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Geology of Tight Oil and Potential Tight Oil Reservoirs in the Lower Part of the Green River Formation, Uinta, Piceance, and Greater Green River Basins, Utah, Colorado, and Wyoming



Scientific Investigations Report 2016–5008

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of Cow Ridge Member of the Green River Formation at Tommys Draw along the west margin of the Piceance Basin.

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By Ronald C. Johnson, Justin E. Birdwell, Tracey J. Mercier, and Michael E. Brownfield

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Conversion Factors

[Inch/Pound to International System of Units]

Multiply	By	To obtain
	Length	
inch (in)	2.54	millimeter (mm)
feet (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
barrel (bbl; petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
	Area	
square mile (sq. mi.)	2.5900	square kilometer (km^2)
	Pressure	
pound per square inch (psi)	6.895	kilopascal (kPa)
	Mass	
pound (lb)	453.59	gram (g)
ton, short (2,000 lb)	0.9072	megagram (Mg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
°C = (°F – 32) / 1.8.

Geology of Tight Oil and Potential Tight Oil Reservoirs in the Lower Part of the Green River Formation in the Uinta, Piceance, and Greater Green River Basins, Utah, Colorado, and Wyoming

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Abstract

The recent successful development of a tight oil play in the Eocene-age informal Uteland Butte member of the lacustrine Green River Formation in the Uinta Basin, Utah, using modern horizontal drilling and hydraulic fracturing techniques has spurred a renewed interest in the tight oil potential of lacustrine rocks. The Green River Formation was deposited by two large lakes, Lake Uinta in the Uinta and Piceance Basins and Lake Gosiute in the Greater Green River Basin. These three basins contain the world's largest in-place oil shale resources with recent estimates of 1.53 trillion, 1.33 trillion, and 1.44 trillion barrels of oil in place in the Piceance, Uinta, and Greater Green River Basins, respectively. The Uteland Butte member was deposited during an early freshwater stage of the lake in the Uinta Basin prior to deposition of the assessed oil shale intervals. This report only presents information on the early freshwater interval and overlying brackish-water interval in all three basins because these intervals are most likely to have tight oil potential. Burial histories of the three basins were reconstructed to study (1) variations in subsidence and lake development, and (2) post deposition burial that led to the development of a petroleum system in only the Uinta Basin. The Uteland Butte member is a successful tight oil play because it is thermally mature for hydrocarbon generation and contains organic-rich shale, brittle carbonate, and porous dolomite. Abnormally high pressure in parts of the Uteland Butte is also important to production. Variations in organic richness of the Uteland Butte were studied using Fischer assay analysis from oil shale assessments, and pressures were studied using drill-stem tests. Freshwater lacustrine intervals in the Piceance and Greater Green River Basins are immature for hydrocarbon generation and contain much less carbonate than the Uteland Butte member. The brackish-water interval in the Uinta Basin is thermally mature for hydrocarbon generation but is clay-rich and contains little carbonate, and thus is a poor prospect for tight oil development.

Introduction

The recent successful horizontal drilling for tight oil in the Uteland Butte member (an informal name) of the Green River Formation in the Uinta Basin (Durham, 2013; Anderson and Roesink, 2013; Vanden Berg and others, 2014) has demonstrated the potential for tight oil development in lacustrine basins. The lacustrine Green River Formation (Paleocene and Eocene) was deposited in three intermountain basins during the Laramide orogeny (Late Cretaceous through Eocene): (1) the Uinta Basin in eastern Utah and western Colorado, (2) the Piceance Basin in western Colorado, and (3) the Greater Green River Basin in southwestern Wyoming and northwestern Colorado (fig. 1). The Greater Green River Basin is subdivided into five individual subbasins separated by structural arches: (1) the Green River Basin west of the Rock Springs uplift, (2) the Hoback Basin separated from the Green River Basin by the Sandy Bend arch, (3) the Great Divide Basin north of the Wamsutter arch, (4) the Washakie Basin defined by Rock Springs uplift, Wamsutter arch, and Cherokee Ridge, and (5) the Sand Wash Basin south of the Cherokee Ridge arch (fig. 1). The Uinta and Piceance Basins are also separated by a structural arch, the Douglas Creek arch (figs. 1, 2). At times, these arches subdivided the lacustrine systems, whereas at other times, lakes extended unbroken across them. The Green River Formation in these three basins contains the world's largest in-place oil shale resources with recent estimates of 1.33 trillion barrels of oil (TBO) in the Uinta Basin (Johnson and others, 2010a), 1.53 TBO in place in the Piceance Basin (Johnson and others, 2010b), and 1.44 TBO in the Greater Green River Basin (Johnson and others, 2011). These oil shale resources were deposited in two large, internally drained saline lakes, Lake Uinta in the Uinta and Piceance Basins and Lake Gosiute in the Greater Green River Basin.

