are interbedded with other lithologies including sandstone, mudstone, and beds of the sodium bicarbonate mineral trona, shortite, and halite. The member intertongues with and is replaced by strata of the Wasatch Formation toward the basin margins (figs. 3 and 12). The world's largest known deposit of trona is in the Wilkins Peak Member, and it is being extensively mined today. The Wilkins Peak Member was originally defined by Bradley (1959), who thought that it was confined to the Green River Basin. Subsequent work by Roehler (1989a, b) demonstrated that it is also present east of the Rock Springs uplift, in the western parts of the Great Divide and Washakie Basins. Lake Gosiute during Wilkins Peak time was described by Bradley and Eugster (1969) as a chemically stratified lake, with the deeper parts having a strong brine of sodium carbonate-sodium chloride composition. Eugster and Surdam (1973) and Eugster and Hardie (1975), however, interpreted the lake at that time to be a shallow "playa lake" complex that had many similarities to Lake Magadi in Africa . Roehler (1993) estimated that, during expanded lake stages, Lake Gosiute was a permanent lake that occupied as much as 8,700 mi^2 and persisted for as long as 20 thousand years and thus could not be classified as a playa lake during these periods.

Eugster and Hardie (1975) subdivided the Wilkins Peak Member into six major lithofacies: flat-pebble conglomerate, lime sandstone, mudstone, oil shale, trona-halite, and siliciclastic sandstone. Trona-halite beds generally range in thickness between 1 and 15 ft but are locally as much as 30 ft (Roehler, 1993). Not all trona beds contain halite. Culbertson (1971) identified 42 trona beds in the Wilkins Peak Member, with 25 attaining a thickness of at least 3 ft. Culbertson

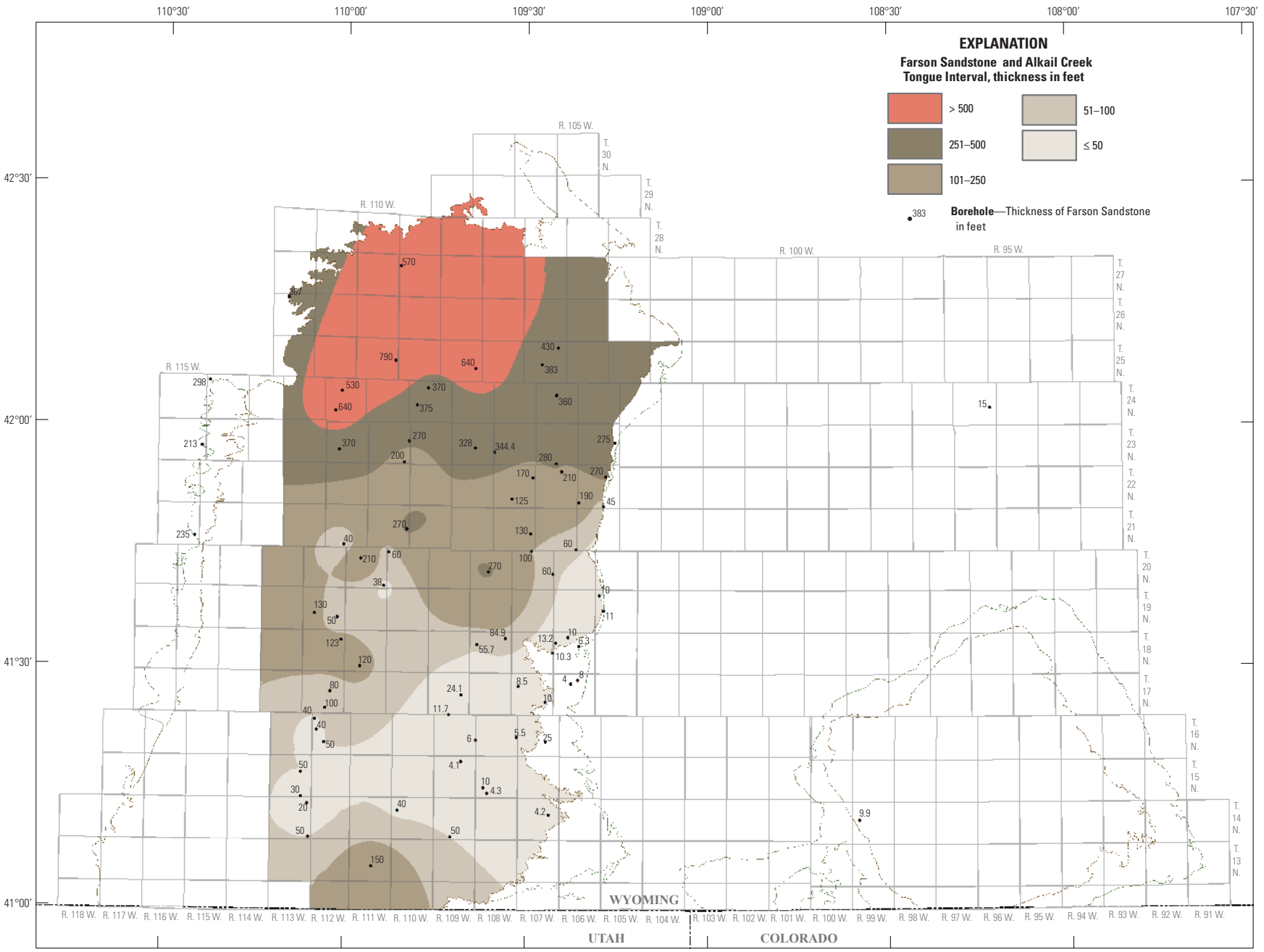


Figure 9. Isopach map of the Farson Sandstone Member of the Green River Formation.

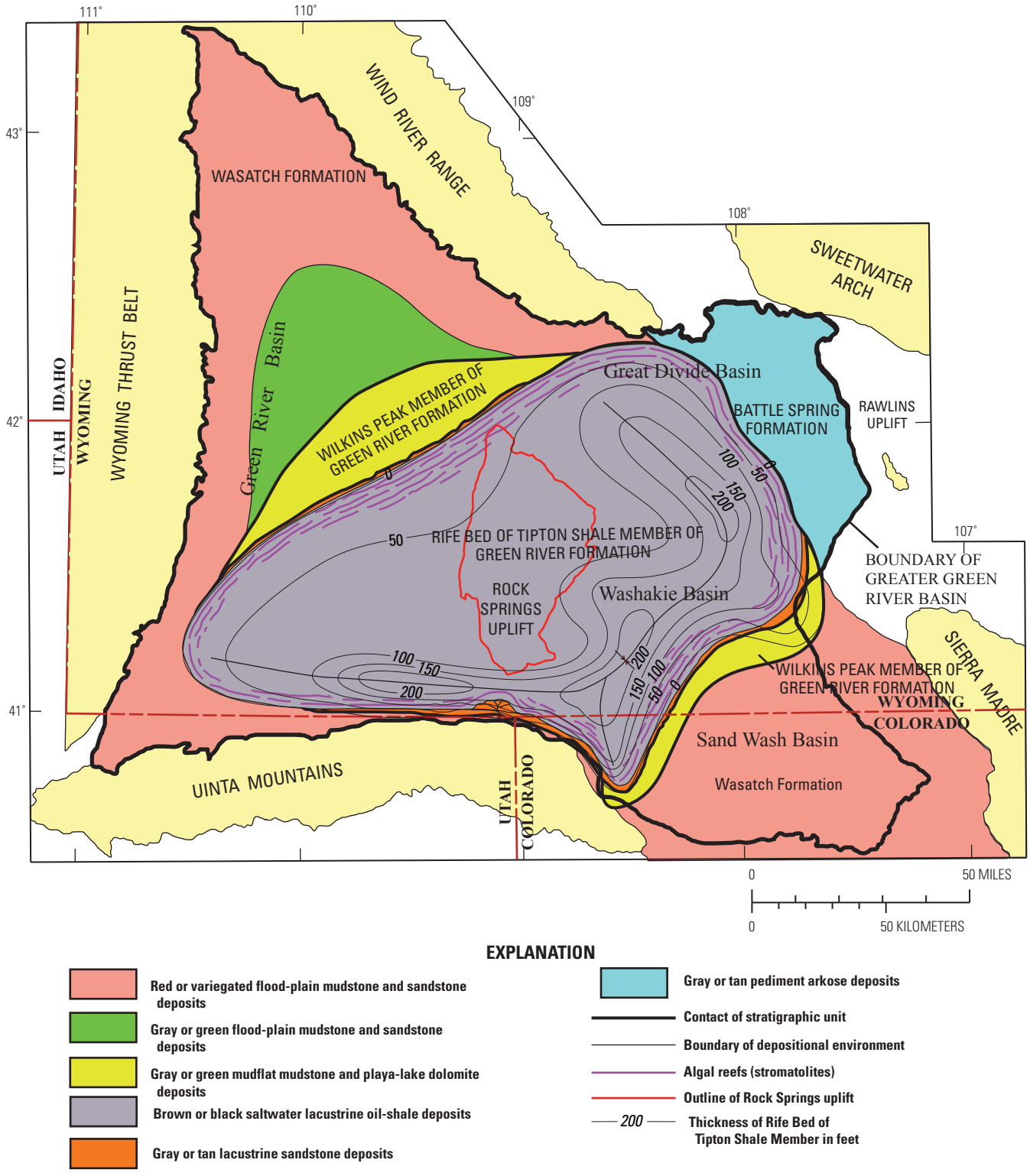


Figure 10. Paleogeographic map of the Rife Bed of the Tipton Shale Member of the Green River Formation.

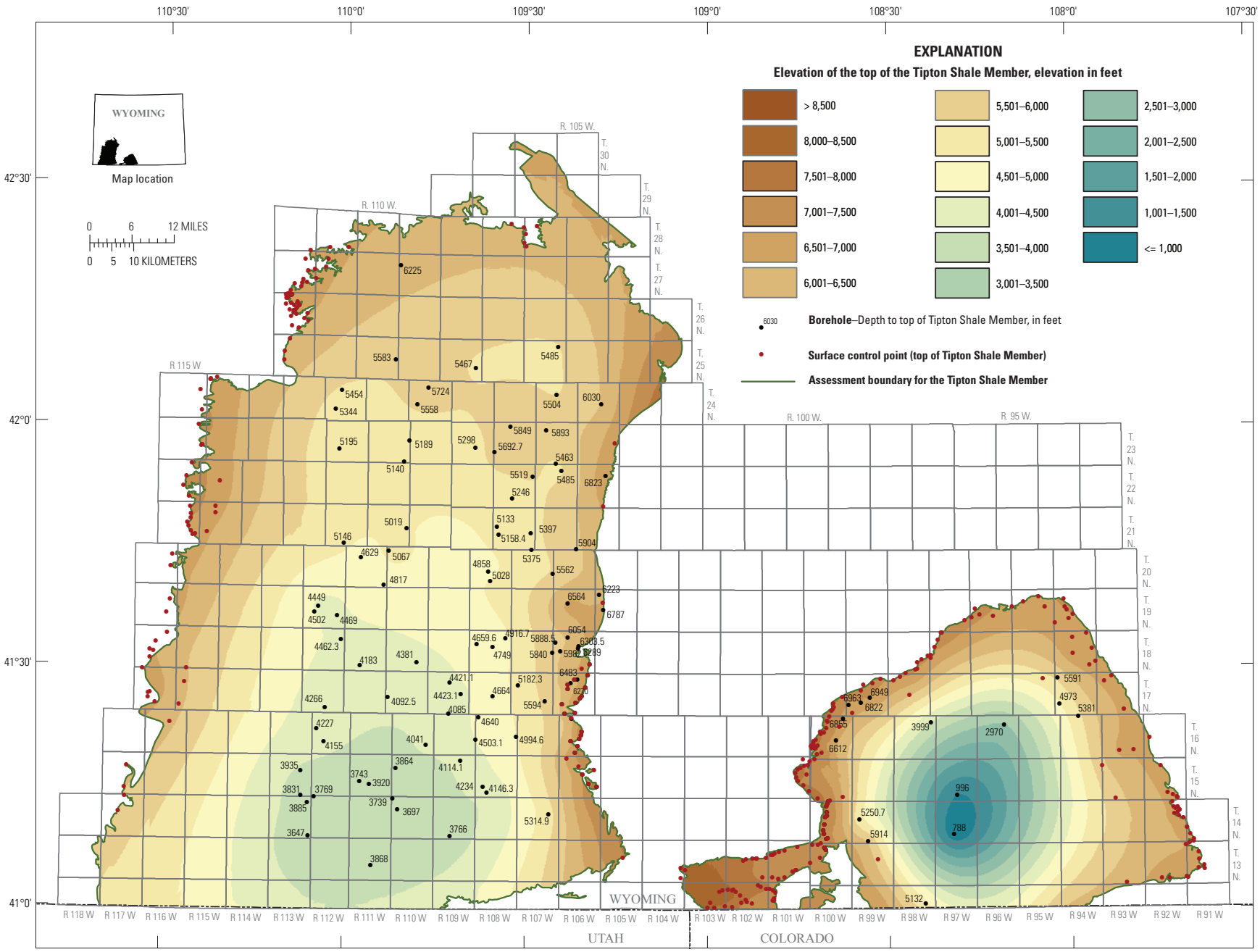


Figure 11. Structure contour map on the top of the Tipton Shale Member of the Green River Formation.

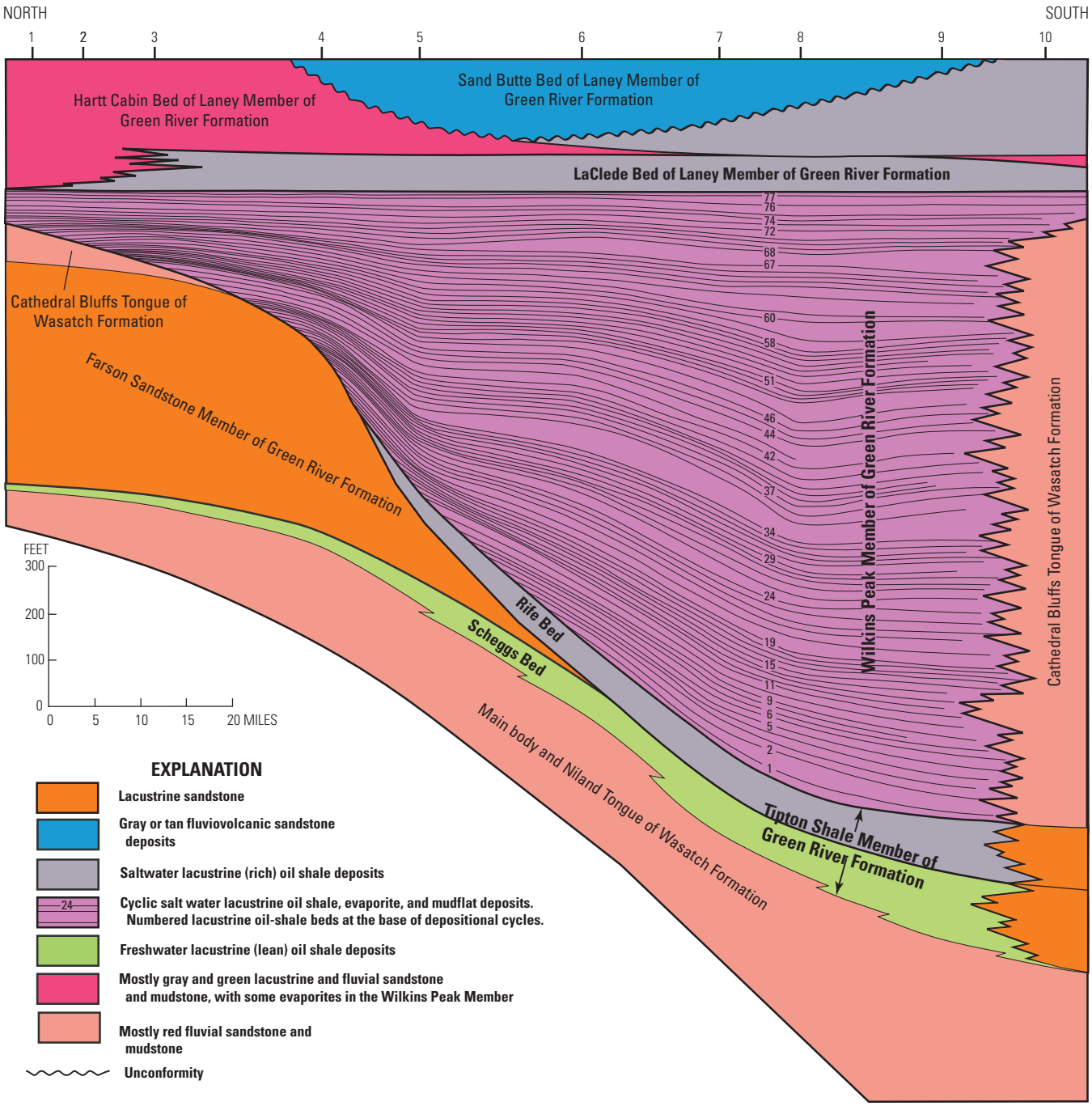


Figure 12. North-south cross section of the Wilkins Peak Member of the Green River Formation and adjacent formations.

(1971) noted that most trona and halite beds are underlain by oil shale. Roehler (1990b; 1992b) identified 77 depositional cycles in the depocenter of the Wilkins Peak Member, each consisting, in ascending order, of oil shale, trona and halite, and mudstone, but he observed that trona and halite beds were not present in every cycle (fig. 12). Beds 1–11 were placed by Roehler in the "lower part of the Wilkins Peak Member," beds 12–67 in the "middle part of the Wilkins Peak Member", and beds 68–77 in the "upper part of the Wilkins Peak member." Figures 13–15 show the various environments of deposition. The lower part, which extends across much of the Greater Green River Basin, is thickest in the southern parts of the Green River and Washakie Basins, locally reaching a maximum thickness of more than 200 ft (fig. 13). At least 10 beds of trona or trona and halite are present in the lower member in the southern part of the Green River Basin. The middle part is largely confined to the Green River Basin and is thickest just north of the Uinta Mountains where it reaches a maximum thickness of over 900 ft (fig. 14); it contains at least 28 beds of trona or trona and halite in the "middle member" (Roehler, 1992b). The upper part is comparatively thin (40–125 ft thick), represents a transition to less saline conditions that characterize the overlying Laney Member, and contains no bedded trona or halite (fig. 15). Roehler (1993) believed that Lake Gosiute began to drain south into Lake Uinta in the Piceance and Uinta Basins at this time, causing the water in Lake Gosiute to become fresher (fig. 15).

Laney Member of the Green River Formation

The Laney Member of the Green River Formation overlies the Wilkins Peak Member and represents a major expansion of Lake Gosiute (figs. 3 and 16). At the onset of Laney deposition, Lake Gosiute evolved from a comparatively small, highly saline lake that may have periodically dried up to a much larger and deeper permanent lake that varied from saline-alkaline to fresh water (Roehler, 1973a; 1993; Surdam and Stanley, 1979). Bradley (1964) and Roehler (1993) attributed this expansion to a climatic shift from hot and dry to more humid. Surdam and Stanley (1980), in contrast, believed that the cause of this expansion was related to an enlargement of the drainage basin to include water from basins to the north and cited as evidence the sudden arrival of volcaniclastic sediments from the Absaroka volcanic field along the north margin of the Greater Green River Basin at the onset of this expansion. Surdam and Stanley (1979; 1980), and Roehler (1993) noted the abundant freshwater mollusks in parts of the Laney Member and suggested that Lake Gosiute drained southward into Lake Uinta near the eastern terminus of the Uinta uplift at this time (fig. 16).

Originally named the "Laney Shale Member" by Schultz (1920) for exposures along Laney Rim in the northern part of the Washakie Basin, the name was shortened to Laney Member by Roehler (1973a) because it includes other lithologies besides shale at its type locality. It has been described by Bradley (1964), Culbertson (1969), Roehler (1973a), and Surdam and Stanley (1980), all of whom generally recognized a lower oil shale unit and an upper sandstone and mudstone unit. Roehler (1973a) subdivided the member, in ascending order, into the LaClede Bed, the Sand Butte Bed, and the Hartt Cabin Bed (figs. 3, 16–18). The LaClede Bed is mainly oil shale, the Sand Butte bed is tuffaceous sandstone and siltstone, and the Hartt Cabin Bed is interbedded sandstone, siltstone, mudstone, shale, oil shale, tuff, limestone, and dolomite. The Laney Member unconformably overlies the Wilkins Peak Member and Cathedral Bluffs Tongue of the Wasatch Formation in the vicinity of the LaBarge Platform in the northern part of the Green River Basin (Roehler, 1992b, p. E3) (fig. 2).

Figure 19 is a structure contour map drawn on the top of the LaClede Bed in the Green River and Washakie Basins. The map was constructed from subsurface data obtained from core holes and oil and gas tests (Mercier and others, this report) and surface elevations and locations from geologic maps including Roehler, (1972a, b; 1973b; 1974b– e; 1977; 1978a– c), Love and Christiansen (1985), and W. C. Culbertson (USGS, unpub. mapping). Elevation of the top of the LaClede varies from about 6,500 to 8,000 ft around the perimeter of the three basins to minimums of about 5,100 ft in the southeastern part of the Green River Basin and about 3,600 ft in the southwestern part of the Washakie Basin (fig. 19).

The Sand Butte and Hartt Cabin Beds are characterized by dacite and andesite fragments sourced from the Absaroka volcanic field north of the Greater Green River Basin (Ebens, 1963; Surdam and Stanley, 1980). These volcaniclastics entered the Greater Green River Basin from one or more points along the north margin and first appeared about the same time as the transgression that initiated deposition of the Laney Member began. Volcanic-rich sediments prograded southward throughout deposition of the Laney Member, filling in Lake Gosiute from north to south. The volcaniclastic sediments complexly intertongue with oil shale of the LaClede Bed or the lower part of the Laney Member. This intertonguing and southward progradation of volcaniclastic sediments was documented in detail in the Green River Basin by Culbertson (1969, his fig. 3) and Culbertson and others (1980, their pl. 1, C–C') (fig. 20, sandstone, marlstone and thin beds of limestone and oil shale facies). Gilbert-type deltas, with foresets ranging from 10 to 25 meters high, have been described in the Laney Member in the northwestern part of the Washakie Basin (Stanley and Surdam, 1978). The upper part of the member is overlain by fluvial strata of the Washakie and Bridger Formations, indicating an end to the prolonged and widespread lacustrine conditions in the Greater Green River Basin.