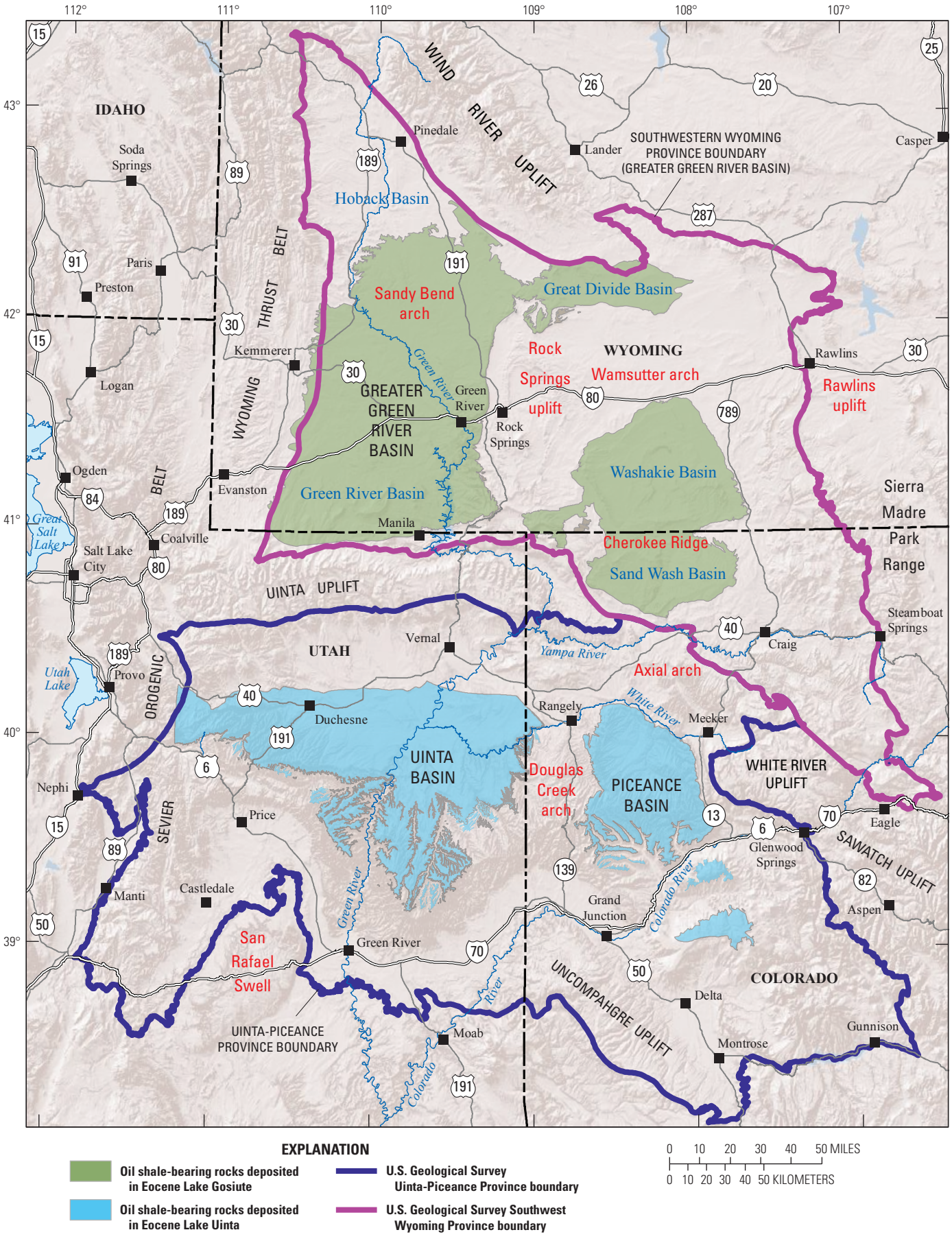

112°
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IDAHO
WYOMING
UTAH
COLORADO
Soda Springs
Pinedale
Lander
Casper
Paris
Preston
Logan
Kemmerer
Rawlins
Rock Springs
Ogden
Evanston
Salt Lake City
Coalville
Manila
Vernal
Craig
Steamboat Springs
Provo
Duchesne
Rangely
Meeker
Nephi
Price
Manti
Castledale
Green River
Grand Junction
Eagle
Glenwood Springs
Aspen
Delta
Montrose
Gunnison
Moab
Great Salt Lake
Utah Lake
WIND RIVER UPLIFT
BELT
THRUST BELT
WYOMING
OROGENIC
SEVIER
UINTA UPLIFT
SOUTHWESTERN WYOMING PROVINCE BOUNDARY (GREATER GREEN RIVER BASIN)
Hoback Basin
Sandy Bend arch
Great Divide Basin
Rock Springs uplift
Wamsutter arch
Rawlins uplift
GREATER GREEN RIVER BASIN
Green River Basin
Washakie Basin
Sierra Madre
Park Range
Cherokee Ridge
Sand Wash Basin
Axial arch
Yampa River
White River
Green River
Colorado River
UINTA BASIN
Douglas Creek arch
PICEANCE BASIN
WHITE RIVER UPLIFT
SAWATCH UPLIFT
San Rafael Swell
UNCOMPAHGRE UPLIFT
UINTA-PICEANCE PROVINCE BOUNDARY
EXPLANATION
Oil shale-bearing rocks deposited in Eocene Lake Gosiute
Oil shale-bearing rocks deposited in Eocene Lake Uinta
U.S. Geological Survey Uinta-Piceance Province boundary
U.S. Geological Survey Southwest Wyoming Province boundary
0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS

Figure 1 (facing page). Map showing extent of Uinta, Piceance, and Greater Green River Basins, and approximate extent of oil shale in the Green River Formation. Subbasins in the Greater Green River Basin labeled in blue. Major uplifts are labeled in black and minor structural arches are labeled in red. Extent of the Uinta and Piceance Basins (dark blue) is the same as the Uinta-Piceance Province boundary (U.S. Geological Survey Uinta-Piceance Assessment Team, 2003). Extent of the Greater Green River Basin is the same as the Southwest Wyoming Province boundary (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005). For the extent of oil shale in the Piceance Basin, the base of the Parachute Creek Member of the Green River Formation as mapped by Tweto (1979) was used for all but the northwest part of the basin where the base of the lower member of the Green River Formation is used. For the extent of oil shale in the eastern part of the Uinta Basin, the base of the Parachute Creek Member as mapped by Cashion (1973) and Rowley and others (1985) was used. In the western part of the Uinta Basin, the top of the informal Mahogany oil shale bed of the Green River Formation as mapped by Witkind (1995) was used. In the northern part of the Uinta Basin, only the area where oil shale is at a depth of 6,000 feet or less is shown; this area was outlined by using a structure contour map of the top of the Mahogany oil shale bed compiled by Johnson and Roberts (2003b). For the Sand Wash, Washakie, Great Divide Basins, and southeastern part of the Green River Basin, the base of the Tipton Shale Member of the Green River Formation as mapped by Tweto (1979) and Love and Christiansen (1985) was used to show extent of oil shale. For the western part of the Green River Basin, the base of the Wilkins Peak Member of the Green River Formation, and for the northern part of the Green River Basin, the base of the Laney Member of the Green River Formation as mapped by Love and Christiansen (1985) were used.