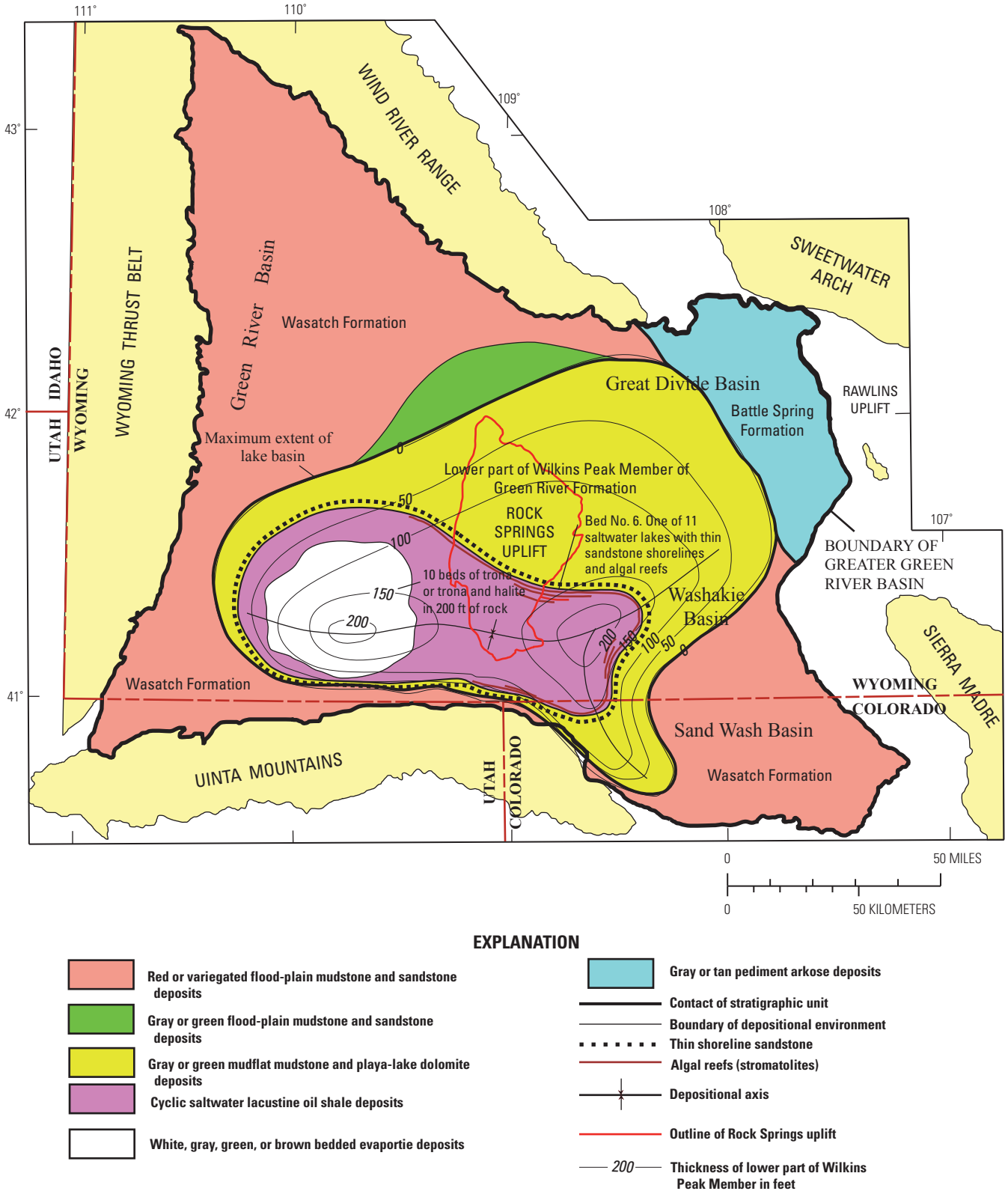


Figure 13. Paleogeographic map of the lower part of the Wilkins Peak Member.

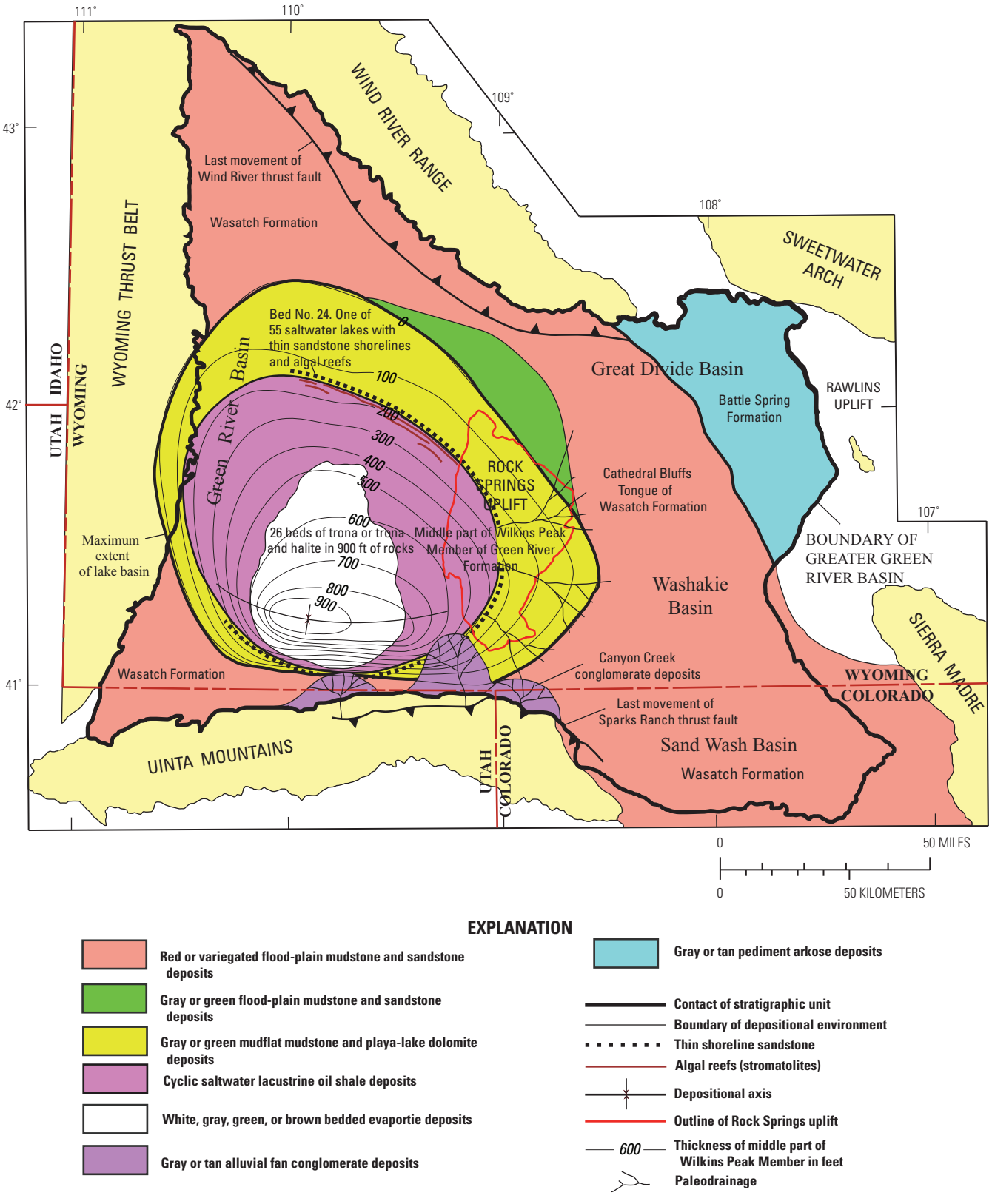


Figure 14. Paleogeographic map of the middle part of the Wilkins Peak Member.

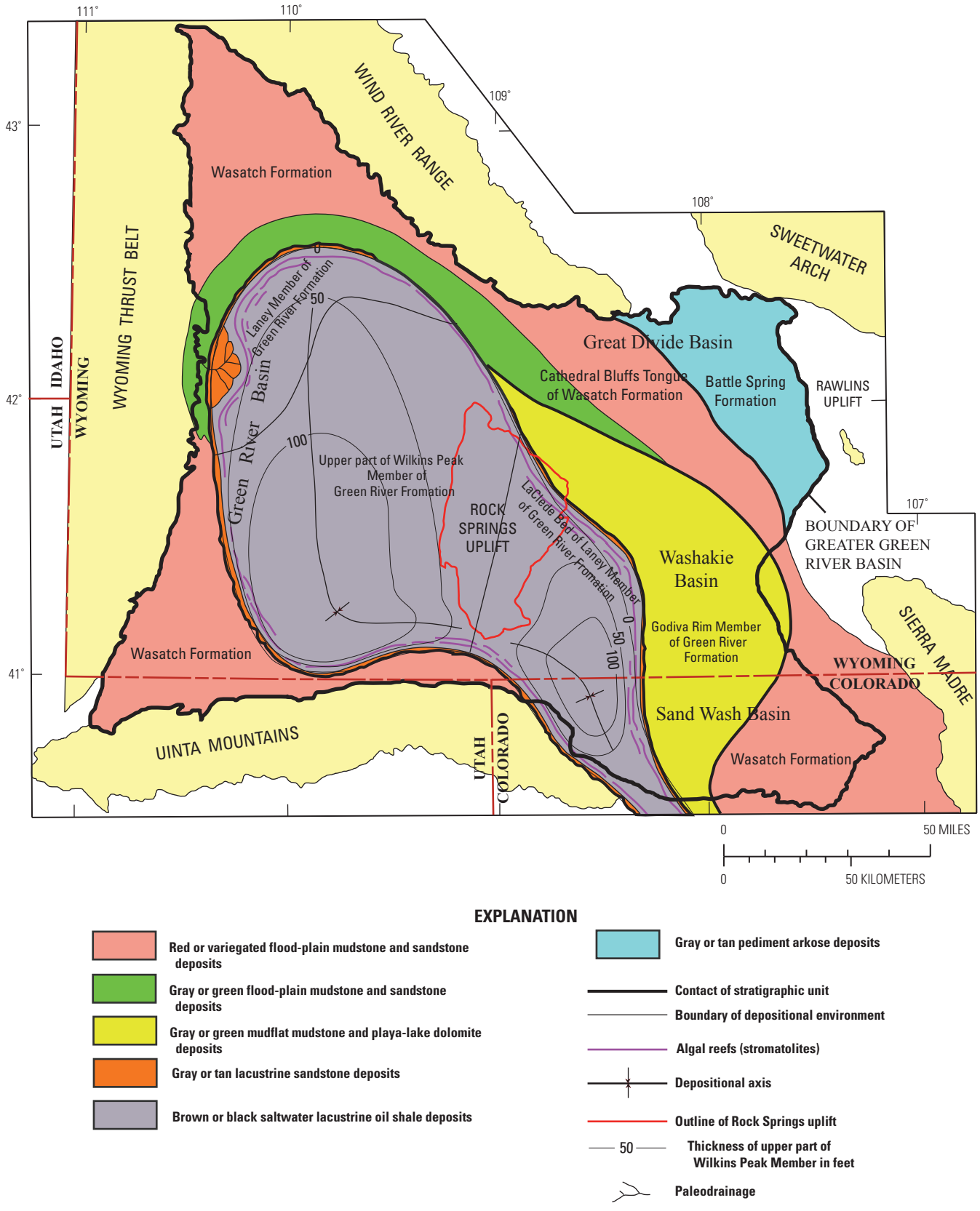


Figure 15. Paleogeographic map of the upper part of the Wilkins Peak Member.

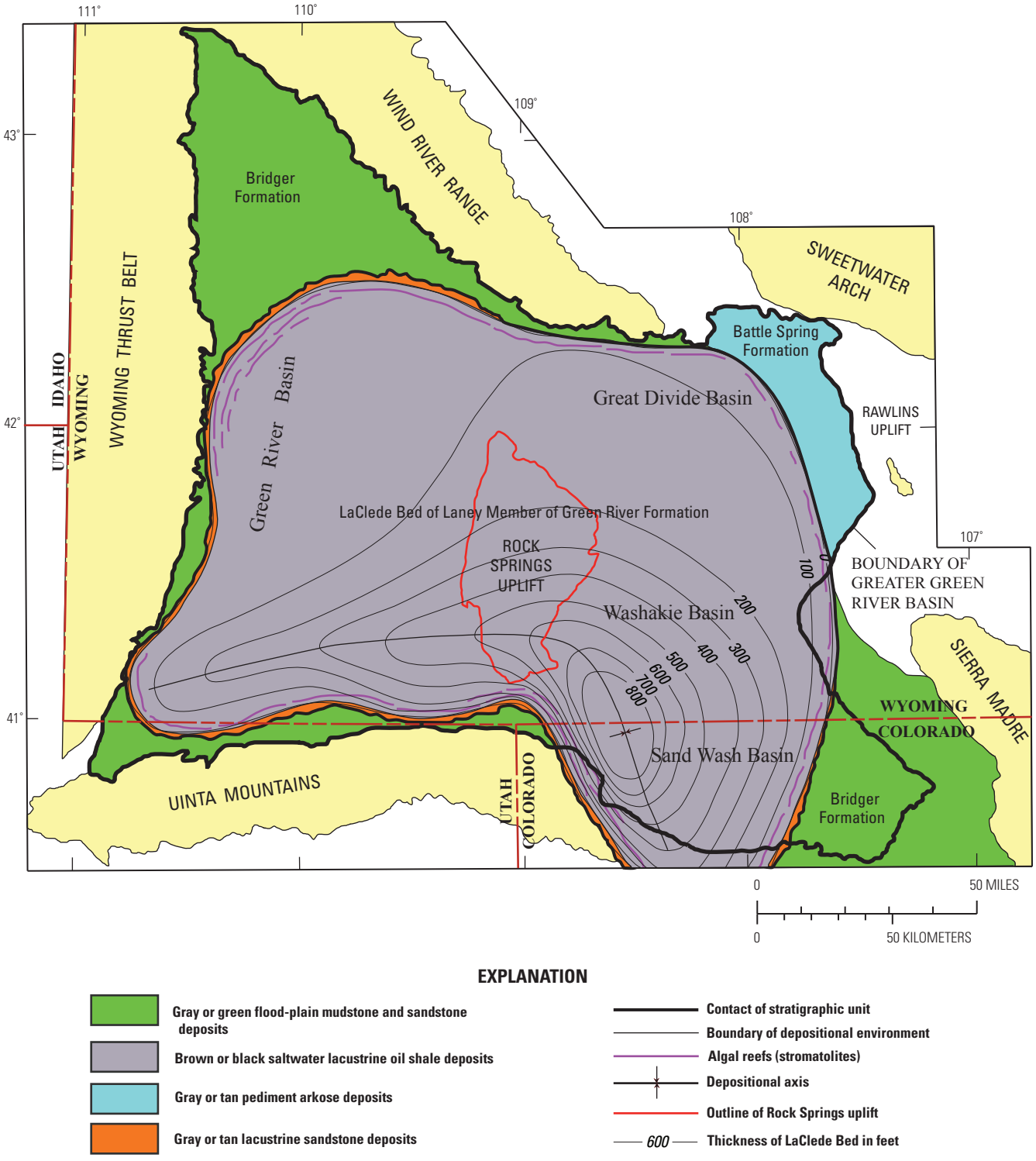


Figure 16. Paleogeographic map of the LaClede Bed of the Laney Member.

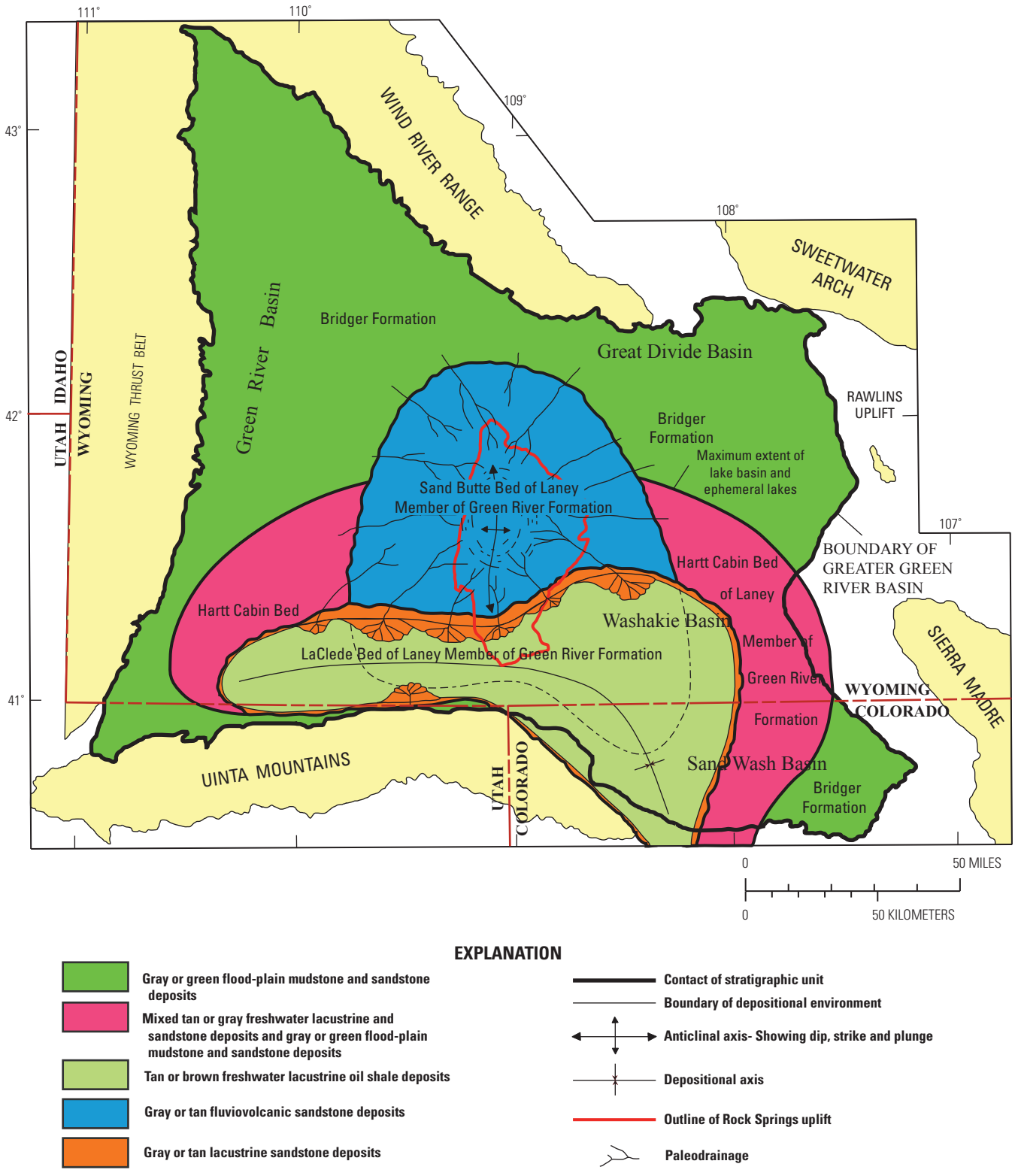


Figure 17. Paleogeographic map of the Sand Butte Bed of the Laney Member.

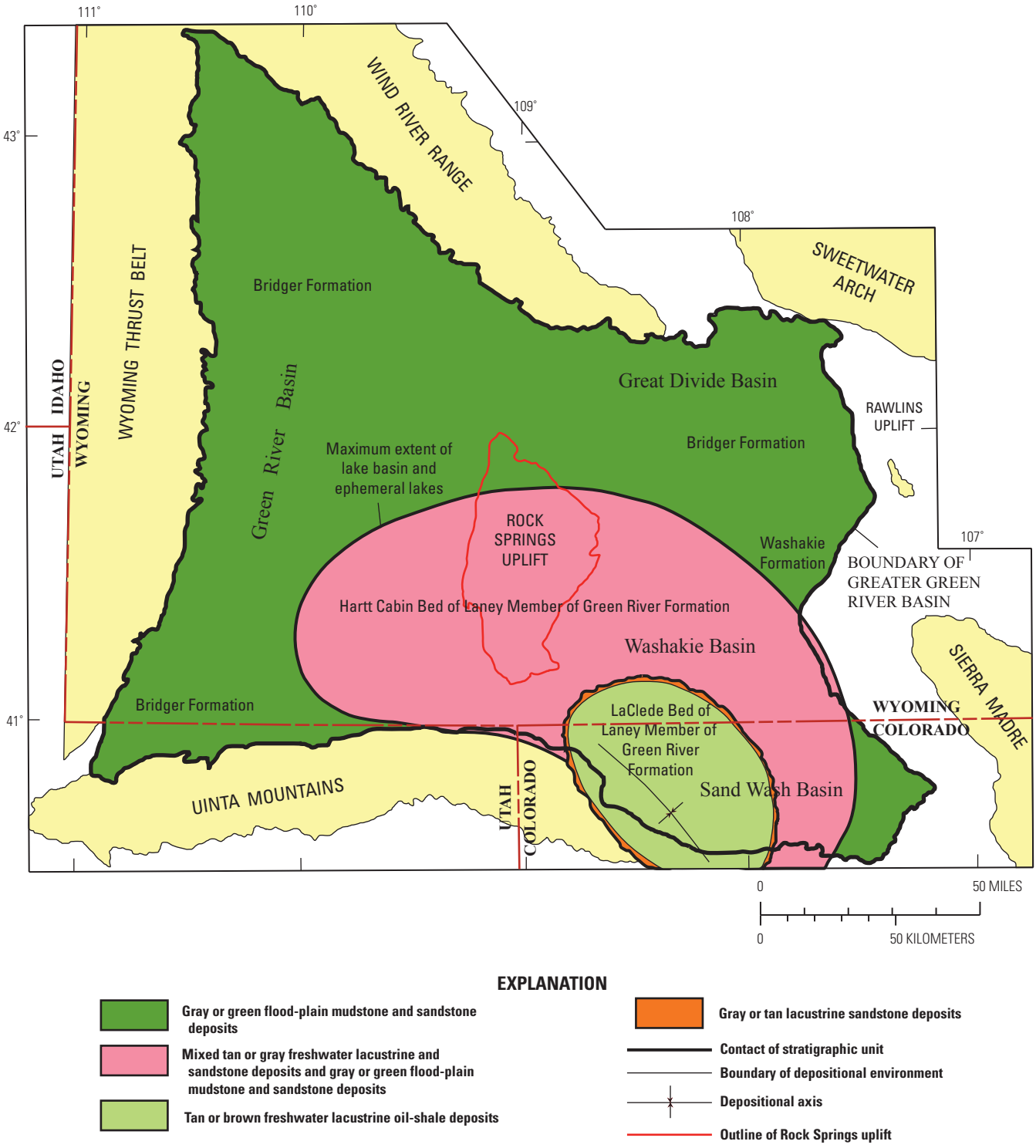


Figure 18. Paleogeographic map of the Hartt Cabin Bed of the Laney Member.

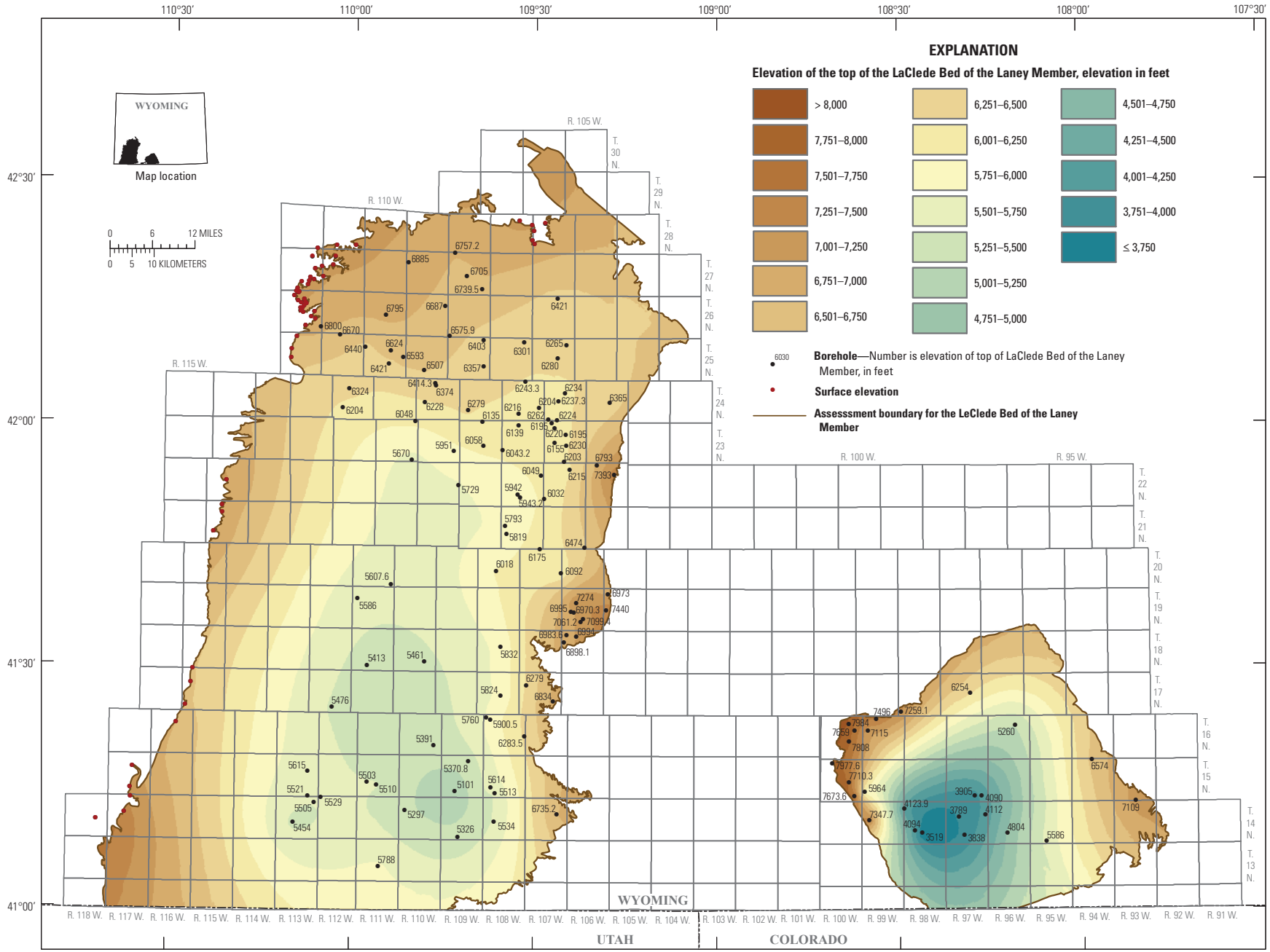


Figure 19. Structure contour map on the top of the LaClede Bed of the Laney Member.