The Uteland Butte member is a freshwater lacustrine unit deposited prior to the main saline-lacustrine oil shale interval of the Green River Formation (fig. 2). The Uteland Butte member was not assessed during the recently completed oil shale assessment of the Uinta Basin (Johnson and others, 2010). However, a perusal of the Uinta Basin database listing oil yields, based on the Fischer Assay method, a standardized method for measuring oil yield potential of oil shale (Stanfield and Frost, 1949; American Society for Testing and Materials, 1980), Mercier and others (2010) found a limited amount of oil yield data for the Uteland Butte member, and these data are used here to help define the limits of the organic-rich offshore lacustrine facies of the Uteland Butte. A limited amount of published vitrinite reflectance data are available for the Uteland Butte and adjacent units (Anders and others, 1992), and these data are used to estimate variations in thermal maturity in the Uteland Butte member. Variations in formation pressures within the Uteland Butte were studied using drill-stem tests and mudweights found at the Utah Department of Natural Resources Oil and Gas Web site (2014), and these data are used here to help define an overpressured "sweet spot" where rates of oil production are unusually high. Prior to the recent horizontal drilling, the Uteland Butte was rarely the primary target for vertically drilled oil wells in the basin but was commonly perforated along with numerous other intervals, because oil shows were frequently encountered while drilling through the Uteland Butte. As such, there is little information on the producibility of the Uteland Butte itself from these vertical tests completed in multiple zones.

The Uinta Basin is the focus of this report because it presently contains the only proven tight oil play in all three basins; however, freshwater lacustrine intervals similar to the Uteland Butte are present in the Piceance and Greater Green River Basins, and these units will be discussed briefly. A brackish-to-saline lacustrine interval overlies the freshwater lacustrine strata and underlies the hypersaline interval in all three basins. This interval will also be discussed briefly, because it may also have some potential for tight oil. A west-to-east cross section across the Uinta and Piceance Basins and intervening Douglas Creek arch is shown in figure 2. Only the interval from the freshwater Flagstaff Member, which underlies the Uteland Butte member in the Uinta Basin, through the brackish-to-saline lacustrine R-0 oil shale zone (defined in Cashion and Donnell, 1972, and referred to as the R-0 zone from hereon; fig. 2) will be discussed here. In the Piceance Basin, the equivalent interval is represented by the freshwater Cow Ridge Member and the R-0 zone. The interval from the base of the R-0 zone and above were deposited in the brackish to hypersaline stages of Lake Uinta and are shown in shades of blue for offshore lacustrine facies and yellow for marginal lacustrine facies. The early freshwater lacustrine rocks pinch out along the crest of the Douglas Creek arch, whereas the entire lacustrine interval, beginning with the R-0 zone, extends unbroken across that crest. The onset of deposition over the crest of the Douglas Creek arch corresponds to a major expansion and deepening of Lake Uinta during the Long Point transgression. This transgression seems to correspond to the loss of Lake Uinta's outlet because the lake became brackish shortly after (Johnson, 1985).

A stratigraphic cross section for the Greater Green River Basin compiled by Roehler (1991) showing depositional settings of the various Eocene units is shown in figure 3. For convenience, settings have been renamed, when possible, to align with those for the Uinta-Piceance shown on figure 2. Some depositional settings such as the "cyclic saltwater lacustrine oil shale, evaporite, and mudflat deposit" are unique to the Greater Green River Basin (indicated by purple area in fig. 3), whereas others such as the "carbonate-rich saline lacustrine oil shale" are unique to the Uinta and Piceance Basins (indicated by light-grayish blue area in fig. 2). Only lacustrine rocks from the freshwater Ramsey Ranch Member of the Wasatch Formation through the fresh-to-brackish water Tipton Shale Member of the Green River Formation (referred to as Tipton Member from hereon) will be discussed here, because

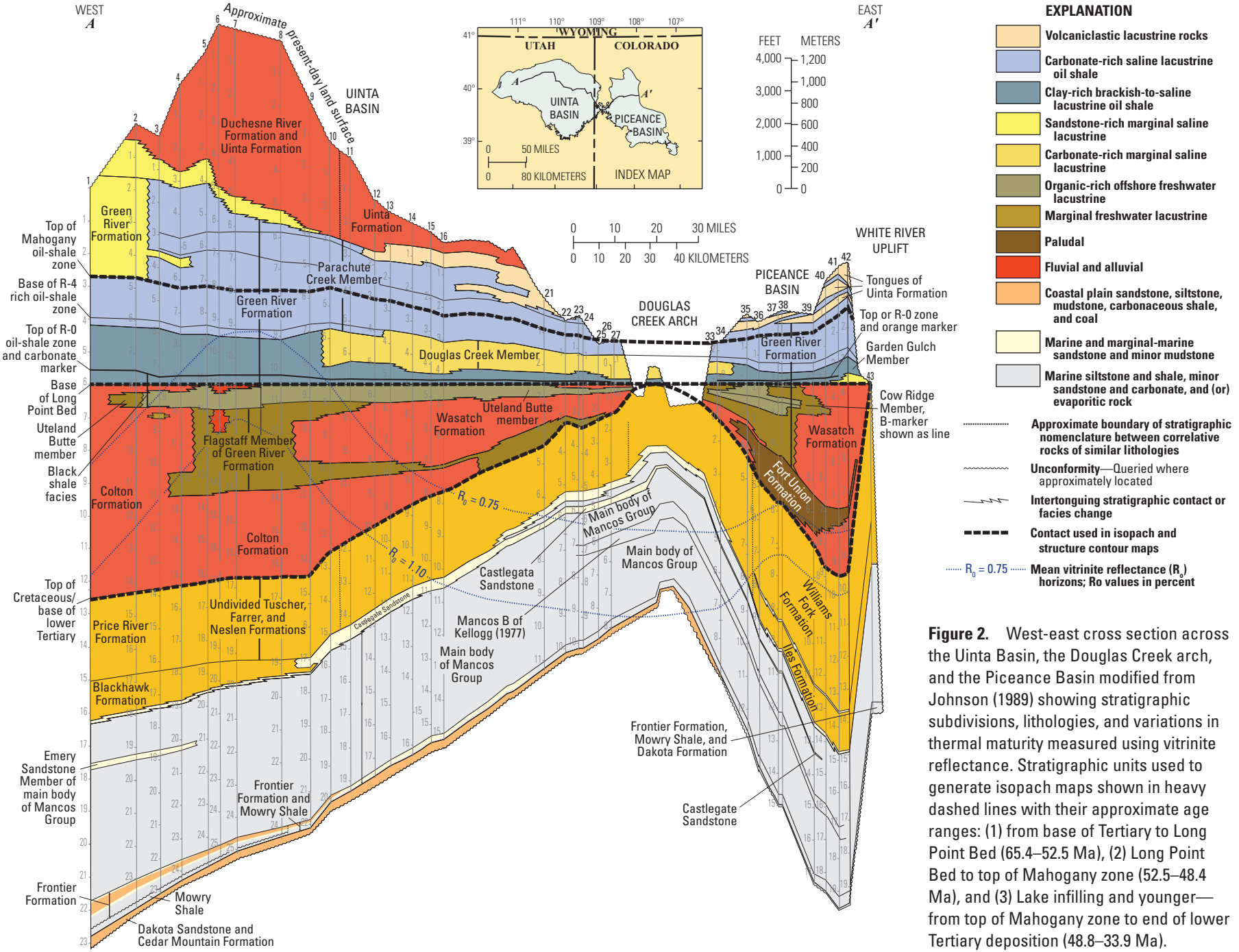


Figure 2. West-east cross section across the Uinta Basin, the Douglas Creek arch, and the Piceance Basin modified from Johnson (1989) showing stratigraphic subdivisions, lithologies, and variations in thermal maturity measured using vitrinite reflectance. Stratigraphic units used to generate isopach maps shown in heavy dashed lines with their approximate age ranges: (1) from base of Tertiary to Long Point Bed (65.4–52.5 Ma), (2) Long Point Bed to top of Mahogany zone (52.5–48.4 Ma), and (3) Lake infilling and younger—from top of Mahogany zone to end of lower Tertiary deposition (48.8–33.9 Ma).