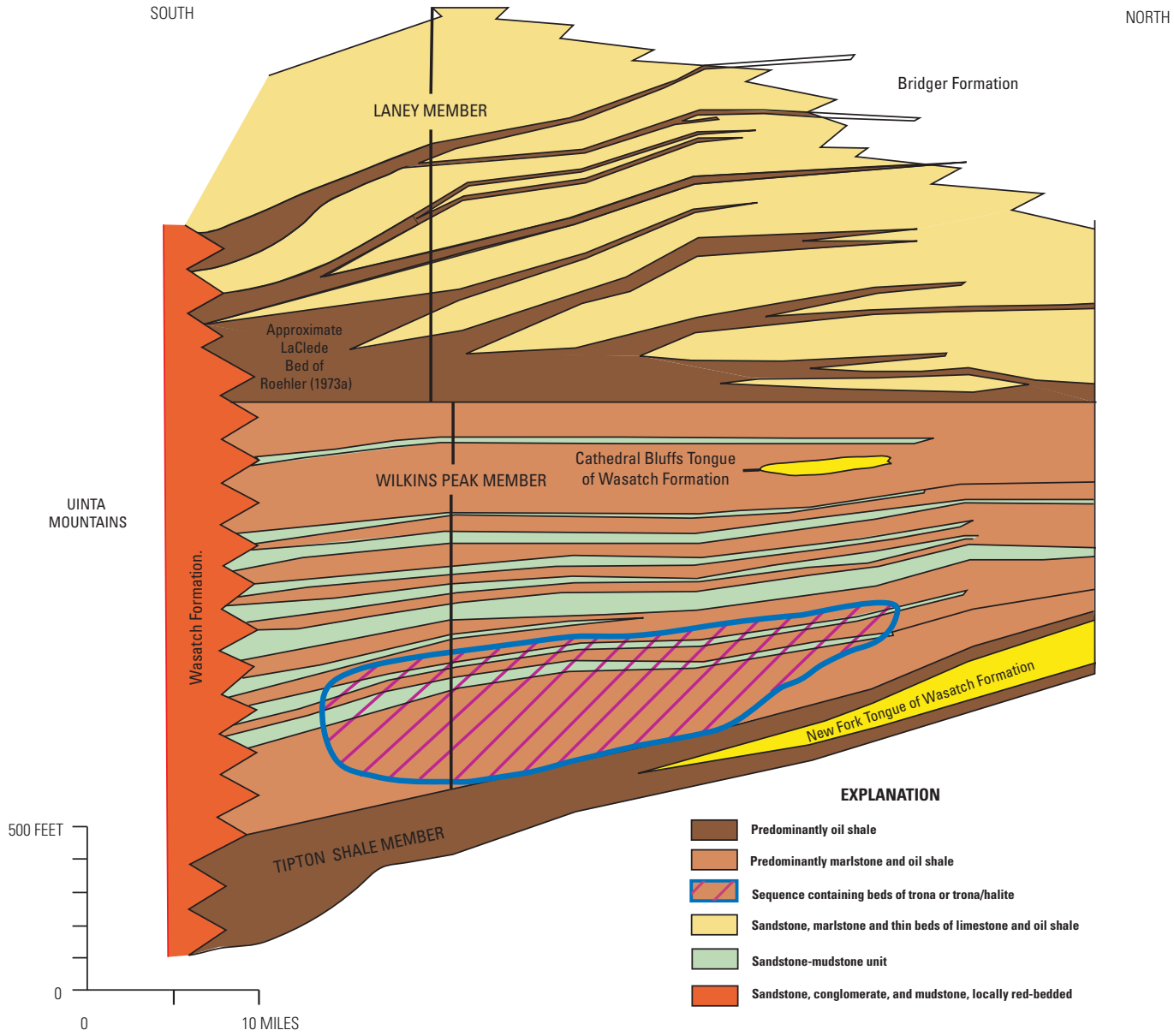


Figure 20. South to north cross section across the Green River Basin. Modified from Culbertson and others (1980, their pl. 1, *C*–*C'*).

Factors Affecting the Precision of Oil-Yield Measurements

Determining the Volume of Oil in a Given Volume of Rock

Determining GPT from a Fischer assay is a straightforward calculation that involves the weight of the original sample and the volume of oil generated, both of which are routinely measured. However, this is not the case for the density of the sample prior to retorting which is a part of the equation that must also be known in order to calculate the amount of oil present in an oil shale interval over a prescribed area. Typically, in-place oil in the Green River Formation is given in the rather arcane unit of barrels of oil per acre (BPA). The method used to convert GPT into BPA in the previous assessment by Pitman and others (1989) was not discussed in their publication. An equation that computes BPA was recovered with the FORTRAN program that was used at the time of the previous assessment. This equation seemed to generate reasonable results, but there was no reference as to its origin or an

explanation of how the many constants used in the equation were generated, so we decided not to use it.

Stanfield and others (1954) reported summary data on volume-weight and oil-yield relationships from about 20,500 USBM oil-yield analyses (table 1). Smith (1956) reported that oil-yield values were related to the specific gravity of the oil shale. Table 1 contains original values for oil yield, gallons per ton, as well as specific gravity and was regenerated using Microsoft Excel. Values for weight of oil shale, volume of oil shale, and oil yield per unit volume were updated using currently accepted formulas (table 2). A 3rd-order trend line with a R^2 value of 0.9998 was generated comparing oil yield vs. specific gravity (fig. 21). As the original table (table 1) contained only integer values for GPT, new records were inserted to fill in values to one decimal place (0.1 ft) creating a new look-up table (Mercier, chapter 3, this report). A linear-trend series fill function in Microsoft Excel 2007 was then used to calculate specific gravity values for each 0.1 ft value for the GPT column. A 3rd-order trend line was then regenerated comparing new oil yield vs. specific gravity data yielding a R^2 value of 0.9997. Values for weight of oil shale, volume of oil shale, and oil yield per unit volume were then calculated using the new values for oil yield and specific gravity. The final look up table contained records for oil yield in GPT, specific gravity, and oil yield per unit volume for oil values ranging from 1.0 to 80.0 GPT.

Shale oil resource numbers in BPA were calculated using the formula:

oil shale interval thickness × *43,560 (*sq. ft/ acre*)* × *oil yield per unit volume*

from the final look-up table, containing values on a 0.1 ft basis / 42 (gals/barrel of oil).

Anomalously High Oil-Yield Values from Cuttings

In a few cases, assay results from a particular rotary hole appeared to give anomalously high oil-yield values based on data from nearby core holes or from regional oil-yield trends; the cause for such values is unclear so they were not included in the resource calculations. One possibility is that the cuttings were high graded prior to assaying by removing sandstone and siltstone chips on the assumption that they were cavings from above rather than from interbeds from within the oil shale.

Discrepancies Between Geophysical Logs and Cuttings Data

The true tops and bases of oil shale intervals, such as for the LaClede Bed and the Tipton Shale Member, can commonly be picked on geophysical logs. However, when these identified well depths are compared to those reported for cuttings, there is commonly a discrepancy because of the difficulty in accurately compensating for the time delay between when a particular interval is drilled through and when the cuttings from that interval reach the surface. For this assessment, we chose to use the reported tops at which the oil shale units were encountered in the cuttings, because using the geophysical log data would have resulted in portions of rich oil shale units being excluded in many of the holes.

Broken Core and Missing Intervals

Almost all core holes and rotary holes have missing intervals that are not recovered during the drilling process. In addition, portions of a core can be moderately to severely broken, and only a quantity of rubble is recovered instead of a continuous core. These circumstances lead to difficulties in properly distributing that portion of the core that is recovered over the entire interval, and consequently to determining the average oil yield for that interval. In any case, assigning oil-yield values to all the missing intervals is essential for calculating resources. As previously discussed, Culbertson and others (1980) filled in the missing data by "extrapolation of nearby core data or from the lithologic description of the unassayed core, or by using geophysical logs (sonic, neutron, density) where available." Pitman and others (1989) did not discuss how missing intervals were handled in their assessment of the Piceance Basin; however, Janet Pitman (U.S. Geological Survey, written commun., 2008) recalled that a missing interval was assigned the average of the oil-yield values of the intervals immediately above and below the missing interval. John R. Donnell (U.S. Geological Survey, oral commun., 2008), who was involved in early assessments of the Piceance Basin, recalled that missing intervals were assigned values based on nearby core holes where the intervals were not missing. Vanden Berg (Utah Geological Survey, written commun., 2009), used both methods in his recent assessment of the Uinta Basin, and stated that missing intervals were assigned oil yield values "based on oil shale above and below and based on nearby wells."

The method used here to assign values to missing intervals was to calculate the average oil yield for the recovered intervals for a particular oil shale zone in a given drill hole and assign that average to all the missing intervals in that zone. Johnson and others (2010a) used this method to assign values to missing intervals in their recent assessment of the oil shale resources in the Piceance Basin of western Colorado. In one example, Johnson and others (2010a) determined that this method calculated similar average oil yield values for the Mahogany zone, a rich oil shale zone in the Piceance and Uinta Basins in five closely-spaced core holes with missing intervals ranging from 0 to 41.2 percent of the total zone. One major concern is that the richness of the oil shale affected the probability of it being recovered. For instance, if rich beds were more likely to be preserved than lean beds, then the calculated average oil yield for a zone would be expected

Table 1. Original volume-weight-oil yield relationships of Green River Formation oil shale. From Stanfield and others (1954).

[GPT, gallons per ton, lbs/ft^3, pounds per cubic foot, ft^3/ton, cubic feet per ton, gal/ft^3, gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
1	2.740	170.98	11.70	0.085
2	2.715	169.42	11.80	0.169
3	2.690	167.86	11.91	0.252
4	2.655	166.30	12.03	0.333
5	2.640	164.74	12.14	0.412
6	2.618	163.36	12.24	0.490
7	2.596	161.98	12.35	0.567
8	2.574	160.61	12.45	0.642
9	2.552	159.24	12.56	0.716
10	2.530	157.87	12.67	0.789
11	2.508	156.49	12.78	0.860
12	2.486	155.12	12.89	0.930
13	2.464	153.75	13.01	0.999
14	2.442	152.38	13.13	1.067
15	2.420	151.01	13.24	1.133
16	2.400	149.76	13.35	1.198
17	2.380	148.51	13.47	1.262
18	2.360	147.26	13.58	1.325
19	2.340	146.02	13.70	1.387
20	2.320	144.77	13.80	1.448
21	2.302	143.64	13.92	1.508
22	2.284	142.52	14.03	1.567
23	2.266	141.40	14.14	1.625
24	2.248	140.78	14.26	1.683
25	2.230	139.15	14.37	1.740
26	2.216	138.28	14.46	1.797
27	2.202	137.40	14.56	1.854
28	2.188	136.53	14.65	1.910
29	2.174	135.66	14.74	1.966
30	2.160	134.78	14.83	2.022
31	2.147	133.97	14.92	2.077
32	2.134	133.16	15.02	2.131
33	2.121	132.35	15.11	2.184
34	2.108	131.54	15.20	2.236
35	2.093	130.73	15.30	2.288
36	2.082	129.92	15.44	2.339
37	2.069	129.11	15.49	2.389
38	2.056	128.29	15.59	2.438
39	2.043	127.48	15.69	2.486
40	2.030	126.67	15.79	2.534
41	2.018	125.92	15.88	2.581

Table 1. Original volume-weight-oil yield relationships of Green River Formation oil shale. From Stanfield and others (1954).—Continued

[GPT, gallons per ton, lbs/ft^3, pounds per cubic foot, ft^3/ton, cubic feet per ton, gal/ft^3, gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
42	2.006	125.17	15.98	2.628
43	1.994	124.43	16.07	2.674
44	1.982	123.68	16.17	2.720
45	1.970	122.93	16.27	2.766
46	1.959	122.24	16.36	2.811
47	1.948	121.56	16.45	2.856
48	1.937	120.87	16.55	2.901
49	1.926	120.18	16.64	2.945
50	1.915	119.50	16.74	2.938
51	1.904	118.81	16.83	3.030
52	1.893	118.12	16.93	3.071
53	1.882	117.44	17.03	3.112
54	1.871	116.79	17.12	3.152
55	1.860	116.06	17.23	3.192
56	1.849	115.38	17.33	3.231
57	1.838	114.69	17.44	3.269
58	1.827	114.00	17.54	3.306
59	1.816	113.32	17.65	3.343
60	1.805	112.63	17.76	3.379
61	1.794	111.95	17.87	3.414
62	1.783	111.26	17.98	3.449
63	1.772	110.57	18.09	3.483
64	1.761	109.89	18.20	3.516
65	1.750	109.20	18.32	3.549
66	1.740	108.58	18.42	3.582
67	1.730	107.95	18.53	3.615
68	1.720	107.33	18.63	3.648
69	1.710	106.70	18.74	3.681
70	1.700	106.08	18.85	3.713
71	1.690	105.46	18.96	3.744
72	1.680	104.83	19.08	3.774
73	1.670	104.21	19.19	3.804
74	1.660	103.58	19.31	3.833
75	1.650	102.96	19.43	3.861
76	1.640	102.34	19.54	3.889
77	1.630	101.71	19.66	3.916
78	1.620	101.09	19.78	3.943
79	1.610	100.46	19.91	3.969
80	1.600	99.84	20.03	3.994
90	1.500	93.75	21.33	4.219

Table 2. Recalculated volume-weight-oil yield relationships for Green River Formation oil shale. From Stanfield and others (1954).

[GPT, gallons per ton, lbs/ft^3, pounds per cubic feet, ft^3/ton, cubic feet per ton, gal/ft^3 , gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
1	2.740	171.06	11.69	0.086
2	2.715	169.50	11.80	0.169
3	2.690	167.94	11.91	0.252
4	2.655	165.75	12.07	0.332
5	2.640	164.82	12.13	0.412
6	2.618	163.44	12.24	0.490
7	2.596	162.07	12.34	0.567
8	2.574	160.69	12.45	0.643
9	2.552	159.32	12.55	0.717
10	2.530	157.95	12.66	0.790
11	2.508	156.57	12.77	0.861
12	2.486	155.20	12.89	0.931
13	2.464	153.83	13.00	1.000
14	2.442	152.45	13.12	1.067
15	2.420	151.08	13.24	1.133
16	2.400	149.83	13.35	1.199
17	2.380	148.58	13.46	1.263
18	2.360	147.33	13.57	1.326
19	2.340	146.09	13.69	1.388
20	2.320	144.84	13.81	1.448
21	2.302	143.71	13.92	1.509
22	2.284	142.59	14.03	1.568
23	2.266	141.47	14.14	1.627
24	2.248	140.34	14.25	1.684
25	2.230	139.22	14.37	1.740
26	2.216	138.34	14.46	1.798
27	2.202	137.47	14.55	1.856
28	2.188	136.60	14.64	1.912
29	2.174	135.72	14.74	1.968
30	2.160	134.85	14.83	2.023
31	2.147	134.04	14.92	2.078
32	2.134	133.23	15.01	2.132
33	2.121	132.41	15.10	2.185
34	2.108	131.60	15.20	2.237
35	2.093	130.67	15.31	2.287
36	2.082	129.98	15.39	2.340
37	2.069	129.17	15.48	2.390
38	2.056	128.36	15.58	2.439
39	2.043	127.54	15.68	2.487

Table 2. Recalculated volume-weight-oil yield relationships for Green River Formation oil shale. From Stanfield and others (1954).—Continued

[GPT, gallons per ton, lbs/ft^3, pounds per cubic feet, ft^3/ton, cubic feet per ton, gal/ft^3 , gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
40	2.030	126.73	15.78	2.535
41	2.018	125.98	15.88	2.583
42	2.006	125.23	15.97	2.630
43	1.994	124.49	16.07	2.676
44	1.982	123.74	16.16	2.722
45	1.970	122.99	16.26	2.767
46	1.959	122.30	16.35	2.813
47	1.948	121.61	16.45	2.858
48	1.937	120.93	16.54	2.902
49	1.926	120.24	16.63	2.946
50	1.915	119.55	16.73	2.989
51	1.904	118.87	16.83	3.031
52	1.893	118.18	16.92	3.073
53	1.882	117.49	17.02	3.114
54	1.871	116.81	17.12	3.154
55	1.860	116.12	17.22	3.193
56	1.849	115.43	17.33	3.232
57	1.838	114.75	17.43	3.270
58	1.827	114.06	17.53	3.308
59	1.816	113.37	17.64	3.344
60	1.805	112.69	17.75	3.381
61	1.794	112.00	17.86	3.416
62	1.783	111.31	17.97	3.451
63	1.772	110.63	18.08	3.485
64	1.761	109.94	18.19	3.518
65	1.750	109.25	18.31	3.551
66	1.740	108.63	18.41	3.585
67	1.730	108.00	18.52	3.618
68	1.720	107.38	18.63	3.651
69	1.710	106.76	18.73	3.683
70	1.700	106.13	18.84	3.715
71	1.690	105.51	18.96	3.745
72	1.680	104.88	19.07	3.776
73	1.670	104.26	19.18	3.805
74	1.660	103.63	19.30	3.834
75	1.650	103.01	19.42	3.863
76	1.640	102.39	19.53	3.891
77	1.630	101.76	19.65	3.918

Table 2. Recalculated volume-weight-oil yield relationships for Green River Formation oil shale. From Stanfield and others (1954).—Continued

[GPT, gallons per ton, lbs/ft^3, pounds per cubic feet, ft^3/ton, cubic feet per ton, gal/ft^3 , gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
78	1.620	101.14	19.78	3.944
79	1.610	100.51	19.90	3.970
80	1.600	99.89	20.02	3.996
90	1.500	93.65	21.36	4.214

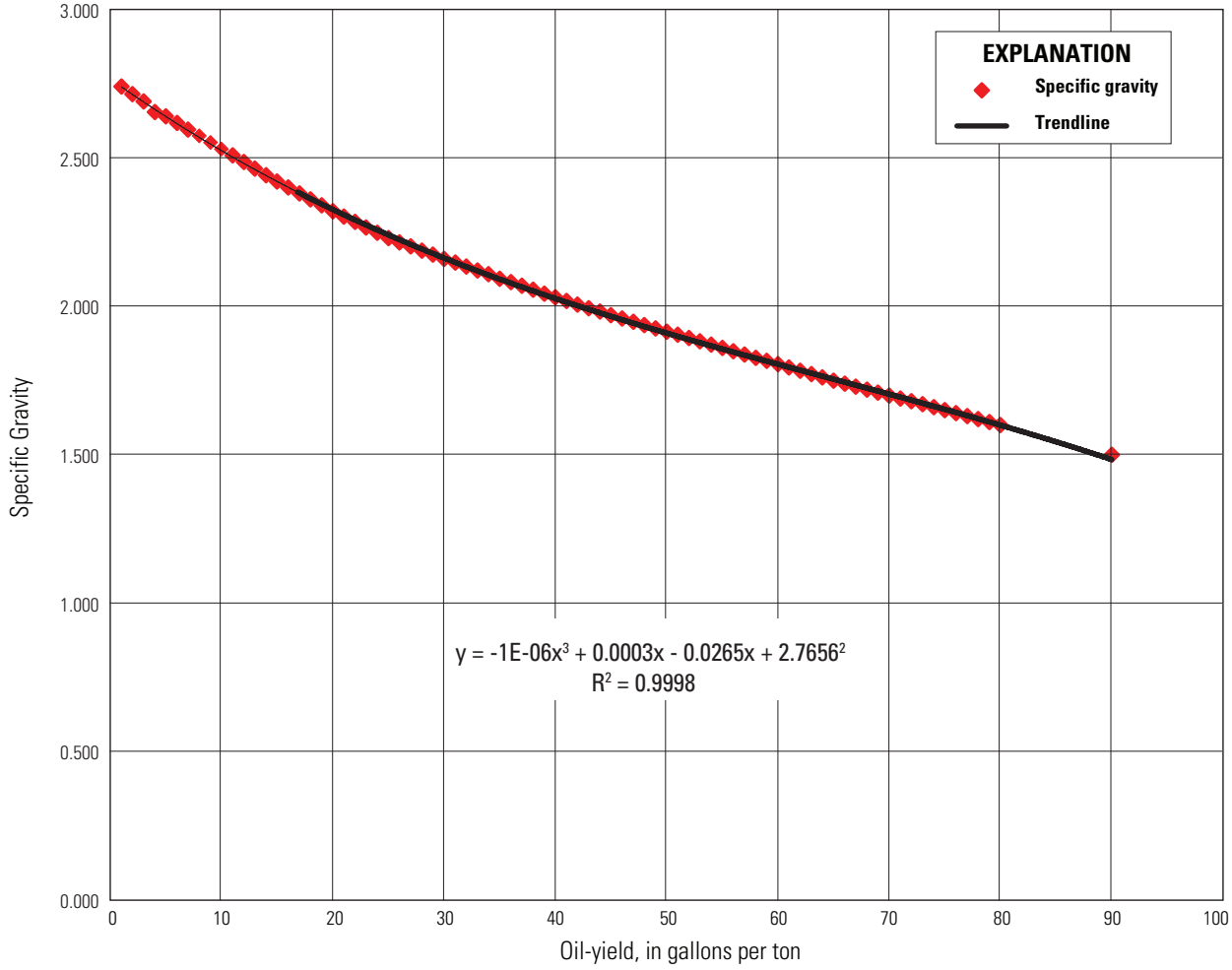


Figure 21. Graph showing the relationship between oil yield for Green River oil shales and specific gravity.

to increase as the percentage of missing core increases. This does not seem to be the case. In addition (Johnson and others, 2010a) demonstrated that both the number of missing intervals and thickness of individual missing intervals are also important because a large number of thin missing intervals randomly distributed throughout an oil shale zone are less likely to affect the average for that zone than if most of the missing core is concentrated in a single or a few missing intervals. Clearly, as the percent of missing intervals increases, the probability that the calculated oil-yield value for a zone will deviate from the true oil yield also increases. To minimize this problem, only those drill holes where there was 30 percent or less missing intervals for a particular oil shale zone were included in the assessment calculations.

Zero Values on Assay Tables

Zero values on the assay tables (chapter 2, this report) could represent (1) missing intervals; (2) intervals that were not assayed because they consist of lithologies, such as sandstone, siltstone, mudstone, limestone, and the saline minerals trona and halite, that were assumed to have no oil; and (or) (3) intervals that were assayed but produced no oil. As previously discussed, any missing interval in a particular oil shale zone was ascribed the average assay values of all core or cuttings for that zone, thus the missing intervals are assumed to have had "average" oil yields for that zone. If, however, an interval with a zero oil yield was assayed but produced no oil or was not assayed because it was assumed to have no oil, then assigning the average oil yield for the entire zone to that interval would artificially inflate the resource calculations for that zone.

When a sample is analyzed using Fischer assay, it will invariably yield some water even if no oil is produced. Of the 47,003 samples analyzed for the Greater Green River Basin, 10,864 listed zero oil recovered. Of these, 4,681 reported that some water was recovered, and it is assumed that these were assayed samples that yielded zero oil. These were given a minimum oil-yield value of 0.0001 GPT to distinguish them from the first two possibilities.

A large number of intervals with zero oil and zero water listed in the assay tables were apparently not assessed because they contain little or no kerogen. An examination of available sample descriptions revealed that many zero values corresponded to intervals in which sandstone, siltstone, and mudstone had been recovered. Unfortunately, sample descriptions were not recovered for many of the drill holes that were assayed, so other methods had to be used to try to identify unassessed intervals.

The Tipton Shale Member is subdivided into the Rife and Scheggs Beds, separated by the Farson Sandstone Member of the Green River Formation (fig. 3), a clastic-rich, kerogen-poor interval. The Rife and Scheggs Beds consist of nearly continuous oil shale, and it is likely that zero oil-yield values in these units represent missing intervals instead of unassessed intervals. These intervals were assumed to be missing and were assigned the average GPT value of the recovered samples. The Farson Sandstone, however, appears to have rarely been assessed, as the assay results for that interval list mainly zero oil and water yield values. For simplicity, we eliminated the entire Farson interval from the assessment of the Tipton.

Similarly, the LaClede Bed of the Laney Member consists mainly of oil shale, and any zero values were assumed to be missing intervals and assigned the average GPT value of the recovered samples. The LaClede Bed also contains a kerogen-poor clastic-rich zone, the buff marker bed, confined largely to the Washakie Basin. Like the Farson Sandstone, the carbonate marker appears to have been rarely assessed, and the interval was not included in the assessment of the LaClede Bed. Thus the Tipton Shale and the LaClede Bed both have clastic intervals that were not included when calculating the estimated GPT values for these zones. Had these clastic intervals been included the GPT values for the Tipton and LaClede would have been significantly lower. The BPA values for these assessed units should not be greatly affected by the omission of these clastic intervals as they contain little oil shale.

The Wilkins Peak Member throughout much of its extent consists of complexly interbedded oil shale and kerogen-poor lithologies such as sandstone, siltstone, mudstone, limestone, trona, and halite. Available sample descriptions and geophysical logs indicate that the majority of the intervals with zero oil and and water yields were not assessed rather than missing. The highest percentage of reported zero oil and water yield values is in the upper part of the Wilkins Peak near its western limit in the western part of the Green River Basin, where that part of the member grades into the Cathedral Bluffs Tongue of the Wasatch Formation (fig. 3). This "transitions zone", which contains minor thin oil shale beds interbedded with kerogen-poor rocks, was excluded from the Wilkins Peak and thus was not assessed. Figure 22 shows the percent of missing core in drill holes of the assessed part of the Wilkins Peak, generally 18 percent or less, except for six with 19 to 29 percent. All of the remaining zero GPT values reported within the assessed area were assumed to be missing intervals rather than non-analyzed intervals and thus were assigned the average GPT for the recovered Wilkins Peak core in that drill hole. By using this assumption, the in-place oil shale resources in the Wilkins Peak could possibly have been overestimated by some small amount. However, GPT values for the six drill holes with the highest missing percentages are similar to nearby drill holes with much smaller percentages of missing intervals, so it is unlikely that this overestimation is large. This is clearly an imperfect process for evaluating resources; the results could be improved if additional sample descriptions are obtained in the future.

Problems Related to Saline Minerals

The Wilkins Peak Member contains significant thicknesses of trona and halite beds throughout much of the Green

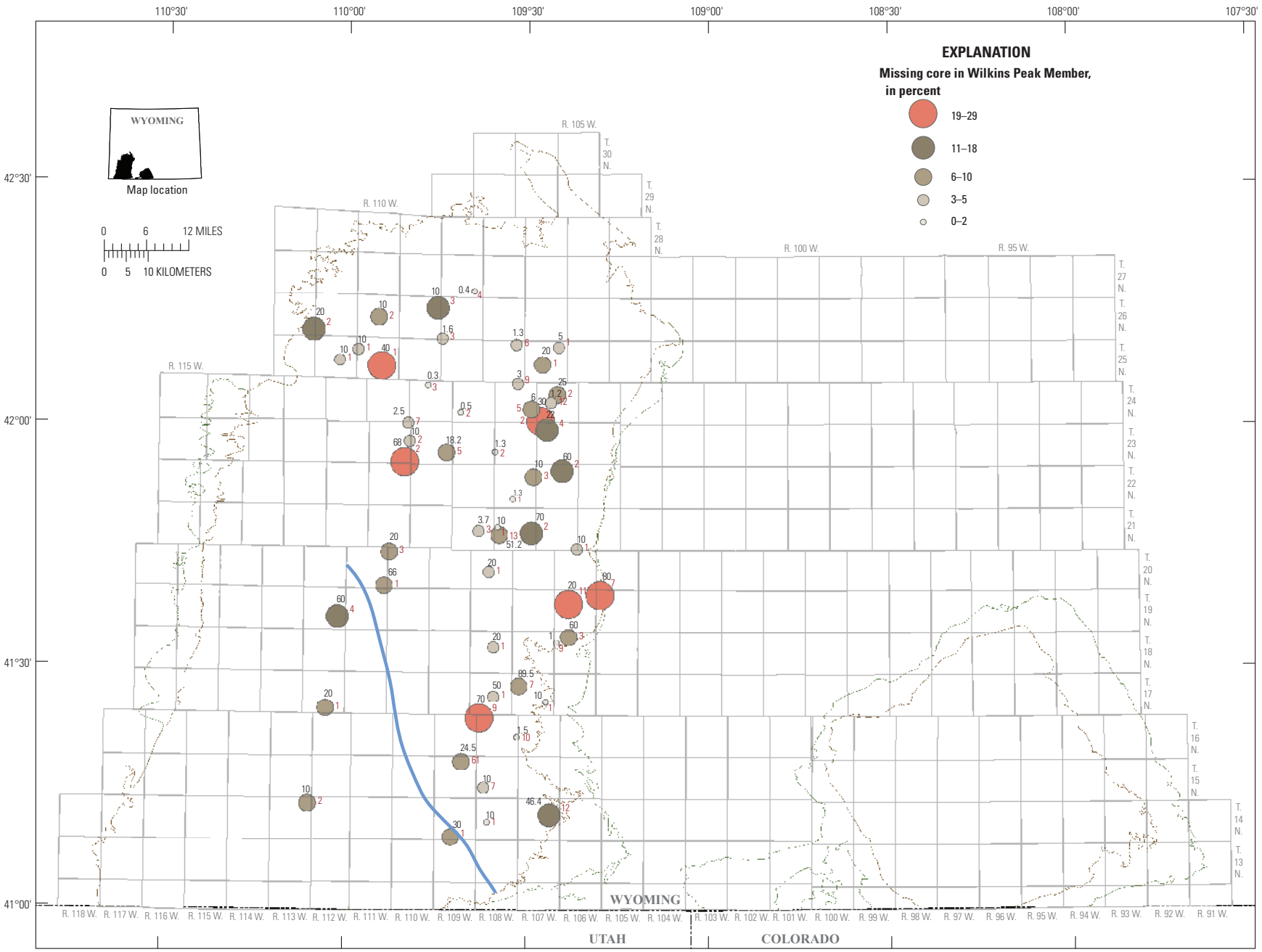


Figure 22. Percent missing intervals in the control points used to assess the Wilkins Peak Member.

River Basin that needed to be identified prior to making resource calculations. Sample descriptions of core holes indicate that trona and halite beds were commonly not analyzed. These beds were assigned minimum GPT value of 0.0001 GPT to distinguish them from missing intervals. In rotary holes, however, it is likely that all of the halite and much of the trona dissolved out of the cuttings before reaching the surface. Thus, the cuttings collected for these intervals would be largely from oil shale beds interbedded with the trona and halite and (or) oil shale cavings from above. Fischer assay analysis of intervals where geophysical logs indicated the presence of thick trona and halite beds commonly yielded significant oil apparently from the thin oil shale interbeds and oil shale cavings. There is no apparent way to precisely compensate for the dissolved trona and halite beds in these rotary holes, so we decided to simply calculate the percent of the total thickness that the trona and halite beds represented, and subtract that percent from the total BPA calculation for that hole.

Methods Used to Generate Isopach Maps and Isoresource Maps

Pitman and others (1989), in their assessment of the Piceance Basin, used geostatistical interpolation by kriging to generate their resource maps and resource numbers. According to them, statistical tests that were done prior to kriging indicated that oil shale resource values were "statistically homogeneous" or that BPA resource values for oil shale core holes spaced a short distance apart tended to be more alike than values for core holes that were farther apart. Pitman and others (1989) used a computer program called BLUEPACK to determine that variations in oil yield were linear for all of the oil shale zones except for two. For these two zones there was a significant amount of variation that could not be predicted from available data and a "nugget-only" model was used to try to capture this variability. Pitman and others (1989) determined that universal kriging gave good results in areas with good control, but in areas with little control such as basin-margin areas, universal kriging calculated anomalously large error limits—as much as nearly 1,300 percent,—and several townships had insufficient control for universal kriging to calculate any resource numbers. They manually determined in-place oil shale resources using isoresource contours and compared the results with those obtained from kriging. Their results were comparable for areas with good control, but for areas with limited control, such as the basin-margin areas, universal kriging greatly overestimated resources. For example, in the township with the approximately 1,300 percent error, kriging estimated 1.1 billion barrels of oil in place for one of the oil shale zones in the Piceance Basin, while hand contouring estimated only 219 million barrels.

We chose to use an RBF-multiquadric function instead of kriging as it facilitated a more rapid generation of models while providing better results than kriging in the areas with little data. The Inverse Distance Weighted (IDW) method was also tried. Both the RBF method and IDW method gave fairly similar results in areas with large numbers of control points, but the RBF method seemed to generate more reasonable results in marginal areas with little control. The RBF-multiquadric function in ESRI's Geostatistical Analyst provided a quick, exact interpolator, and kept the model within our methodology's native software format (ESRI's ArcGIS). Rusu and Rusu (2006) recently demonstrated that "soft computing methods" such as Radial Basis Functions (RBF) compare favorably with conventional "hard computing methods" such as kriging, and compared results when the RBF method and kriging were applied to the same data set. They cited a recent study in which the Radioactivity Environmental Monitoring Group of the Institute for Environment and Sustainability at the Joint Research Center of the European Commission invited participants to apply both RBF and kriging to a data set depicting variations in daily mean values of gamma-ray doses in southwestern Germany. Part of the data points were hidden, and the participants were asked to estimate values at these hidden locations using the data points given. In general, both the RBF method and kriging were equally good at predicting the correct results, except for areas with limited data where a proper variogram required for kriging is difficult to construct. In these areas, the RBF method gave better results. According to Rusu and Rusu (2006, p. 126) "The results and the execution time are quite similar for RBF and kriging, but the ease of use of RBF is overwhelming, compared to the use of kriging. When using RBF, the user has to choose only the radial functions type and the smoothing parameter. When using kriging, complex variogram modeling has to be done." The problems with generating a proper variogram with limited data may be in part why, in the previous assessment by Pitman and others (1989) kriging gave values with unacceptable margins of error for areas with limited data.

The RBF method in ESRI's GeoStatistical Analyst (GA) is an exact interpolator that will honor all data points and not introduce errors at those data point locations unless a smoothing function is used. If a smoothing function is used, the RBF can also extrapolate values above or below the actual values outside the data point locations. The final resource models were created with the RBF method using a sampling method containing eight moving window sectors with eight neighbors in each sector. No smoothing function was used. After numerous iterations, we determined that the RBF method using these parameters yields surfaces that we believe to best fit geologic relations.

Although the RBF method does not generate as complete an error estimate as kriging it does give the difference between the predicted and measured value for each control point, as well as the overall error for an entire map. To obtain the difference between the predicted value and the measured value, the RBF method predicts a value at a given control point from the eight nearest control points without knowing the actual value measured at that control point. That predicted value is then

compared with the measured value, and the difference between the two is calculated.

Four maps were generated for each oil shale zone assessed: (1) an isopach map, (2) variations in oil yield in GPT, (3) variations in BPA, and (4) total in-place oil in each 36 square mile township in the basin. The barrels-per-township maps were generated by first intersecting the Greater Green River Basin township polygon file with the outcrop polygon files. The resultant files included only those townships or parts of townships that are underlain by the oil shale zones to be assessed. Using ESRI's Spatial Analyst's Zonal Statistics function, we were able to quantify each township in each BPA resource model (cell size = 1 acre) by using each "clipped" township polygon (the result of intersecting the township polygon with the outcrop polygon) as the zone to quantify. In short, the function totals the sum of all of the one-acre cells contained by each polygon to be assessed in the zone dataset. The resultant summary table (table 3) contains a sum total of barrels for each township, as well as several other statistics. Maps were then generated by joining the summary table to each zone polygon file. For a more complete explanation of this procedure see Mercier and others (this report).

Assessment Results

An assessment is presented here of all oil shale regardless of grade in the Tipton Shale Member, the Wilkins Peak Member and the LaClede Bed of the Laney Member in the Green River and Washakie Basins of the Greater Green River Basin (fig. 2). The oil shale resources in the Great Divide and Sand Wash Basins were not assessed because surface sections (Roehler, 1989a, d, e) and the limited Fischer assay data available indicate that only very low-grade oil shale is present there. No attempt was made to estimate the amount of oil that is economically recoverable, largely because there has yet to be a process developed to recover oil economically from Green River oil shale. Estimates of the amount of shale oil that is technically recoverable without considering economics have been made for the Piceance Basin of western Colorado but not for the Greater Green River Basin. Estimates for the Piceance Basin using underground room-and pillar mining methods vary from 45 percent (Taylor, 1987) to 55 to 75 percent (Prien, 1974) and as high as 80 percent for open pit mining (Taylor, 1987). Recoveries will be likely lower in the Greater Green River Basin, if indeed production does take place, because most of the oil shale in the Wilkins Peak Member (fig. 3) is interbedded with barren rock. At present, there are no estimates of the percent of the resource that could be recovered using the *in-situ* methods that are currently being developed. However, Taylor (1987) stressed that the amount of oil that can be recovered from any *in-situ* process depends on both the percent of oil that can be recovered from within the retort and the amount of oil left behind in the spaces between retorts. The *in-situ* method, currently being developed by Shell Exploration and Development in the Piceance Basin (Vinigar, 2006), uses a freeze wall to isolate the *in-situ* retort, and it would probably not be possible to recover oil in the area occupied by the freeze walls. The dimensions of the freeze wall that Shell will ultimately use in commercial retorts have not been established.

Although it is not feasible to estimate volumes of economically recoverable shale oil at this time, our primary goals here is to provide basic geologic and resource data that will facilitate the making of such estimates once extraction methods are developed. For instance, Mercier and others (this report) calculate cubic meters of overburden on the Laney and Tipton Shale Members. These calculations can be integrated with estimates of in place oil to generate "strip ratio" maps for strip mining the oil shale. For each of the three units of the Green River Formation included in this assessment in ascending order: the Tipton Shale Member, Wilkins Peak Member, and LaClede Bed of the Laney Member, four maps were generated: (1) isopach map, (2) isoresource map showing variations in GPT, (3) isoresource map showing variations in BPA, and (4) isoresource map showing total amount of in-place oil in each 36-square mile township. Figure 23 is an isopach map that includes all three assessed units, as well as the thick, unassessed clastic-rich intervals of the Farson Sandstone Member of the Green River Formation and the Cathedral Bluffs Tongue of the Wasatch Formation (fig. 3). Only in the southeastern part of the Green River Basin do all three assessed oil shale units occur in a continuous stratigraphic sequence, but even in this limited area there are numerous sandstone, siltstone, and mudstone units within the Wilkins Peak Member. The isopach interval thickens from 750 ft in the northern part of the Green River Basin to more than 2,200 ft in the southern part of the Green River Basin adjacent to the Uinta Mountains, and reaches a maximum of 3,360 ft in the central part of the Washakie Basin (fig. 23). The southward and southeastward thickening of this interval is largely due to increased subsidence in those directions. In addition, the upper contact of the LaClede Bed climbs stratigraphically to the south and southeast as northward-thickening units of mainly volcaniclastics rocks wedge out (pl. 1, fig. 20, sandstone, marlstone, and thin beds of limestone and oil shale facies).

Tipton Shale Member

The Tipton Shale Member is assessed as a single unit and not subdivided into the Scheggs and Rife Beds. This is in large part because the Farson Sandstone Member, which separates the Scheggs and Rife Beds, is thin or absent throughout much of the Green River and Washakie Basins, and in these areas it is difficult to distinguish between the Scheggs and Rife Beds in the subsurface. The base of the member as mapped by Tweto (1979) and Love and Christiansen (1985), was used to define its extent in the Washakie Basin and along the eastern margin of the Green River Basin. The base of the Wilkins Peak Member, as mapped by Love and Christiansen (1985), is used to define the extent of the Tipton in the western part

Table 3. In-place oil resources, in barrels of oil, in the Green River Formation, Greater Green River Basin, Wyoming.

Township	Range	Tipton	Wilkins Peak	LaClede	Township
T29N	R108W	0	118,371,000	0	118,371,000
T29N	R107W	0	47,217,400	0	47,217,400
T28N	R112W	0	364,673	55,265	419,938
T28N	R111W	0	162,311,000	21,241,900	183,552,900
T28N	R110W	567,039,000	983,327,000	0	1,550,366,000
T28N	R109W	703,808,000	1,019,430,000	0	1,723,238,000
T28N	R108W	0	764,592,000	0	764,592,000
T28N	R107W	0	634,965,000	0	634,965,000
T27N	R112W	0	189,180,000	29,545,100	218,725,100
T27N	R111W	0	1,185,690,000	164,510,000	1,350,200,000
T27N	R110W	940,662,000	1,869,190,000	0	2,809,852,000
T27N	R109W	944,541,000	1,983,820,000	0	2,928,361,000
T27N	R108W	0	1,507,820,000	0	1,507,820,000
T27N	R107W	0	1,411,850,000	386,140,000	1,797,990,000
T27N	R106W	0	1,179,830,000	347,082,000	1,526,912,000
T27N	R105W	0	1,375,840,000	397,413,000	1,773,253,000
T27N	R104W	0	0	121,845,000	121,845,000
T26N	R112W	0	423,138,000	77,620,800	500,758,800
T26N	R111W	0	1,304,840,000	235,771,000	1,540,611,000
T26N	R110W	794,690,000	1,633,470,000	346,832,000	2,774,992,000
T26N	R109W	821,072,000	2,399,880,000	466,563,000	3,687,515,000
T26N	R108W	0	2,670,630,000	562,789,000	3,233,419,000
T26N	R107W	0	2,481,340,000	674,743,000	3,156,083,000
T26N	R106W	358,551,000	2,244,360,000	578,356,000	3,181,267,000
T26N	R105W	174,846,000	2,253,530,000	536,132,000	2,964,508,000
T26N	R104W	0	0	473,514,000	473,514,000
T25N	R112W	364,385,000	968,957,000	147,107,000	1,480,449,000
T25N	R111W	480,018,000	1,799,530,000	314,869,000	2,594,417,000
T25N	R110W	591,912,000	2,020,850,000	502,032,000	3,114,794,000
T25N	R109W	548,298,000	3,070,010,000	612,637,000	4,230,945,000
T25N	R108W	774,453,000	5,000,210,000	877,371,000	6,652,034,000
T25N	R107W	723,634,000	4,444,390,000	821,023,000	5,989,047,000
T25N	R104W	0	2,470,920,000	648,569,000	3,119,489,000
T25N	R105W	155,270,000	3,406,710,000	723,947,000	4,285,927,000
T25N	R103W	0	189,488,000	0	189,488,000
T25N	R106W	326,532,000	3,864,680,000	724,874,000	4,916,086,000
T24N	R112W	640,307,000	1,965,960,000	265,792,000	2,872,059,000
T24N	R111W	580,023,000	2,489,040,000	423,959,000	3,493,022,000
T24N	R110W	434,462,000	3,625,670,000	478,522,000	4,538,654,000
T24N	R109W	315,678,000	4,988,040,000	1,260,550,000	6,564,268,000
T24N	R108W	717,101,000	5,307,110,000	1,550,220,000	7,574,431,000
T24N	R107W	756,340,000	4,182,100,000	1,089,590,000	6,028,030,000
T24N	R104W	0	614,855,000	166,798,000	781,653,000
T24N	R105W	157,872,000	3,683,760,000	783,550,000	4,625,182,000
T24N	R106W	474,460,000	4,665,350,000	971,158,000	6,110,968,000

Table 3. In-place oil resources, in barrels of oil, in the Green River Formation, Greater Green River Basin, Wyoming.—Continued

Township	Range	Tipton	Wilkins Peak	LaClede	Township
T23N	R112W	793,128,000	2,663,720,000	304,983,000	3,761,831,000
T23N	R109W	732,497,000	7,191,740,000	1,120,420,000	9,044,657,000
T23N	R110W	636,501,000	5,313,160,000	658,092,000	6,607,753,000
T23N	R105W	166,240,000	5,044,030,000	1,042,370,000	6,252,640,000
T23N	R106W	919,517,000	7,391,330,000	1,126,240,000	9,437,087,000
T23N	R107W	1,473,040,000	5,947,250,000	1,536,340,000	8,956,630,000
T23N	R111W	713,382,000	3,201,840,000	447,111,000	4,362,333,000
T23N	R108W	993,281,000	8,087,850,000	1,762,860,000	10,843,991,000
T22N	R112W	805,259,000	3,229,930,000	0	4,035,189,000
T22N	R111W	914,680,000	4,097,450,000	0	5,012,130,000
T22N	R110W	956,437,000	5,480,680,000	814,455,000	7,251,572,000
T22N	R105W	464,511,000	4,505,770,000	1,009,700,000	5,979,981,000
T22N	R106W	1,820,580,000	8,837,310,000	1,471,140,000	12,129,030,000
T22N	R107W	2,695,680,000	8,106,310,000	1,471,410,000	12,273,400,000
T22N	R108W	1,654,720,000	8,291,250,000	1,122,970,000	11,068,940,000
T22N	R109W	1,093,570,000	7,025,720,000	924,211,000	9,043,501,000
T21N	R112W	944,487,000	4,108,300,000	0	5,052,787,000
T21N	R111W	1,402,360,000	4,645,230,000	0	6,047,590,000
T21N	R110W	1,547,710,000	5,942,400,000	534,469,000	8,024,579,000
T21N	R109W	1,578,250,000	8,298,960,000	688,156,000	10,565,366,000
T21N	R108W	1,978,500,000	9,803,840,000	873,463,000	12,655,803,000
T21N	R107W	2,154,980,000	9,943,940,000	1,442,790,000	13,541,710,000
T21N	R106W	2,575,180,000	8,351,110,000	2,045,170,000	12,971,460,000
T21N	R105W	1,354,860,000	3,154,240,000	1,035,890,000	5,544,990,000
T20N	R113W	691,468,000	4,709,110,000	0	5,400,578,000
T20N	R112W	1,244,620,000	5,289,080,000	0	6,533,700,000
T20N	R111W	2,112,160,000	4,631,450,000	273,540,000	7,017,150,000
T20N	R110W	2,472,840,000	7,435,490,000	539,873,000	10,448,203,000
T20N	R109W	2,272,600,000	13,158,600,000	778,710,000	16,209,910,000
T20N	R107W	2,707,450,000	10,311,200,000	2,699,300,000	15,717,950,000
T20N	R106W	3,416,220,000	5,640,800,000	2,507,170,000	11,564,190,000
T20N	R105W	376,586,000	292,160,000	118,184,000	786,930,000
T20N	R108W	2,277,180,000	17,353,600,00	1,312,040,000	20,942,820,000
T19N	R113W	615,626,000	5,708,720,000	0	6,324,346,000
T19N	R112W	1,286,320,000	7,335,280,000	50,875,500	8,672,475,500
T19N	R111W	2,751,080,000	6,518,500,000	417,838,000	9,687,418,000
T19N	R109W	3,094,890,000	14,722,300,00	1,422,870,000	19,240,060,000
T19N	R110W	3,415,140,000	8,993,320,000	889,339,000	13,297,799,000
T19N	R108W	2,853,190,000	17,088,600,00	2,034,990,000	21,976,780,000
T19N	R107W	3,171,760,000	11,358,600,00	2,578,470,000	17,108,830,000
T19N	R106W	3,559,460,000	8,704,130,000	2,264,880,000	14,528,470,000
T19N	R105W	646,397,000	817,385,000	269,759,000	1,733,541,000
T19N	R97W	373,225,000	0	0	373,225,000
T19N	R94W	1,001,430,000	0	0	1,001,430,000
T19N	R95W	2,167,270,000	0	0	2,167,270,000

Table 3. In-place oil resources, in barrels of oil, in the Green River Formation, Greater Green River Basin, Wyoming.—Continued