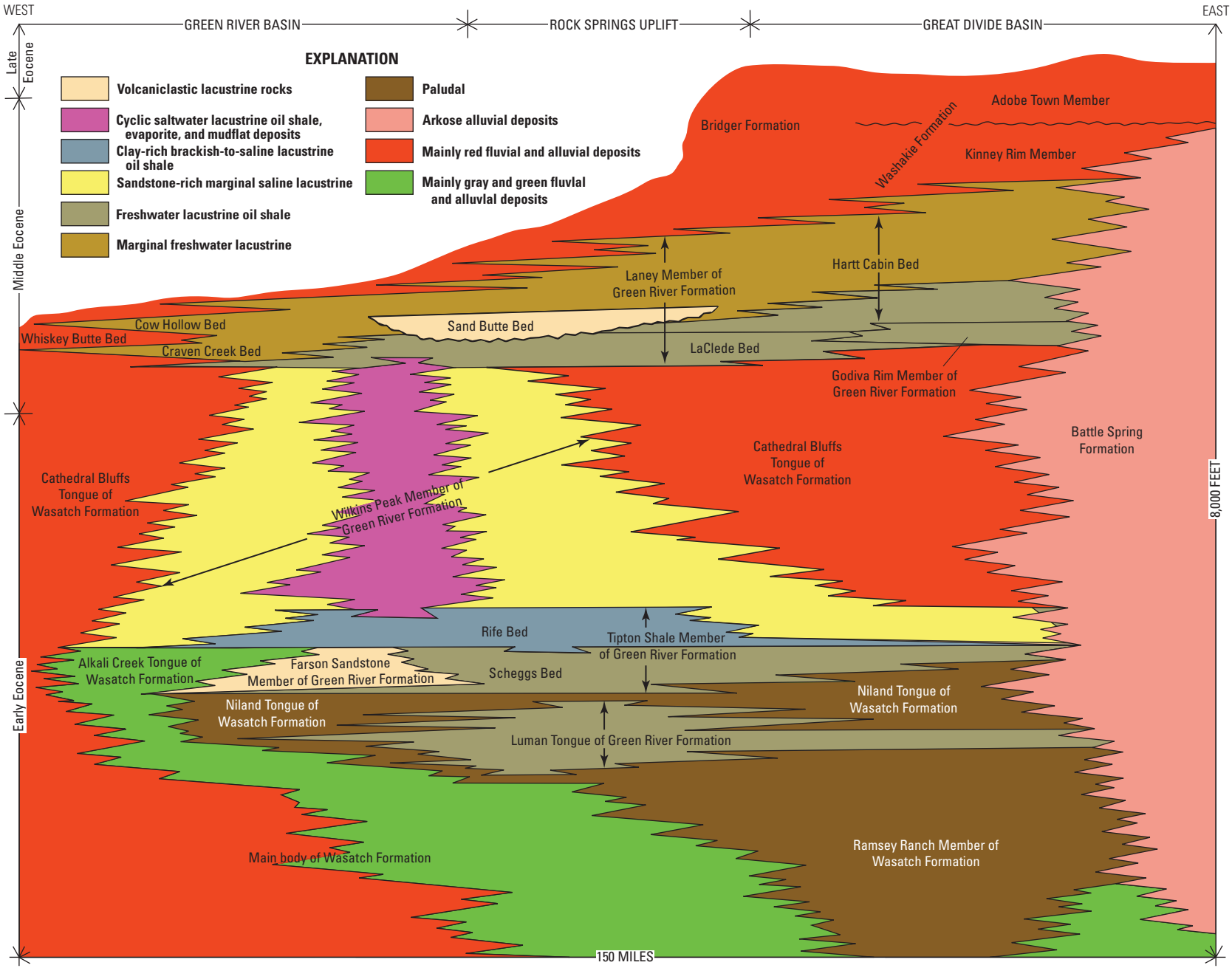


Figure 3. Generalized west-east cross section of Eocene rocks in the Greater Green River Basin, Wyoming, Colorado, and Utah, showing stratigraphic units and environments of deposition. Modified from Roehler (1991).

these units are the ones most likely to have tight oil potential. Similar to Lake Uinta in the Uinta and Piceance Basins, the transition from freshwater to brackish lacustrine in the Greater Green River Basin was preceded by a major transgression and deepening of the lake represented by the base of the Tipton Member (fig. 3). However, Roehler (1991) believed that Lake Gosiute remained fresh for a while after maximum transgression was reached, transitioning from fresh-to-brackish near the base of the Rife Bed of the Tipton Member (fig. 3). The transgression at the base of the Tipton Member has been dated at about 52.5 Ma; however, there are no radiometric dates near the base of the R-0 zone in the Uinta and Piceance Basins. Thus, it is unclear whether both lakes underwent expansion at the same time.

A brief history of the structural development of these basins during the Laramide orogeny, using isopach and structure contour maps, is also presented to study the relationship between variations in subsidence and lake phases and to study variations in the thermal maturities between the three basins.