Township	Range	Tipton	Wilkins Peak	LaClede	Township
T19N	R96W	1,734,000,000	0	0	1,734,000,000
T18N	R113W	1,370,600,000	5,571,100,000	0	6,941,700,000
T18N	R112W	2,201,250,000	6,677,730,000	112,916,000	8,991,896,000
T18N	R111W	3,865,510,000	7,404,940,000	796,567,000	12,067,017,000
T18N	R109W	3,798,490,000	14,240,100,00	2,637,050,000	20,675,640,000
T18N	R110W	4,756,560,000	10,307,000,00	2,254,900,000	17,318,460,000
T18N	R108W	3,076,960,000	14,961,800,00	2,826,470,000	20,865,230,000
T18N	R107W	3,413,290,000	6,972,110,000	2,068,050,000	12,453,450,000
T18N	R106W	2,921,200,000	3,004,000,000	585,228,000	6,510,428,000
T18N	R105W	13,030,800	0	0	13,030,800
T18N	R98W	360,180,000	0	11,752,900	371,932,900
T18N	R97W	2,700,400,000	0	1,404,010,000	4,104,410,000
T18N	R94W	2,301,010,000	0	0	2,301,010,000
T18N	R93W	155,992,000	0	0	155,992,000
T18N	R95W	3,286,470,000	0	0	3,286,470,000
T18N	R96W	3,428,610,000	0	2,575,320,000	6,003,930,000
T17N	R113W	2,254,450,000	4,677,370,000	30,926,300	6,962,746,300
T17N	R112W	3,769,110,000	5,153,430,000	353,822,000	9,276,362,000
T17N	R111W	5,247,060,000	6,662,620,000	1,293,510,000	13,203,190,000
T17N	R110W	5,548,620,000	9,974,220,000	2,868,580,000	18,391,420,000
T17N	R109W	4,111,750,000	13,645,200,00	3,409,900,000	21,166,850,000
T17N	R108W	3,586,250,000	16,458,700,00	3,054,030,000	23,098,980,000
T17N	R107W	4,585,560,000	10,432,800,00	3,056,280,000	18,074,640,000
T17N	R106W	2,835,760,000	12,590,900	2,883,760	2,851,234,660
T17N	R100W	235,093,000	0	11,922,000	247,015,000
T17N	R99W	1,843,090,000	0	171,965,000	2,015,055,000
T17N	R98W	2,517,620,000	0	2,646,740,000	5,164,360,000
T17N	R97W	3,324,440,000	0	3,976,900,000	7,301,340,000
T17N	R94W	1,537,990,000	0	0	1,537,990,000
T17N	R93W	510,771,000	0	0	510,771,000
T17N	R96W	4,098,010,000	0	3,932,250,000	8,030,260,000
T17N	R95W	3,351,260,000	0	3,447,080,000	6,798,340,000
T16N	R113W	3,075,390,000	3,616,660,000	312,939,000	7,004,989,000
T16N	R112W	4,209,960,000	3,563,380,000	765,435,000	8,538,775,000
T16N	R111W	6,047,200,000	6,058,530,000	1,691,340,000	13,797,070,000
T16N	R110W	6,106,510,000	8,921,940,000	2,758,660,000	17,787,110,000
T16N	R109W	4,556,530,000	10,939,600,000	3,561,850,000	19,057,980,000
T16N	R108W	4,077,520,000	10,902,000,000	4,043,240,000	19,022,760,000
T16N	R107W	4,359,320,000	4,993,070,000	2,090,310,000	11,442,700,000
T16N	R106W	1,813,750,000	0	0	1,813,750,000
T16N	R100.5	654,163	0	0	654,163
T16N	R100W	1,484,400,000	0	3,450,770,000	4,935,170,000
T16N	R99W	2,690,670,000	0	7,309,480,000	10,000,150,000
T16N	R98W	3,135,460,000	0	7,892,140,000	11,027,600,000
T16N	R96W	4,455,430,000	0	6,175,040,000	10,630,470,000

Table 3. In-place oil resources, in barrels of oil, in the Green River Formation, Greater Green River Basin, Wyoming.—Continued

Township	Range	Tipton	Wilkins Peak	LaClede	Township
T16N	R97W	3,836,310,000	0	7,078,270,000	10,914,580,000
T16N	R95W	2,811,110,000	0	4,655,720,000	7,466,830,000
T16N	R94W	750,275,000	0	2,019,790,000	2,770,065,000
T16N	R93W	320,025,000	0	1,466,460	321,491,460
T16N	R92W	22,227,700	0	0	22,227,700
T15N	R112W	4,640,330,000	2,868,270,000	1,146,440,000	8,655,040,000
T15N	R111W	6,078,260,000	5,484,680,000	1,804,660,000	13,367,600,000
T15N	R110W	6,565,230,000	7,891,340,000	2,795,220,000	17,251,790,000
T15N	R109W	5,223,050,000	9,739,810,000	3,537,150,000	18,500,010,000
T15N	R108W	4,615,580,000	9,605,490,000	4,590,050,000	18,811,120,000
T15N	R107W	4,471,050,000	5,676,700,000	2,893,380,000	13,041,130,000
T15N	R113W	3,075,170,000	2,402,210,000	575,103,000	6,052,483,000
T15N	R106W	2,927,100,000	884,462,000	424,779,000	4,236,341,000
T15N	R101W	596,454,000	0	0	596,454,000
T15N	R100.5	42,345,200	0	0	42,345,200
T15N	R100W	3,531,500,000	0	4,019,350,000	7,550,850,000
T15N	R99W	3,918,240,000	0	10,112,400,000	14,030,640,000
T15N	R98W	3,626,860,000	0	10,715,000,000	14,341,860,000
T15N	R97W	3,765,790,000	0	10,000,900,000	13,766,690,000
T15N	R96W	3,329,130,000	0	7,478,500,000	10,807,630,000
T15N	R95W	0	0	5,600,990,000	5,600,990,000
T15N	R94W	0	0	4,139,440,000	4,139,440,000
T15N	R93W	0	0	1,380,870,000	1,380,870,000
T14N	R112W	3,645,780,000	2,966,840,000	1,249,240,000	7,861,860,000
T14N	R111W	4,264,060,000	4,279,390,000	1,965,630,000	10,509,080,000
T14N	R108W	4,907,040,000	9,703,760,000	4,546,940,000	19,157,740,000
T14N	R107W	4,822,490,000	7,752,330,000	4,023,480,000	16,598,300,000
T14N	R110W	4,871,570,000	6,678,950,000	3,317,750,000	14,868,270,000
T14N	R109W	5,192,870,000	9,240,780,000	4,457,840,000	18,891,490,000
T14N	R106W	4,337,120,000	651,988,000	332,465,000	5,321,573,000
T14N	R105W	740,429,000	0	0	740,429,000
T14N	R113W	2,313,190,000	2,887,030,000	660,602,000	5,860,822,000
T14N	R100W	3,260,940,000	0	358,705,000	3,619,645,000
T14N	R99W	4,111,950,000	0	8,218,970,000	12,330,920,000
T14N	R98W	2,886,920,000	0	10,532,500,000	13,419,420,000
T14N	R97W	2,262,140,000	0	11,541,600,000	13,803,740,000
T14N	R96W	2,097,770,000	0	9,887,620,000	11,985,390,000
T14N	R95W	0	0	6,801,990,000	6,801,990,000
T14N	R94W	0	0	5,589,650,000	5,589,650,000
T14N	R93W	0	0	5,005,050,000	5,005,050,000
T14N	R92W	0	0	572,058,000	572,058,000
T13N	R111W	2,504,850,000	2,386,970,000	1,500,270,000	6,392,090,000
T13N	R110W	3,631,030,000	5,052,830,000	3,219,030,000	11,902,890,000
T13N	R112W	1,715,410,000	2,575,270,000	912,083,000	5,202,763,000

Table 3. In-place oil resources, in barrels of oil, in the Green River Formation, Greater Green River Basin, Wyoming.—Continued

Township	Range	Tipton	Wilkins Peak	LaClede	Township
T13N	R108W	4,612,720,000	8,757,290,000	4,735,060,000	18,105,070,000
T13N	R109W	4,480,920,000	7,791,190,000	4,657,260,000	16,929,370,000
T13N	R107W	0	2,974,070,000	1,617,100,000	4,591,170,000
T13N	R113W	1,243,750,000	3,203,940,000	0	4,447,690,000
T13N	R100W	1,333,210,000	0	0	1,333,210,000
T13N	R99W	2,017,270,000	0	3,652,090,000	5,669,360,000
T13N	R98W	1,663,890,000	0	9,644,310,000	11,308,200,000
T13N	R97W	1,178,630,000	0	10,951,600,000	12,130,230,000
T13N	R96W	1,168,570,000	0	10,172,100,000	11,340,670,000
T13N	R95W	0	0	7,763,970,000	7,763,970,000
T13N	R94W	0	0	5,147,800,000	5,147,800,000
T13N	R93W	0	0	1,188,330,000	1,188,330,000
T13N	R92W	0	0	80,333,000	80,333,000
T12N	R111W	0	1,564,730,000	1,087,430,000	2,652,160,000
T12N	R112W	0	1,432,400,000	631,477,000	2,063,877,000
T12N	R109W	0	3,167,760,000	2,032,660,000	5,200,420,000
T12N	R108W	0	2,032,600,000	1,215,810,000	3,248,410,000
T12N	R110W	0	2,833,810,000	1,980,000,000	4,813,810,000
T12N	R107W	0	19,232,200	11,182,300	30,414,500
T12N	R99W	717,026,000	0	0	717,026,000
T12N	R98W	708,072,000	0	0	708,072,000
T12N	R97W	529,838,000	0	0	529,838,000
T12N	R96W	475,228,000	0	0	475,228,000
Total		377,184,520,285	1,444,991,951,321	362,816,116,863	704,991,314,173

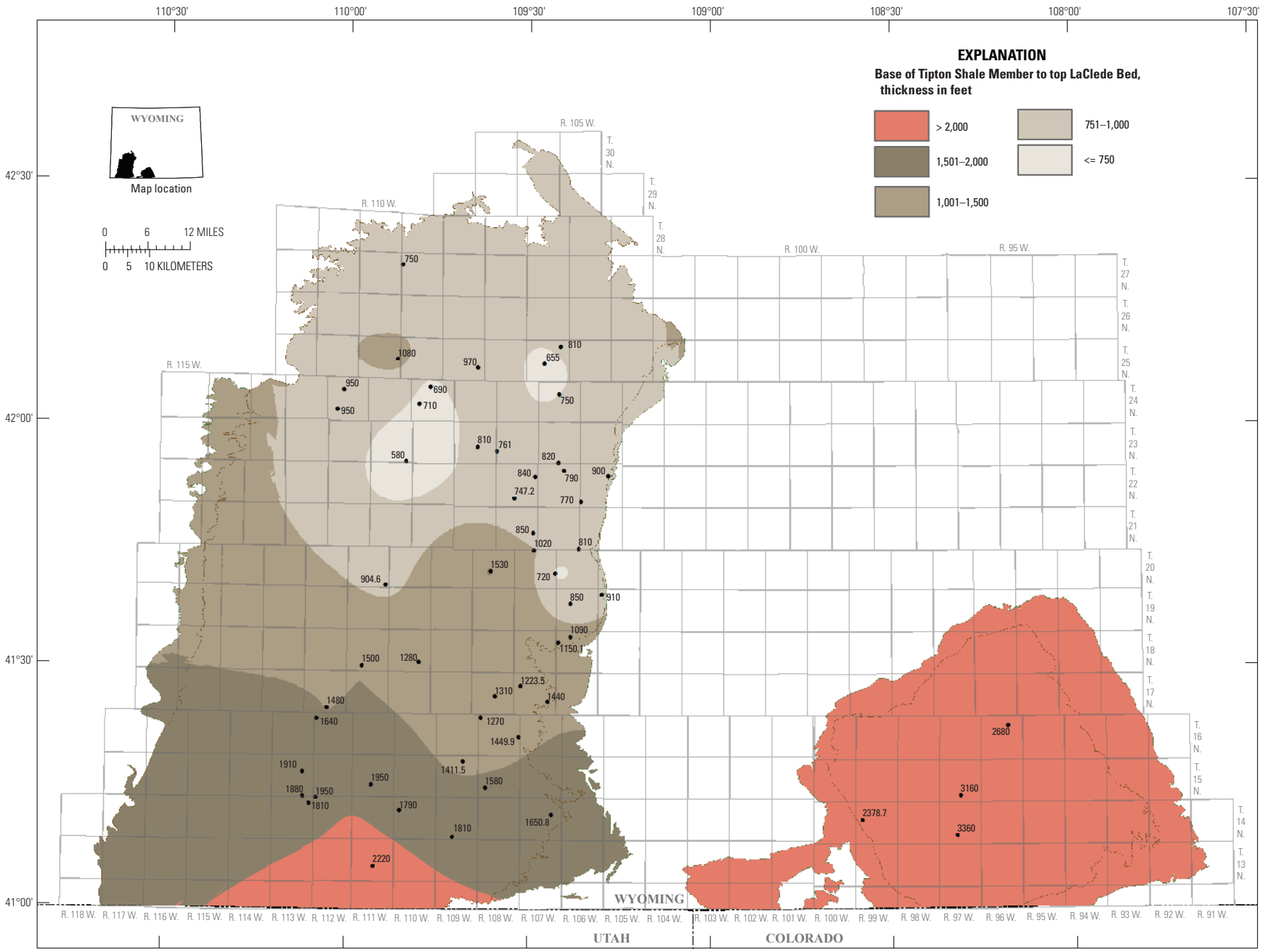


Figure 23. Isopach map of the total assessed interval in the Green River Basin.

of the Green River Basin where the base of the Tipton has not been mapped. In the northern part of the Green River Basin (fig. 3), the base of the Laney Member, as mapped by Love and Christiansen (1985) was used, as the base of the Tipton has not been mapped there. According to Roehler (1992b), the top of the Rife Bed is close to the base of the Laney in that area (fig. 12).

The top and base of the Tipton, as defined by us in the Washakie Basin, are stratigraphically different than those of Roehler (1989d, e). He picked his contacts based on his concepts concerning the development of Lake Gosiute, whereas we chose contacts that would best characterize the oil shale deposit. Roehler (1989d, e) included an interval of lacustrine shale with low oil yields in the lower part of his Tipton that we excluded because it does not contain significant oil shale; if included, it would have significantly lowered the average oil yield of the Tipton Shale Member in the Washakie Basin. An oil shale sequence immediately overlying the Tipton as defined by Roehler (1989d, e) in the Washakie Basin, was included by him in the overlying Wilkins Peak Member because he believed it to be genetically related to the Wilkins Peak phase of the lake. This sequence forms a single unbroken oil shale sequence with the underlying Tipton Shale, and we included it in the Tipton for assessment purposes.

Figure 24 is an isopach map of the Tipton Shale Member. In the Washakie Basin, it is 310 to 390 ft thick along a northeast-trending area that includes the deep trough of the basin and a portion of the southwest basin margin. In the Green River Basin, it varies in an irregular fashion from 128 to over 400 ft thick. The Tipton thickens to as much as 411 ft in the northern part of the Green River Basin as a result of the northward thickening of the Farson Sandstone Member, which separates the Rife Bed and Scheggs Beds of the Tipton (fig. 3). The Farson thickens to the north across the Green River Basin from a minimum of less than 5 ft in the southeast part to a maximum of 790 ft in the northern part (figs. 8, 12). The Rife Bed, however, could only be recognized locally in the northern part of the Green River Basin. Where the Rife bed is absent, the Tipton consists of only the Scheggs Bed and thins to as little as 20 ft (fig. 24).

A total of 18 core holes and 65 rotary holes were used in assessing the oil shale resources in the Tipton Shale Member (fig. 24); total area assessed is 5,088 mi^2, which excluded some basin margin areas where control is sparse (fig. 24). As previously discussed, the Farson Sandstone Member where present was subtracted from the Tipton Shale Member interval and not assessed. Figure 25 is an isoresource map showing variations in GPT; oil yields are generally greater than 15 GPT throughout much of Green River Basin, reaching a maximum of 22.3 GPT in the south-central part. Oil yields decrease to the north across the Green River Basin with values reaching a minimum of less than 7.5 GPT in the northern part of the Basin (fig. 25). Oil yields in the Washakie Basin vary from 1.2 to 11.5 GPT, with the highest values along the northwest margin of the basin. Total in-place oil (1) reaches a maximum of 345,000 BPA in the south-central part of the Green River sub-basin, decreasing in all directions away from this depocenter, and (2) varies from 160,000 to 253,000 BPA along a northeast trend in the northern part of the Washakie Basin (fig. 26). Maximum in-place oil in a single township is nearly 6.6 billion barrels in the south-central part of the Green River Basin (fig. 27). Total in-place oil in the Tipton Shale Member is estimated at 362,816,000,000 barrels, of which some 4.1 billion barrels are in the Washakie Basin (table 3).

Wilkins Peak Member

The Wilkins Peak Member is assessed here as a single unit, however, as more data become available it should be possible to assess individual oil shale zones based on the regional stratigraphic framework that has been established (fig. 12). The top of the Wilkins Peak Member–base of the Laney Member as mapped by Love and Christiansen (1985) was used to define the limits of the Wilkins Peak assessment unit.

Figure 28 is an isopach map from the base of the LaClede Bed of the Laney Member to the top of the Tipton Shale Member (see fig. 3). It includes the entire stratigraphic interval of the Wilkins Peak as well as laterally equivalent parts of the Cathedral Bluffs Tongue of the Wasatch Formation in basin margin areas (fig. 3). In areas of the northern part of the Green River Basin where the Rife Bed of the Tipton Shale Member is absent, the isopach interval extends from the base of the LaClede Bed to the top of the Scheggs Bed of the Tipton Shale Member. Although both the upper and lower contacts of this interval are time transgressive, the thickness variations shown are generally related to variations in subsidence during this time period. The interval thickens to the south across the Green River Basin from less than 100 ft in the northern part of the basin to 1,800 ft along the south margin of the Green River Basin adjacent to the Uinta Mountains (fig. 28). There are only four control points in the Washakie Basin, but the interval is thickest near the middle of the basin, 2,160 to 2,440 ft and thinnest near the basin margins, 1,803 to1,870 ft (fig. 28).

Figure 29 is an isopach map of that part of the Wilkins Peak Member that was assessed. This interval reaches a maximum thickness of over 1,500 ft locally in the southern part of the Green River Basin. It thins to the west and south due to the upper part grading laterally into the Cathedral Bluffs Tongue of the Wasatch Formation. It also thins to the north due to a combination of lower subsidence rates and grading in part into the Cathedral Bluffs Tongue of the Wasatch Formation and Farson Sandstone Member of the Green River Formation (fig. 12). A comparatively thin interval of the member was identified along the west margin of the Washakie Basin between the Cathedral Bluffs Tongue of the Wasatch Formation and the Tipton Shale Member by Roehler (1989d), but was not assessed here because it lacks significant oil shale. Farther to the east in the Washakie Basin the entire Wilkins Peak grades into the Cathedral Bluffs Tongue.

A total of 33 core holes and 58 rotary holes were used in our assessment of oil shale resources in the Wilkins Peak

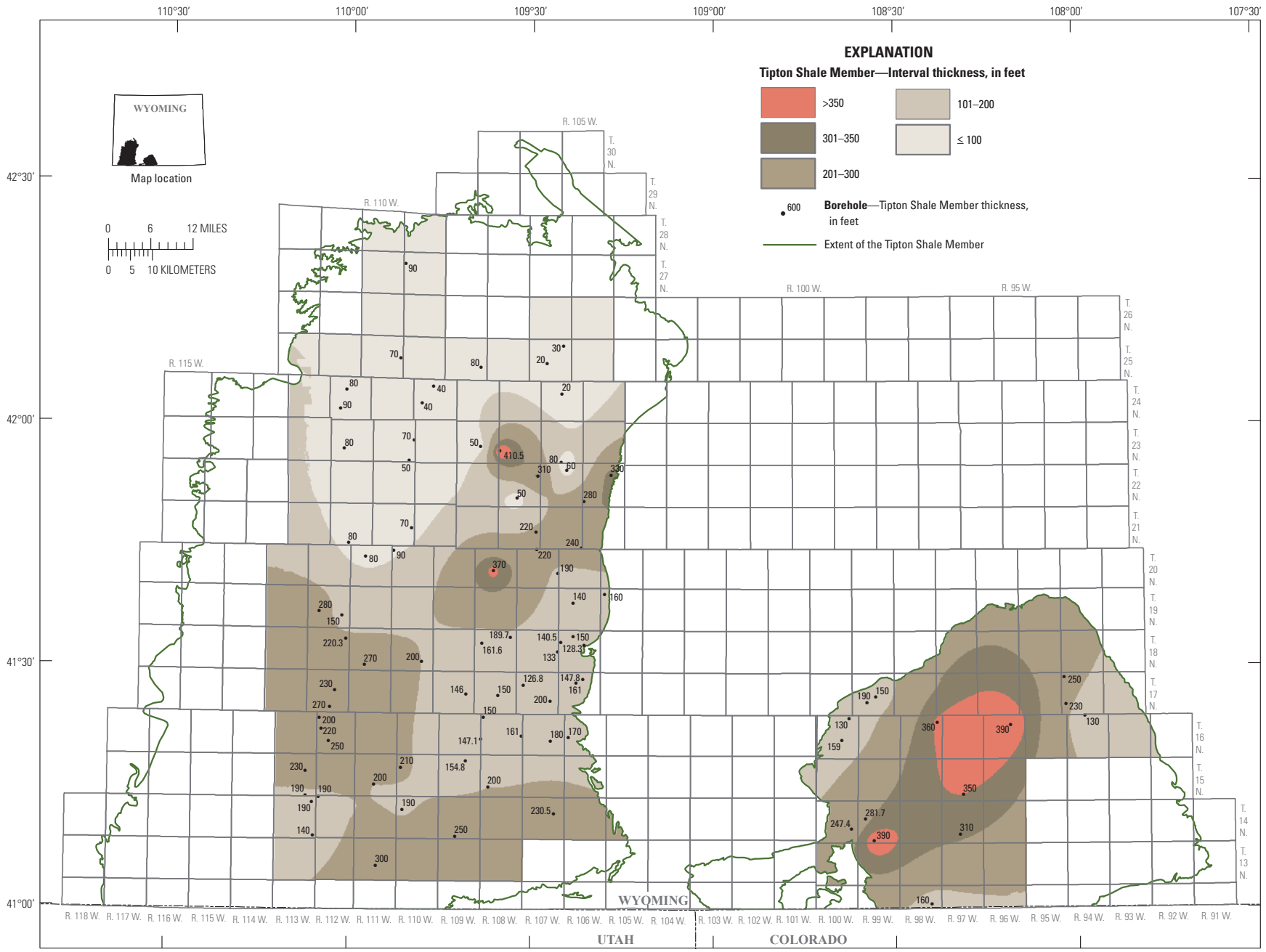


Figure 24. Isopach map of the Tipton Shale Member.

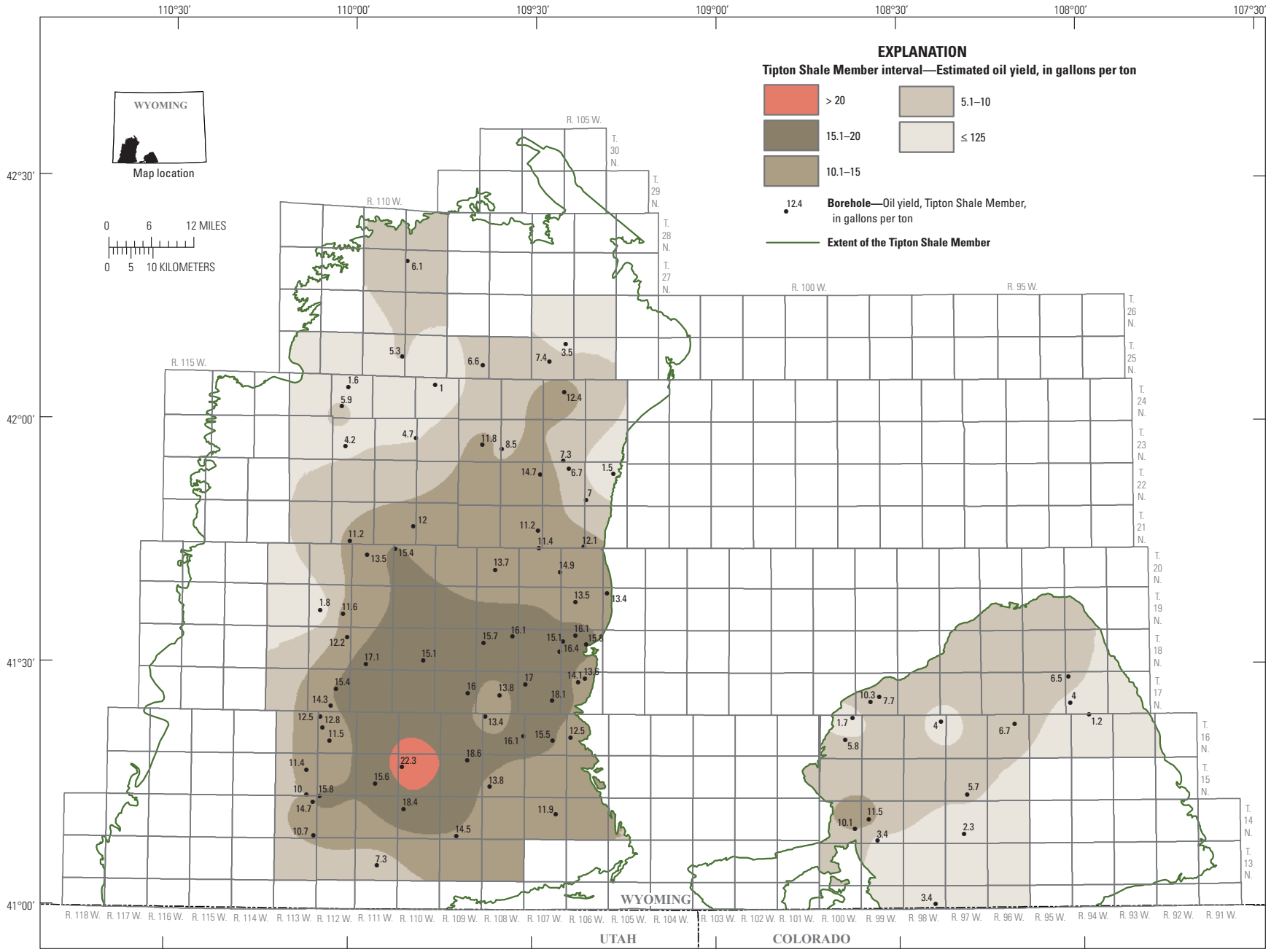


Figure 25. Isoresource map showing the oil yield in gallons per ton for the Tipton Shale Member.

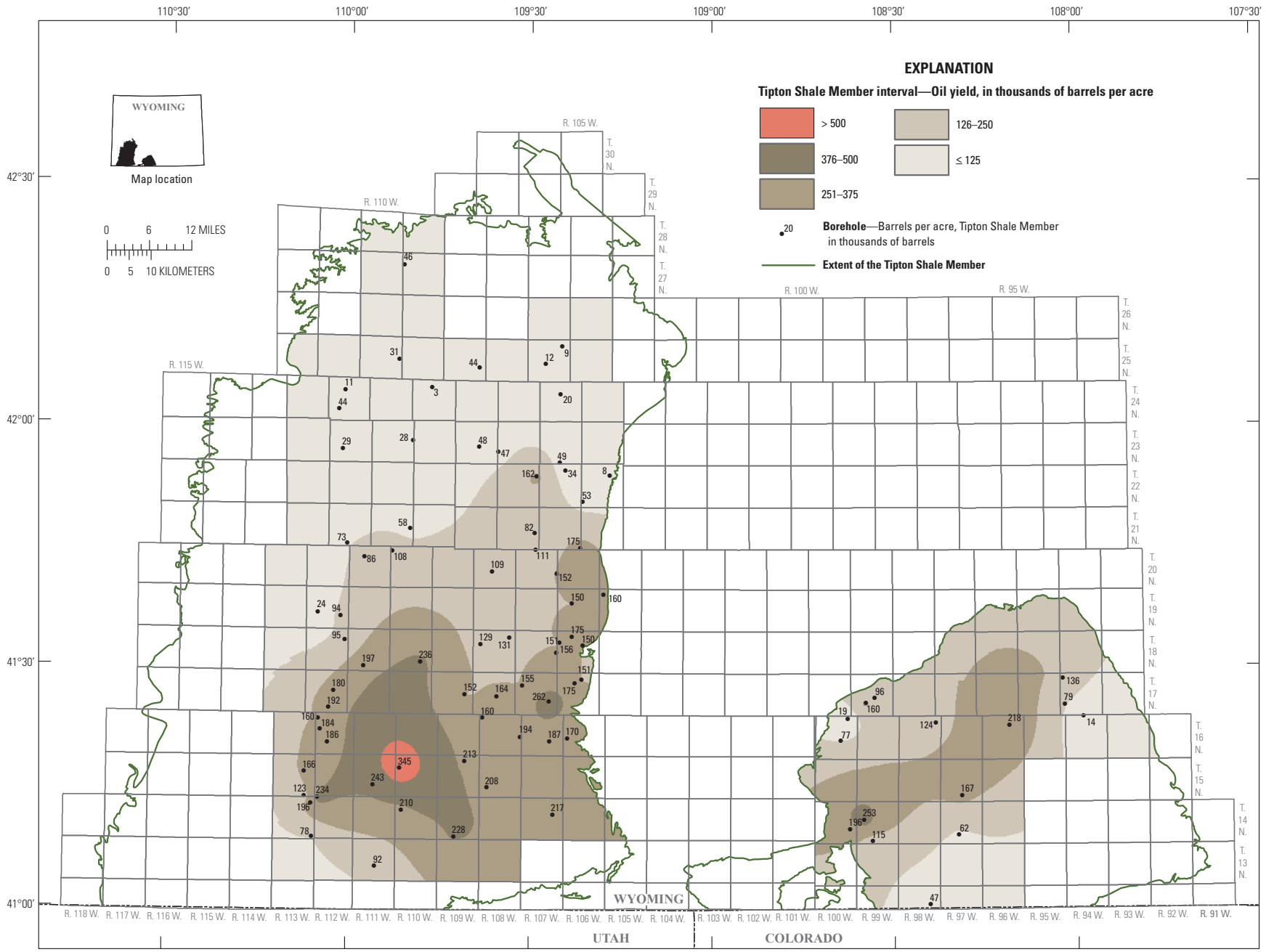


Figure 26. Isoresource map showing the oil yield in barrels per acre for the Tipton Shale Member.

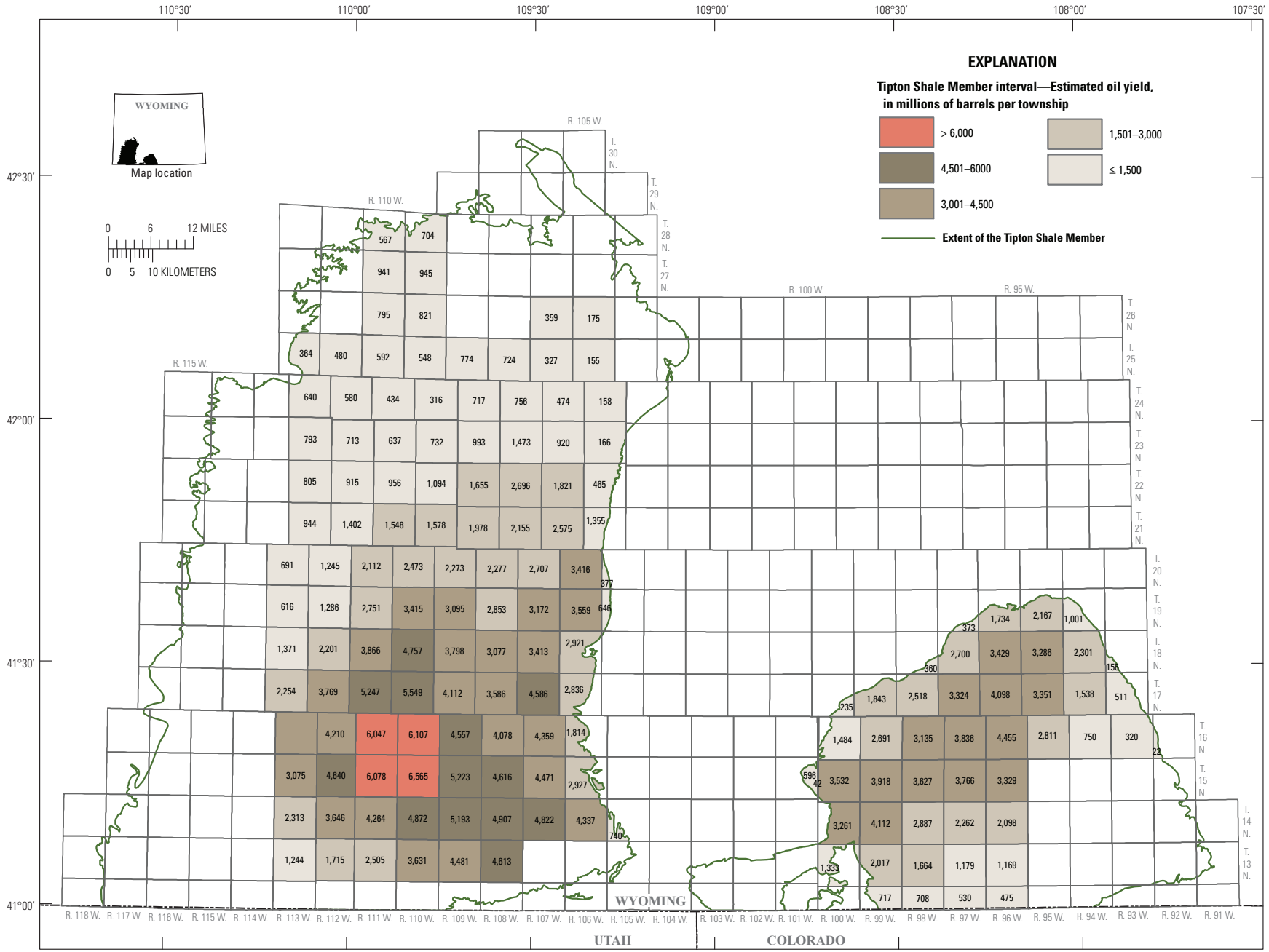


Figure 27. Isoresource map of the Tipton Shale Member showing barrels of oil in each Township.

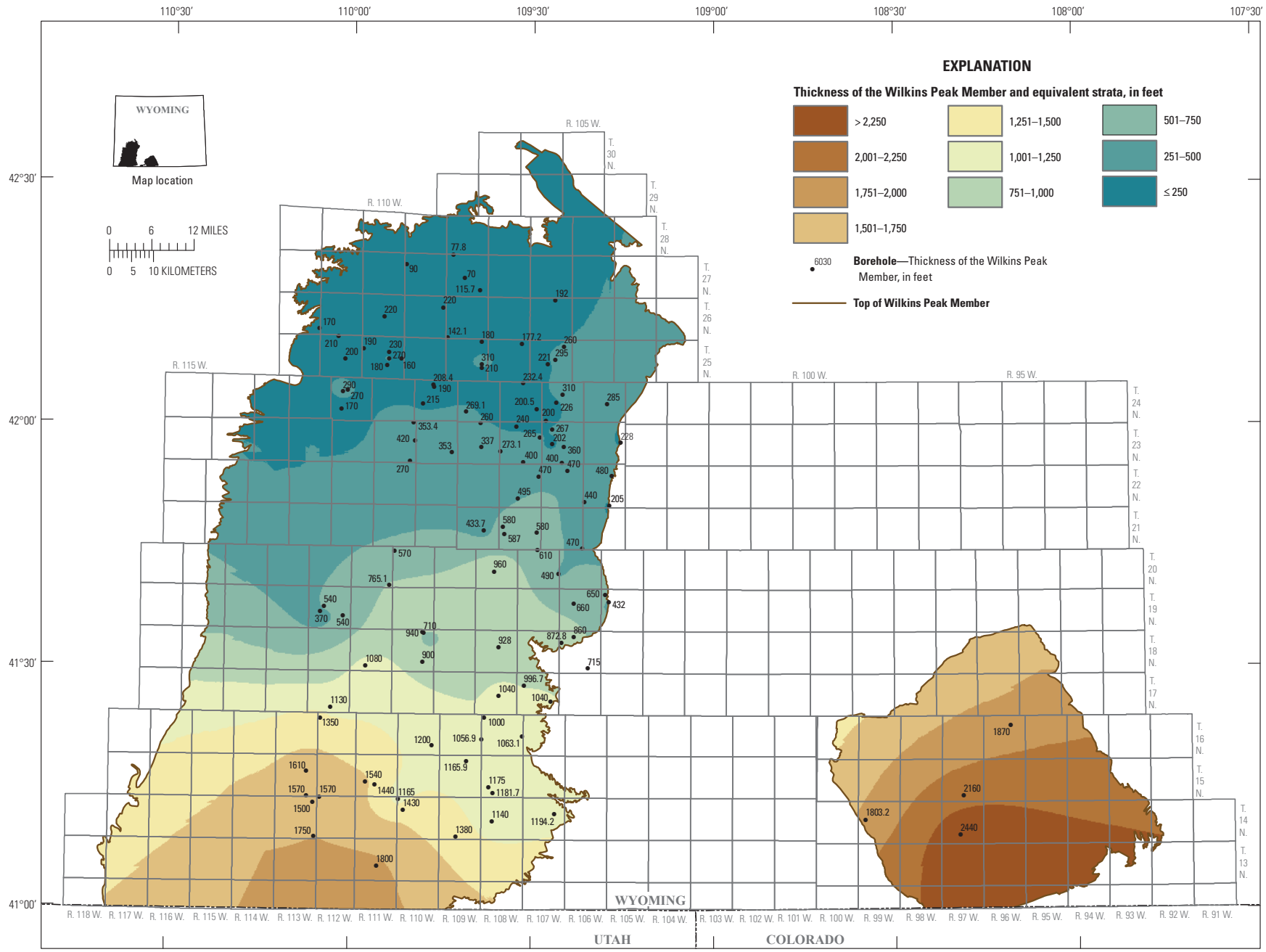


Figure 28. Isopach map from the base of the LaClede Bed to the top of the Tipton Shale Member.

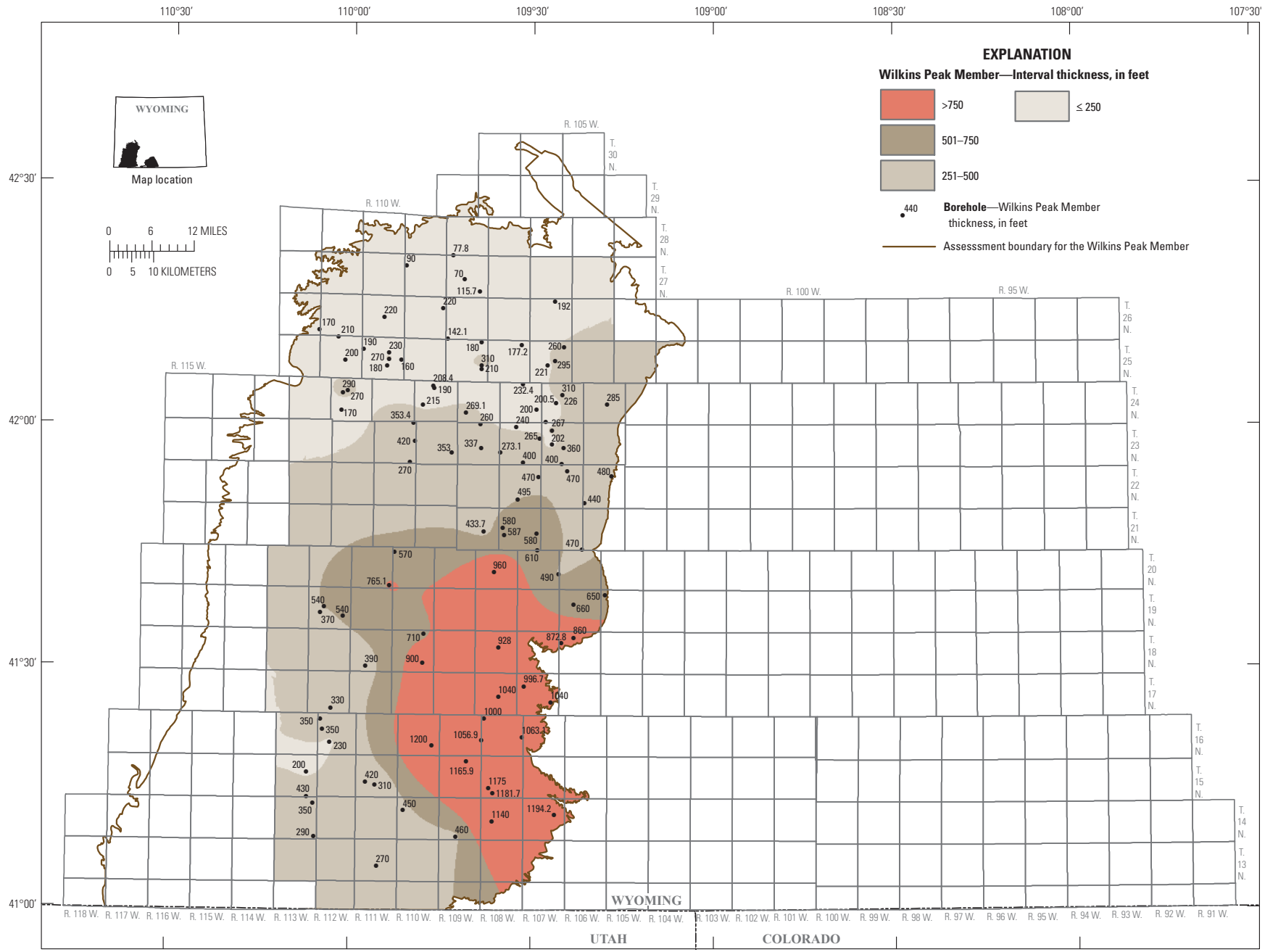


Figure 29. Isopach map of the Wilkins Peak Member.

Member. Total area assessed is 4,102 mi^2; the west margin of the Green River Basin and the northeastern part of the Green River Basin were not assessed due to lack of control (fig. 30). Oil yield is greatest in the north-central part of the Green River Basin, averaging between 12 and 18.2 GPT (fig. 30) in an area where the Wilkins Peak is comparatively thin but contains a higher proportion of oil shale beds as kerogen-poor lithologies pinch out. Oil yields in the saline depocenter in the central part of the Green River Basin (fig. 14) are much lower, averaging about 5 to 10.5 GPT (fig. 30). Maximum in-place oil, in contrast, is in the northern part of the saline depocenter, in large part because the Wilkins Peak is much thicker there than in the northern part of the Green River Basin (figs. 29 and 31). Maximum in-place oil in a township, over 17 billion barrels, is in the central part of the Green River Basin (fig. 32). Total in-place oil in the Wilkins Peak Member is 704,991,000,000 barrels (table 3).

LaClede Bed of the Laney Member

The LaClede Bed includes most of the oil shale in the Laney Member. It is the only unit in the member that was assessed, and is the area extending into the subsurface from mapped outcrops of the base of the Laney Member (base of LaClede). As the unit typically forms a steep slope or cliff in the lowermost part of the Laney Shale Member, the top of the LaClede Bed is generally shown in map view to be close to the base of the Laney. The top of the LaClede Bed has been mapped only locally in the Washakie Basin (Roehler, 1973b; 1974b, c; 1977; 1978a, c). Laney Member strata above the LaClede Bed, which contains little oil, generally form a slope, and the top of the Laney typically crops out many miles from the outcrop line for the base of the Laney. Thus, assessing the LaClede Bed to the outcrop line at the base of the Laney Member very slightly overestimates its in-place resources as opposed to markedly underestimating the resources if the top of the Laney had been used.

The lower part of the LaClede Bed, as defined by Roehler (1991b) in the Washakie Basin, is laterally equivalent to the upper part of the underlying Wilkins Peak Member in the Green River Basin to the west (pl. 1). The Sand Butte Bed, which overlies the LaClede Bed in the vicinity of the Rock Springs uplift, is tuffaceous sandstone and siltstone, and the Hartt Cabin Bed, which overlies the LaClede Bed in other areas of the Greater Green River Basin, is interbedded sandstone, siltstone, mudstone, shale, oil shale, tuff, limestone, and dolomite (figs. 3 and 17).

The LaClede Bed thickens generally toward the southeast from less than 50 ft in the northwestern part of the Green River Basin to a maximum of 650 ft in the central part of the Washakie Basin (fig. 34). Most of this thickening is due to the inclusion of progressively younger tongues of oil shale in the LaClede Bed towards the southeast (fig. 20, plate. 1), which were not assessed until they merged with the LaClede Bed. In plate 1, for example, a tongue of oil shale that is separated from the LaClede Bed by 80 ft of marginal lacustrine rock containing little oil in the Union Pacific RR Co. El Paso 44-3 well was not assessed, but was assessed as part of the LaClede Bed in the Natl. Pk. Serv. Buckboars Crossing well 5.7 miles to the southeast.

A total of 54 core holes and 71 rotary holes were used to assess the LaClede; total area that was assessed is 4,686 mi^2, which did not include areas where control is absent in basin margin areas (fig. 33). Average GPT is highest, varying from about 11 to 23 GPT, along the east margin of the Green River Basin as well as along the west margin of the Washakie Basin (fig. 34). Maximum BPA is about 350,000 to 570,000 in the southwestern part of the Washakie Basin where the bed is thickest (fig. 35). Maximum in-place oil in a single township is more than 11.5 billion barrels in the southwestern part of the Washakie Basin (fig. 36). Total in-place oil is 377,185,000,000 barrels (table 3).

Discussion

Estimated total in-place oil shale resources for the Eocene Green River Formation in the Greater Green River Basin is 1.44 trillion barrels (table 3), not too dissimilar from the estimated in-place resources of 1.52 trillion barrels for the Piceance Basin of Colorado of (Johnson and others, 2010a) and 1.32 trillion barrels for the Uinta Basin of Utah (Johnson and others, 2010a). However, the assessed area of the Greater Green River Basin, about 5,500 mi^2, is about 1.4 times larger than the assessed area of the Uinta Basin (3,834 mi^2) and over 4 times larger than the assessed area of the Piceance Basin (1,335 mi^2). Thus, the oil shale deposits of the Greater Green River Basin are, overall, the lowest grade of the three basins. Maximum in-place oil in a single 6-mile by 6-mile township in the Greater Green River Basin is 23.1 billion barrels in T. 17 N., R. 108 W (fig. 37). This compares with a maximum of 74.3 billion barrels of oil in place in a single township in the Piceance Basin (fig. 38). It should be noted that none of these estimates includes all of the oil shale that is present, as many marginal areas of the Greater Green River and Uinta Basins and the southernmost part of the Piceance Basin were not assessed due to lack of data. Oil shale in some of the early freshwater lacustrine stages in all three basins was excluded from all three assessments.

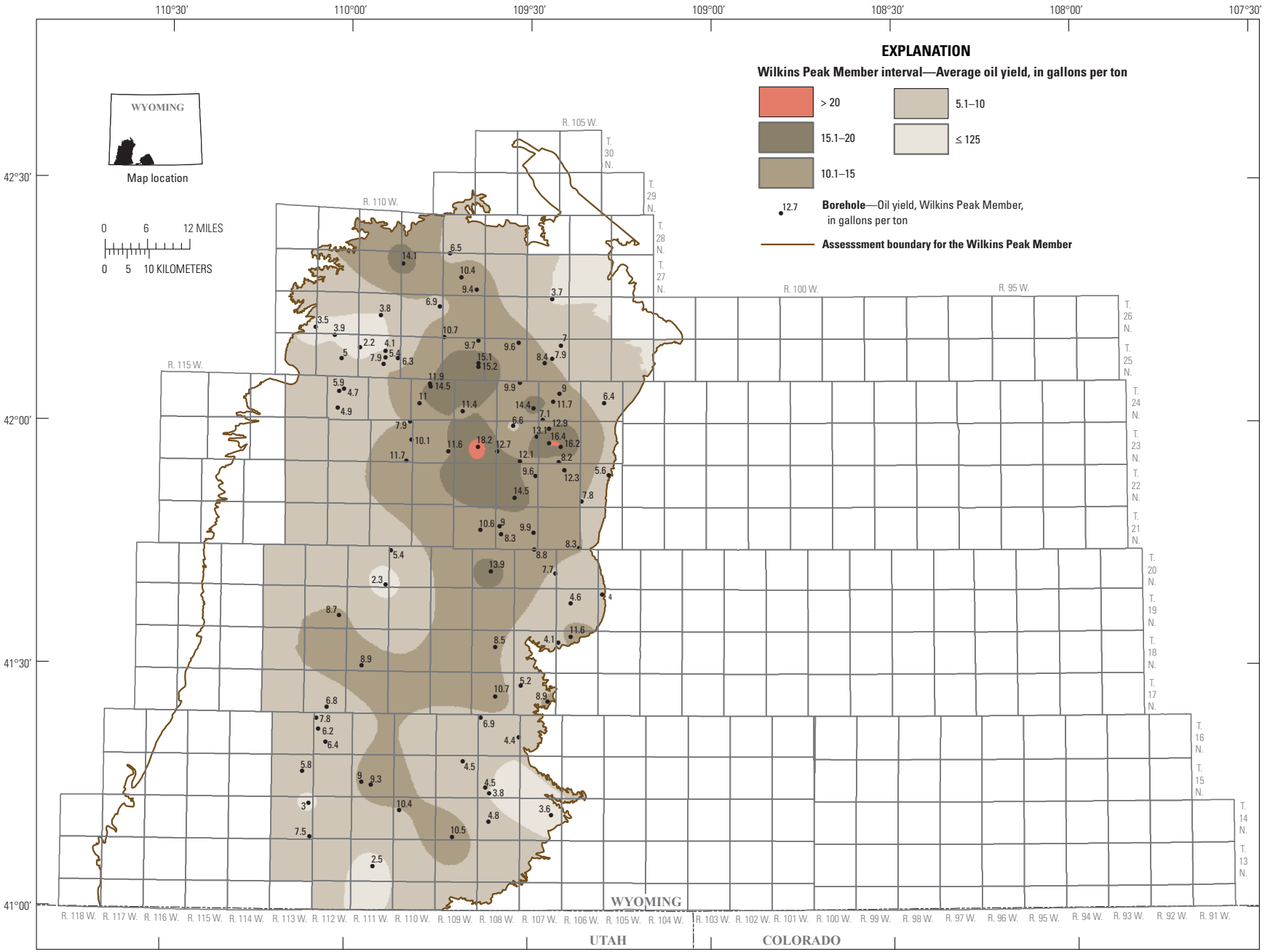


Figure 30. Isoresource map showing the oil yield in gallons per ton for the Wilkins Peak Member.

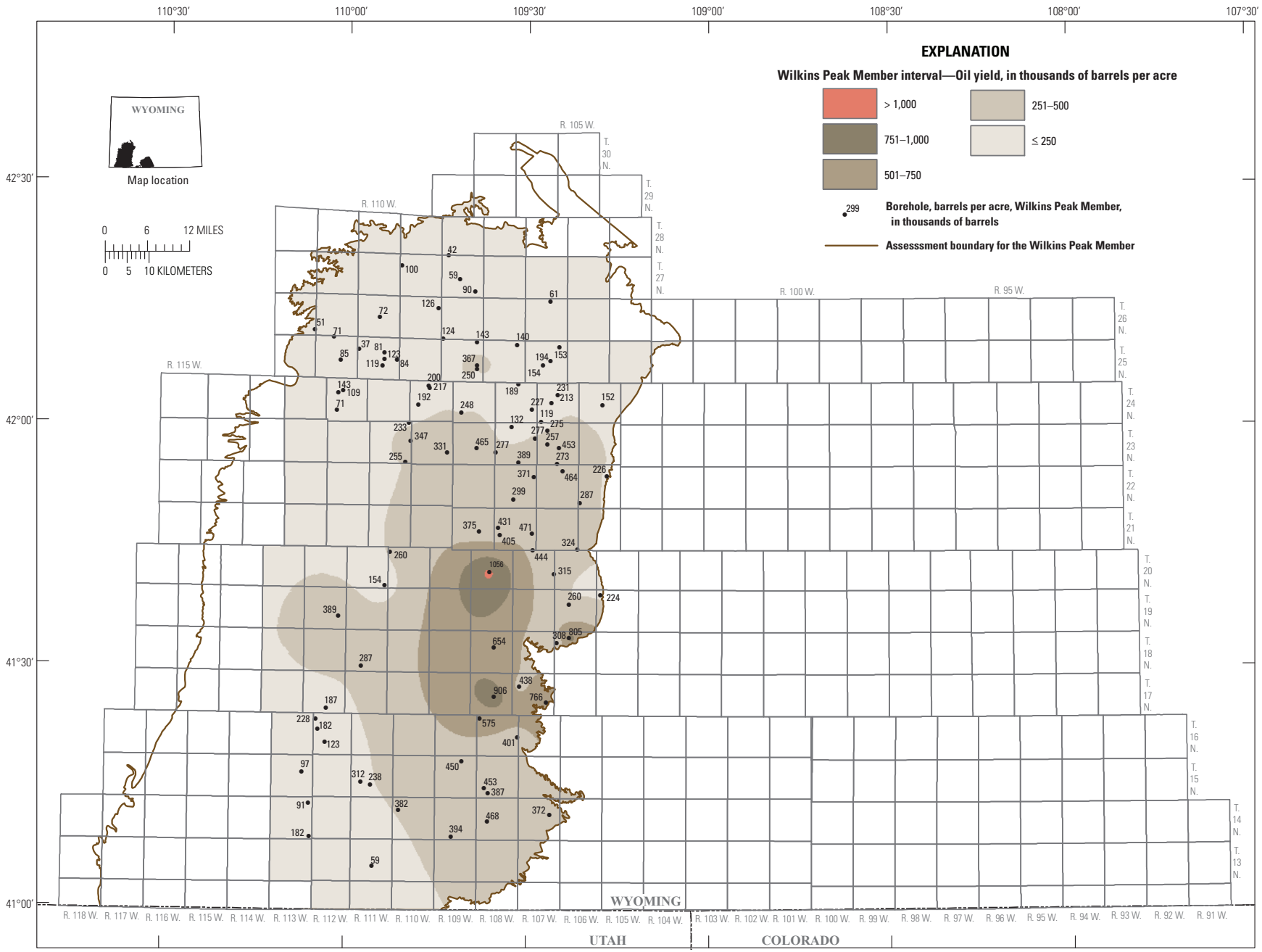


Figure 31. Isoresource map showing the oil yield in barrels per acre for the Wilkins Peak Member.

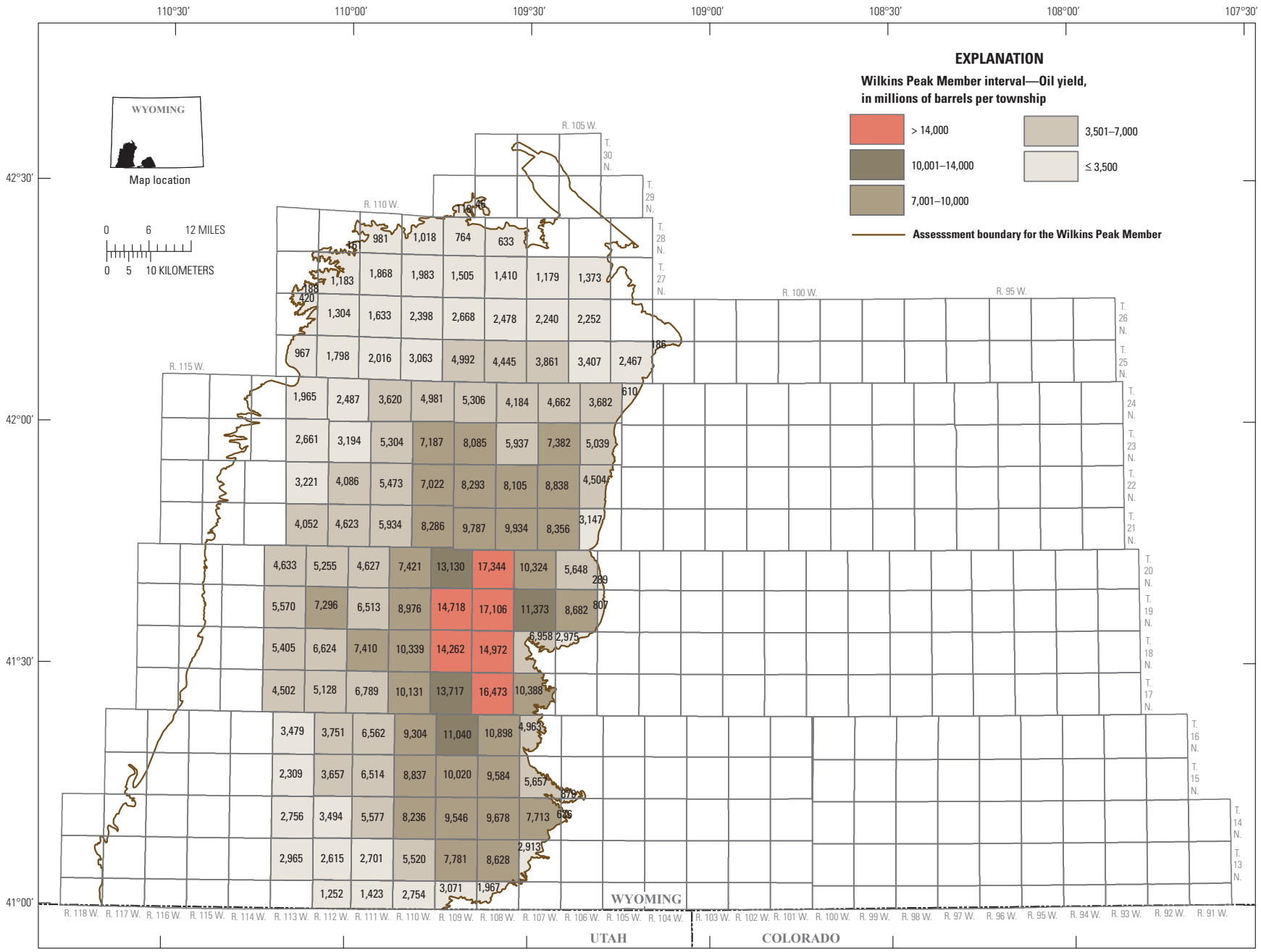


Figure 32. Isoresource map of the Wilkins Peak Member of the Green River Formation showing total barrels of oil in each Township.

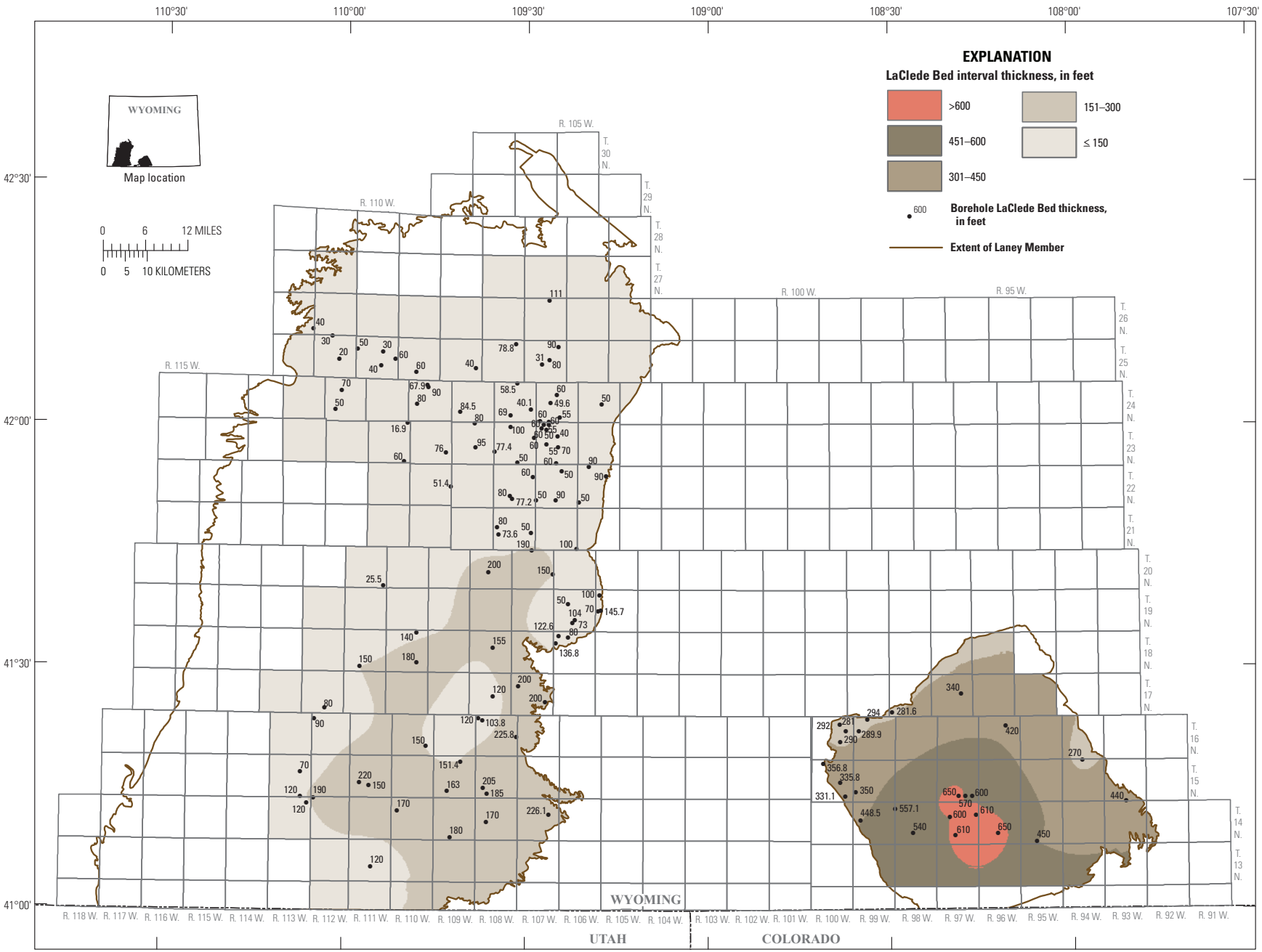


Figure 33. Isopach map of the LaClede Bed of the Laney Member.

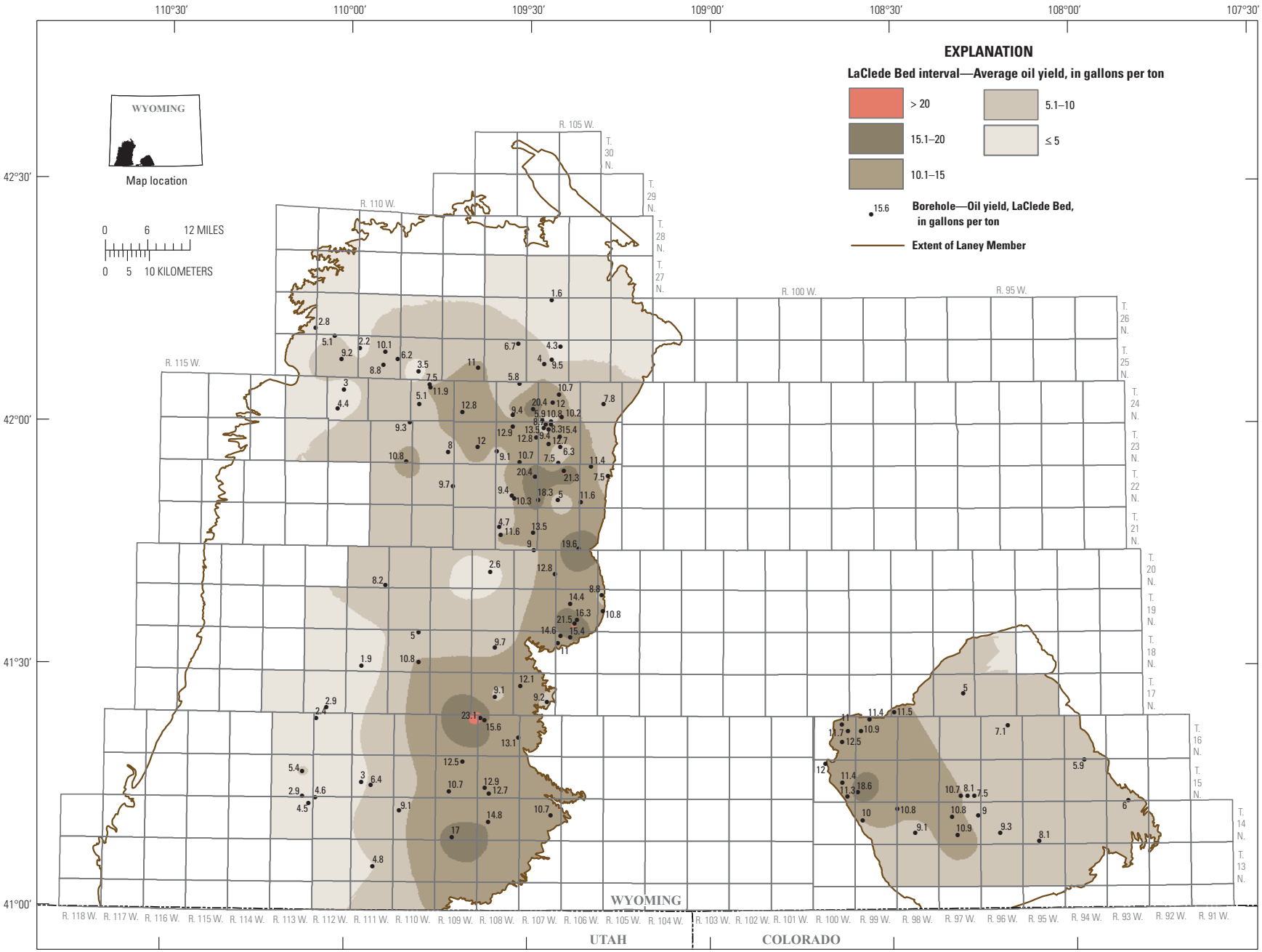


Figure 34. Isoresource map showing the oil yield in gallons per ton for the LaClede Bed.

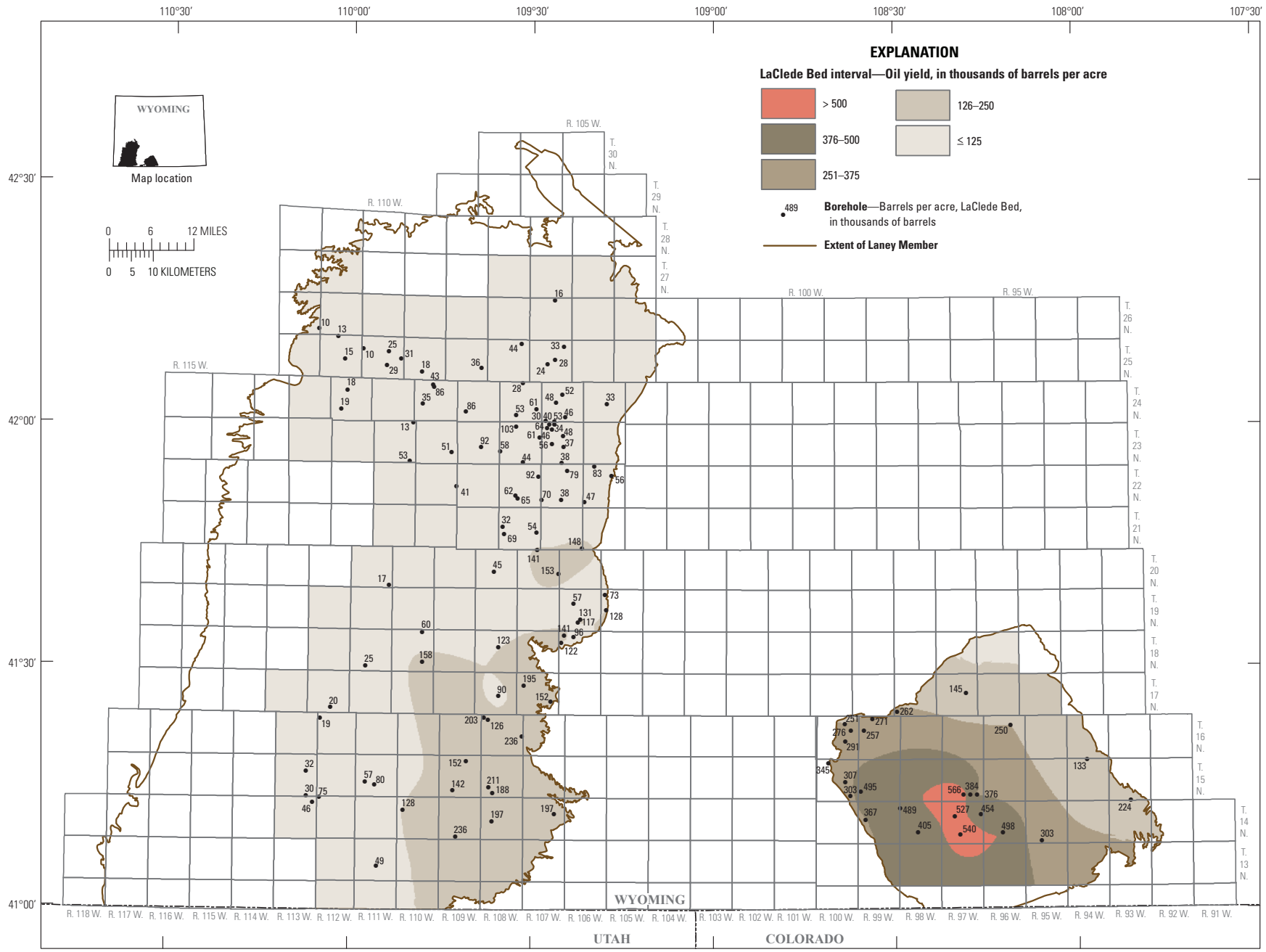


Figure 35. Isoresource map showing the oil yield in barrels per acre for the LaClede Bed.

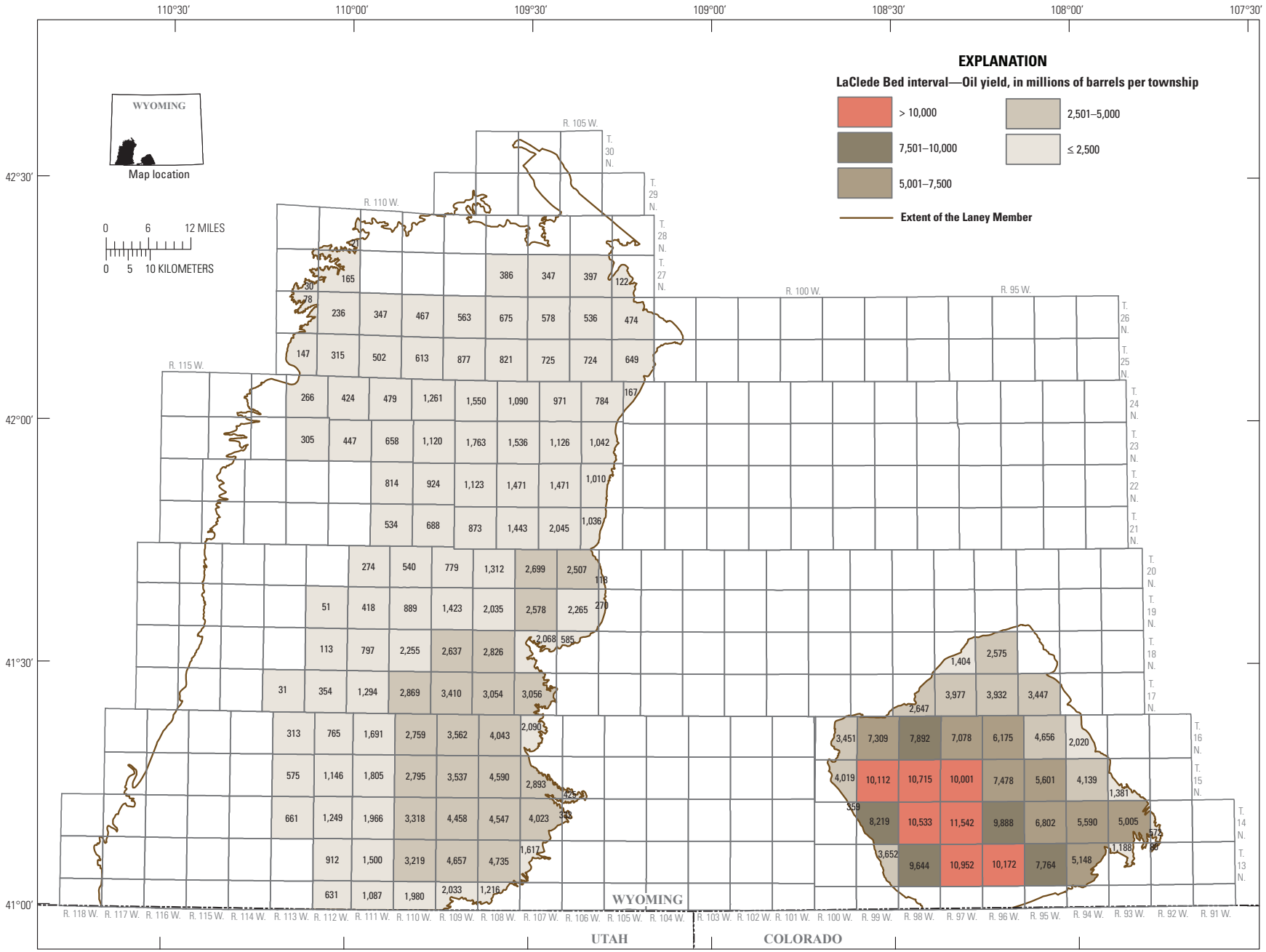


Figure 36. Isoresource map of the LaClede Bed of the Laney Member of the Green River Formation showing total barrels of oil in each Township.

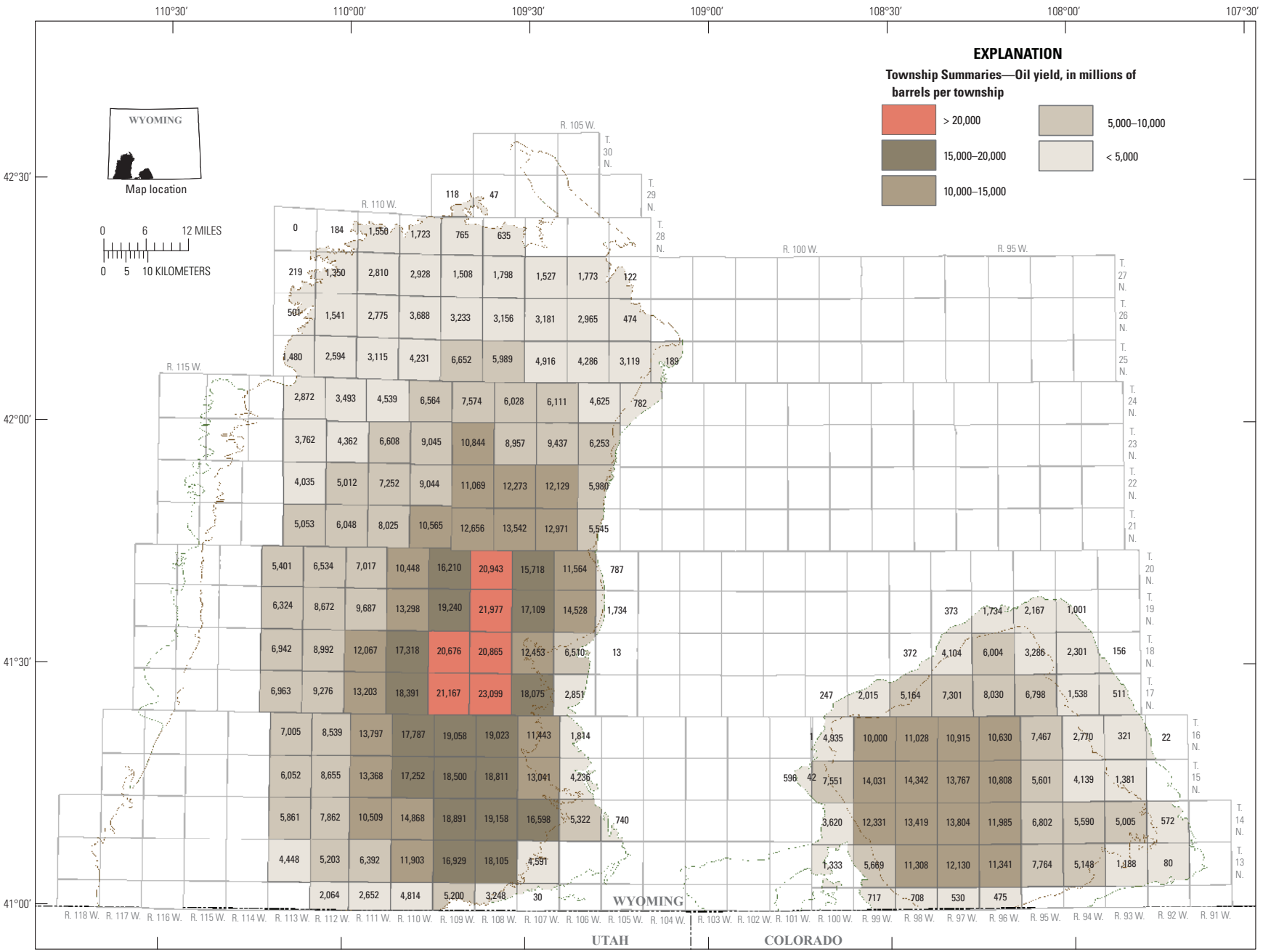


Figure 37. Isoresource map for the Greater Green River Basin showing total barrels of oil in each township for all three assessed units combined.

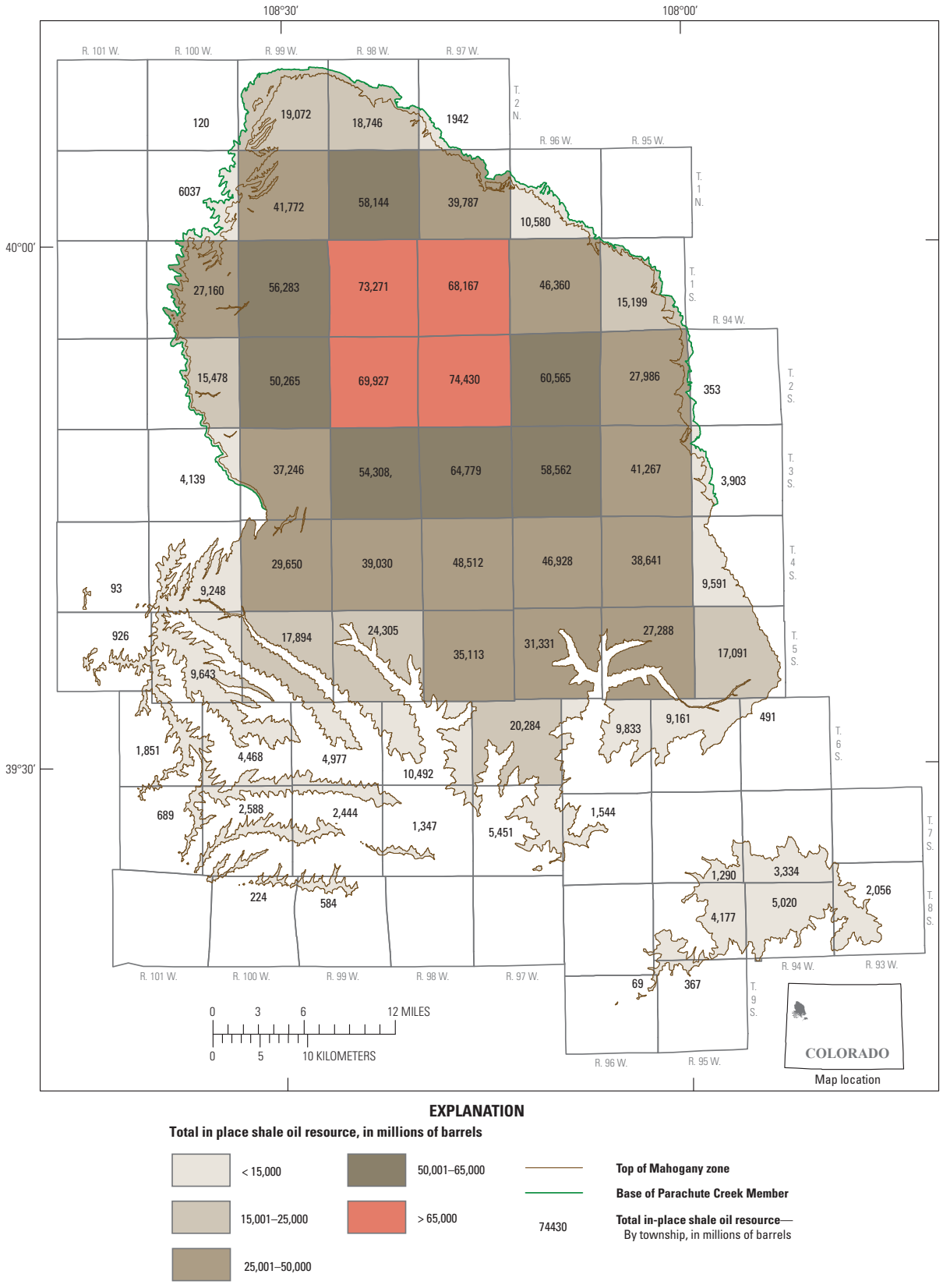


Figure 38. Isoresource map for the Piceance Creek Basin showing total barrels of oil in each township for all the assessed oil shale units combined.

References Cited

American Society for Testing Materials, 1984, Designation D 388–80, Standard test method for oil from oil shale: Annual Book of ASTM Standards, 1984, p. 513–525.

Bradley, W.H., 1959, Revision of stratigraphic nomenclature of Green River Formation of Wyoming: American Association of Petroleum Geologists Bulletin, v. 43, no. 5, p. 1072–1075.

Bradley, W.H., 1963, Eocene—Green River Formation, *in* Frey, D.G., ed., Limnology in North America, The University of Wisconsin Press, p. 629–644.

Bradley, W.H., 1964, Geology of Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey Professional Paper 495–A, 86 p.

Bradley, W.H., and Eugster, H.P., 1969, Geochemistry and paleolimnology of the trona deposits and associated authigenic minerals of the Green River Formation of Wyoming: U.S. Geological Survey Professional Paper 496–B, 71 p.

Brownfield, M.E., Self, J.G., and Mercier, T.J., 2008, Fischer assay histograms of oil-shale drill cores and cuttings from the Great Divide, Green River, and Washakie Basins, southwestern Wyoming, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Fischer assays of oil-shale drill cores and rotary cuttings from the Greater Green River Basin, southwestern Wyoming: U.S. Geological Survey Open-File Report 2008–1152, chap. 2.

Cashion, W.B., 1973, Geologic and structure map of the Grand Junction quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I–736, scale 1:250,000.

Culbertson, W.C., 1969, Oil shale in the Green River Formation, Green River Basin, Wyoming: Wyoming Geological Association, 21st Annual Field Conference, Guidebook, p. 191–195.

Culbertson, W.C., 1971, Stratigraphy of the trona deposits in the Green River Formation, southwest Wyoming: Wyoming University Contributions to Geology, v. 10, no. 1, p. 15–23.

Culbertson, W.C., Smith, J.W., Trudell L.G., 1980, Oil shale resources and geology of the Green River Formation in the Green River Basin, Wyoming: U.S. Department of Energy Laramie Energy Technology Center LETC/RI-80/6, 102 p.

Dyni, J.R., 2003, Geology and resources of some world oil-shale deposits: Oil Shale, v. 20, no. 3, p. 193–252, Estonian Academy Publishers.

Dyni, J.R., Mercier, T.J., and Brownfield, M E., 2008, Analyses of oil shale samples from core holes and rotary-drilled wells from the Green River Formation, southwestern Wyoming, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Fischer assays of oil-shale drill cores and rotary cuttings from the Greater Green River Basin, southwestern Wyoming: U.S. Geological Survey Open-File Report 2008–1152, chap. 1.

Ebens, R.J., 1963, Petrography of the Eocene Tower Sandstone lenses at Green River, Sweetwater County, Wyoming: Laramie, University of Wyoming, M.S. thesis, 46 p.

Eugster, H.P., and Surdam, R C., 1973, Depositional environment of the Green River Formation of Wyoming—A preliminary report: Geological Society of America Bulletin v. 84, p. 1115–1120.

Eugster, H.P., and Hardie, L.A., 1975, Sedimentation in an ancient playa-lake complex—The Wilkins Peak Member of the Green River Formation of Wyoming: Geological Society of American Bulletin, v. 86, p. 319–334.

Johnson, R.C., 1985, Early Cenozoic history of the Uinta and Piceance Creek Basins, Utah and Colorado, with special reference to the development of Eocene Lake Uinta, *in* Flores, R.M., and Kaplan, S.S., eds, Cenozoic Paleogeography of the West-Central United States, Rocky Mountain Paleography Symposium 3: The Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 247–276.

Johnson, R.C., and Roberts, L.N., 2003, Depths to selected stratigraphic horizons in oil and gas wells for Upper Cretaceous and Lower Tertiary strata of the Uinta Basin, Utah, *in* U.S. Geological Survey Uinta-Piceance Assessment Team, eds., Petroleum systems and geologic assessment of the oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, chap. 13, 30 p.

Johnson, R.C., Finn, T.M., and Roberts, L.N., 2005, The Mesaverde Total Petroleum System, Southwestern Wyoming Province, *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, eds., Petroleum Systems and geologic assessment of oil and gas in the southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–D, chap. 8, 38 p.

Johnson, R.C., Mercier, T.J., Brownfield, M.E., Pantea, M.P., and Self, J.G., 2010a, An assessment of in-place oil shale resources in the Eocene Green River Formation, Piceance Basin, Colorado, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Oil Shale and Nahcolite Resources of the Piceance Basin, Colorado: U. S. Geological Survey Digital Data Series DDS–69–Y, chap. 1, 187 p.

Johnson, R.C., Mercier, T.J., Brownfield, M.E., and Self, J.G., 2010b, Assessment of in-place oil shale resources of the Uinta Basin, Utah and Colorado, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Oil shale resources of the Uinta Basin, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–BB, chap. 1, 153 p.

Love, J.D., and Christiansen, A.C., 1985, Geologic Map of Wyoming: U.S Geological Survey, scale 1:500,000.

Mercier, T.J., Brownfield, M.E., and Johnson, R.C., 2010, Methodology for calculating oil shale resources for the Uinta Basin, Utah and Colorado, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Oil shale resources of the Uinta Basin, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–BB, chap. 3, 49 p.

Pietras, J.T., Carroll, A.R., and Rhodes, M.K., 2003, Lake basin response to tectonic drainage division—Eocene Green River Formation, Wyoming: Journal of Paleolimnology, v. 30, p. 115–125.

Pipiringos, G.N., 1961, Uranium-bearing coal in the central part of the Great Divide Basin: U.S. Geological Survey Bulletin 1099–A, 104 p.

Pitman, J.K., 1982, Oil shale Fischer assay analysis from selected core holes in the Piceance Basin, Colorado: National Technical Information Service [magnetic tape] PB82–134875/XDD.

Pitman, J.K., and Van Trump, George, 1974, Oil shale Fischer assay data for core holes in the Piceance Creek Basin, Colorado: National Technical Information Service [magnetic tape] PB–230 607/4/XDD.

Pitman, J.K., and Van Trump, George, 1975, Magnetic tape containing oil shale Fischer assay data for core holes in the Uinta Basin, Utah: National Technical Information Service [magnetic tape] PB–238 682/9/XDD.

Pitman, J.K., Wahl Pierce, Frances, and Grundy, W.D., 1989, Thickness, oil-yield, and kriged resource estimates for the Eocene Green River Formation, Piceance Creek Basin, Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC–132.

Prien, C.H., 1974, Current oil shale technology—A summary, *in* Murray, D. Keith, ed., Guidebook to the Energy Resources of the Piceance Creek Basin, Colorado: Rocky Mountain Association of Geologists 25th Field Conference, p. 141–150.

Roehler, H.W., 1972a, Geologic Map of the Four J Rim quadrangle, Sweetwater County, Wyoming and Moffat County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1002, scale 1:24,000.

Roehler, H.W., 1972b, Geologic Map of the Red Creek Ranch quadrangle, Wyoming, Utah, and Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1001, scale 1:24,000.

Roehler, H.W., 1973a, Stratigraphic divisions and geologic history of the Laney Member of the Green River Formation in the Washakie Basin in southwestern Wyoming: U.S. Geological Survey Bulletin 1372–E, 28 p.

Roehler, H.W., 1973b, Geologic Map of the Chicken Creek East quadrangle, Sweetwater County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–1128, scale 1:24,000.

Roehler, H.W., 1974a, Depositional environments of Eocene rocks in the Piceance Creek Basin, Colorado, *in* Murray, D. Keith, ed., Guidebook to the Energy Resources of the Piceance Creek Basin, Colorado, Rocky Mountain Association of Geologists 25th Field Conference, p. 57–64.

Roehler, H.W., 1974b, Geologic map of the Pine Butte quadrangle, Sweetwater County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–1199, scale 1:24,000.

Roehler, H.W., 1974c, Geologic Map of the Chicken Creek West quadrangle, Sweetwater County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–1139, scale 1:24,000.

Roehler, H.W., 1974d, Geologic Map of the Scrivner Butte quadrangle, Sweetwater County, Wyoming and Moffat County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1166, scale 1:24,000.

Roehler, H.W., 1974e, Geologic Map of the Burley Draw quadrangle, Sweetwater County, Wyoming; U.S. Geological Survey Geologic Quadrangle Map, GQ–1200, scale 1:24,000.

Roehler, H.W., 1977, Geologic map of the Sand Butte Rim NW quadrangle, Sweetwater County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–1362, scale 1:24,000.

Roehler, H.W., 1978a, Geologic Map of the Chicken Creek SE quadrangle, Sweetwater County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–1454, scale 1:24,000.

Roehler, H.W., 1978b, Geologic Map of the Chicken Creek SW quadrangle, Sweetwater County, Wyoming, and Moffat County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1443, scale 1:24,000.

Roehler, H.W., 1978c, Geologic Map of the Antelope Flats quadrangle, Sweetwater County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–1437, scale 1:24,000.

Roehler, H.W., 1989a, Correlation of surface sections of the intertongued Eocene Wasatch and Green River Formations, Great Divide Basin, southwest Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–2102.

Roehler, H.W., 1989b, Correlation of surface section of the intertongued Eocene Wasatch and Green River Formations along the western margins of the Greater Green River Basin in southwest Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–2103.

Roehler, H.W., 1989c, Correlation of surface section of the intertongued Eocene Wasatch and Green River Formations along the west flank of the Rock Springs uplift in southwest Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–2104.

Roehler, H.W., 1989d, Correlation of surface sections of the intertongued Eocene Wasatch and Green River Formations along the western margins of the Sand Wash Basin, northwest Colorado, and Washakie Basin, southwest Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–2105.

Roehler, H.W., 1989e, Correlation of surface section of the intertongued Eocene Wasatch and Green River Formations along the central part of the Sand Wash Basin, northwest Colorado, and eastern part of the Washakie Basin, southwest Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–2106.

Roehler, H.W., 1990a, Sedimentology of freshwater lacustrine shorelines in the Eocene Scheggs Bed of the Tipton Tongue of the Green River Formation, Sand Wash Basin, Northwest Colorado: U.S. Geological Survey Bulletin 1911, 12 p.

Roehler, H.W., 1990b, Correlation and depositional analysis of oil-shale and associated rocks in the Eocene Green River Formation, greater Green River Basin, southwest Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I–2226.

Roehler, H.W., 1991a, Revised stratigraphic nomenclature for the Wasatch and Green River Formations of Eocene age, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506–B, 38 p.

Roehler, H.W., 1991b, Correlation and depositional analysis of oil shale and associated rocks in the Eocene Green River Formation, Greater Green River Basin, southwest Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I–2226.

Roehler, H.W., 1992a, Description and correlation of Eocene rocks in stratigraphic reference sections for the Green River and Washakie Basins, southwest Wyoming: U.S. Geological Survey Professional Paper 1506–D, 83 p.

Roehler, H.W., 1992b, Correlation, composition, areal distribution, and thickness of Eocene stratigraphic units, Greater Green River Basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506–E, 49 p.

Roehler, H.W., 1993, Eocene climates, depositional environments, and geography, Greater Green River Basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506–F, 74 p.

Rowley, P.D., Hansen, W.R., Tweto, Ogden, and Carrara, P.E., 1985, Geologic Map of the Vernal 1°× 2° quadrangle, Colorado, Utah, and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I–1526, scale: 1:250,000.

Rusu, Cristian, and Rusu, Virginia, 2006, Radial basis functions versus geostatistics *in* Bramer, Max, ed., Artificial Intelligence in Theory and Practice: Boston, International Federation for Information Processing (IFIP), v. 217, Springer Verlag, p. 119–128.

Schultz, A.R., 1920, Oil possibilities in and around Baxter Basin in the Rock Springs uplift, Sweetwater County, Wyoming: U.S. Geological Survey Bulletin 702, 107 p.

Smith, J.W., 1956, Specific gravity-oil yield relationships of two Colorado oil shale cores: Industrial and Engineering Chemistry, v. 48, no. 3, p. 441–444.

Smith, M.E., Carroll, A.R., and Singer, B.S., 2008, Synoptic reconstruction of a major ancient lake system—Eocene Green River Formation, western United States: Geological Society of America Bulletin v. 120, nos. 1 and 2, p. 54–84.

Stanfield, K.E., Frost, I.C., 1949, Method of assaying oil shale by a modified Fischer retort: U.S. Bureau of Mines Report of Investigations 4477, 13 p.

Stanfield, K.E., Rose, C.K., McAuley, W.S., and Tesch, W.J., Jr., 1954, Oil yields of sections of Green River oil shale in Colorado, Utah, and Wyoming, 1945–52: U.S. Bureau of Mines Report of Investigation 5081, 153 p.

Stanley, K.O., and Surdam, R.C., 1978, Sedimentation on the front of Eocene Gilbert-type deltas, Washakie Basin, Wyoming: Journal of Sedimentary Petrology, v. 48, no. 2, p. 557–573.

Surdam, R.C., and Stanley, K.O., 1979, Lacustrine sedimentation during the culminating phase of Eocene Lake Gosiute, Wyoming (Green River Formation): Geological Society of America Bulletin, Part 1, v. 90, p. 93-110.

Surdam, R.C., and Stanley, K.O., 1980, Effects of changes in drainage-basin boundaries on sedimentation in Eocene Lakes Gosiute and Uinta of Wyoming, Utah, and Colorado: Geology, v. 8, p. 135-139.

Taylor, O.J., 1987, Benefits, requirements, and effects of different levels of oil-shale development: *in* O.J. Taylor, ed., Oil Shale, Water Resources, and Valuable Minerals of the Piceance Basin, Colorado: The Challenges and Choices of Development: U.S. Geological Survey Professional Paper 1310, p. 125–136.

Trudell, L.G., Roehler, H.W., and Smith, J.W., 1973, Geology of Eocene rocks and oil yields of Green River oil shales on part of Kinney Rim, Washakie Basin, Wyoming: U.S. Bureau of Mines Report of Investigations 7775, 151 p.

Tweto, Ogden, 1976, Geologic Map of the Craig 1°× 2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Map I–972, scale: 1:250,000.

Tweto, Ogden, 1979, Geologic Map of Colorado: U.S. Geological Survey, scale: 1:500,000.

U.S. Geological Survey Oil Shale Assessment Team, 2009, Fischer assays of oil shale drill cores and rotary cuttings from the Piceance Basin, Colorado—2009 Update: U.S. Geological Survey Open-File Report 98–483 v. 2.0, 16 p.

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005, The Southeastern Wyoming Province—Introduction to a geologic assessment of undiscovered oil and gas resources, *in* U.S. Geologic Survey Southwestern Wyoming Province Assessment Team, eds., Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming Province, Colorado and Utah: U.S. Geological Survey Digital Data Series DDS–69–D, chap. 2, 34 p.

U.S Geological Survey Uinta-Piceance Assessment Team, 2003, The Uinta-Piceance Province—Introduction to a geologic assessment of undiscovered oil and gas resources, *in* U.S. Geological Survey Uinta-Piceance Assessment Team, eds, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, chap. 2, 27 p.

Vinigar, Harold, 2006, Shell's in-situ conversion process for oil shale [abs.], *in* 26th Oil Shale Symposium, Golden, Colo., Oct. 16–26, Colorado Energy Research Institute Document CERI 2007–3, Golden, Colo., Colorado School of Mines.

Wilf, P., 2000, Late Paleocene-early Eocene climate changes in southwestern Wyoming: Paleobotanical analysis: Geological Society of America Bulletin, v. 112, p. 292–307.

Witkind, I.J., 1995, Geologic map of the Price 1° × 2° quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I–2462, scale 1:250,000.



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