Development of Green River Lacustrine Basins

During the Laramide orogeny (Late Cretaceous through Eocene), the central part of the Rocky Mountain foreland basin, which extended from the Artic to the Gulf of Mexico, was broken up into much smaller structural and sedimentary basins by rising Laramide uplifts (fig. 4). These uplifts gradually disrupted the existing eastward-flowing drainages to form more local drainage systems that flowed away from uplifts and toward the rapidly subsiding troughs of these newly formed basins. Because drainages were being realigned into more local systems, external drainage out of these basins was maintained for a considerable period of time as the paludal and lacustrine systems that occupied these basins remained freshwater well into the Eocene.

A paleogeographic reconstruction of the Rocky Mountain region in late Paleocene time, modified from Flores and Nichols (1999), is shown in figure 4. The realignment of drainages had begun, but several external drainages to the east were still maintained. By this time, most but not all Laramide uplifts had begun to rise. Most notably for this study, the White River uplift east of the Piceance Basin (fig. 4) was not yet actively rising and would not begin to rise until near the beginning of the Eocene (Johnson and Flores, 2003). Freshwater lakes, Lake Flagstaff in the Uinta Basin and Lake Waltman in the Wind River Basin, were present by the late Paleocene, whereas paludal systems dominated sedimentary basins in the rest of the region. The Uinta Basin probably drained eastward across the low-lying Douglas Creek arch and into the Piceance Basin, which in turn drained northward into the Greater Green River Basin during this period (Johnson and Flores, 2003).

Continued movement on Laramide uplifts ultimately resulted in the loss of all external drainages out of the Uinta, Piceance, and Greater Green River Basins by about 52 Ma (Smith and others, 2008), at which time all three basins had become dominated by large saline lakes. External drainage was lost in the Greater Green River Basin after deposition of the Scheggs Bed of the Tipton Shale Member of the Green River Formation and prior to deposition of the Rife Bed of the Tipton (fig. 3) (Roehler, 1991). In the Uinta and Piceance Basins, external drainage was lost after the Long Point transgression, during deposition of the R-0 zone (fig. 3).

Subsidence Patterns in Green River Lacustrine Basins

The relation between variations in rates of subsidence and lacustrine development and evolution during the lower Tertiary is studied using two isopach maps and one structure contour map. The first isopached interval, from the top of the Cretaceous/base of lower Tertiary to the base of the Long Point Bed in the Uinta and Piceance Basins and from the top of Cretaceous/base of lower Tertiary to the top of the Tipton Member in the Greater Green River Basin (fig. 5) generally covers the period of freshwater lacustrine and paludal deposition during the early stages of the Laramide orogeny. The second isopached interval (fig. 6) covers the period when lakes varied from brackish to hypersaline, depositing organic-rich sediments that later became the rich oil shale deposits. This interval extends from the base of the Long Point Bed in the Uinta and Piceance Basins to the top of the Mahogany oil shale zone in the Piceance Basin and top of the Mahogany oil shale bed in the Uinta Basin. In the Greater Green River Basin, the isopached interval extends from the top of the Tipton Member to the top of the LaClede Bed of the Laney Member.

Age of the top of the Tipton Member is about 52 Ma, and age of the LaClede Bed is about 49.5 Ma (Smith and others, 2008). The Long Point Bed has not been dated but is believed to be similar to the age of the base of the Tipton Member in the Greater Green River Basin or about 52.5 Ma. Age of the Mahogany oil shale bed/zone is about 48.8 Ma (Smith and others, 2008). As previously discussed in the "Introduction" section, it is not certain that Lakes Uinta and Gosiute transitioned from fresh-to-brackish water at the same time.

Subsidence patterns after deposition of the main oil shale interval are studied using a structure contour map on the top of those strata (fig. 7). This time interval is important in understanding why a major lacustrine petroleum system developed in the Uinta Basin, but not the other Green River lacustrine basins.

A south-to-north structural cross section across the Uinta Basin, simplified from Johnson (2014), is shown in figure 8. The three units used to generate the two isopach maps and the structure contour map are marked with heavy dashed lines in ascending order: (1) top of Cretaceous/base of lower Tertiary, (2) base of the Long Point Bed, and (3) top of the Mahogany oil shale bed. Datum is sea level. Information on the cross sections includes (1) stratigraphic units, (2) depositional settings,

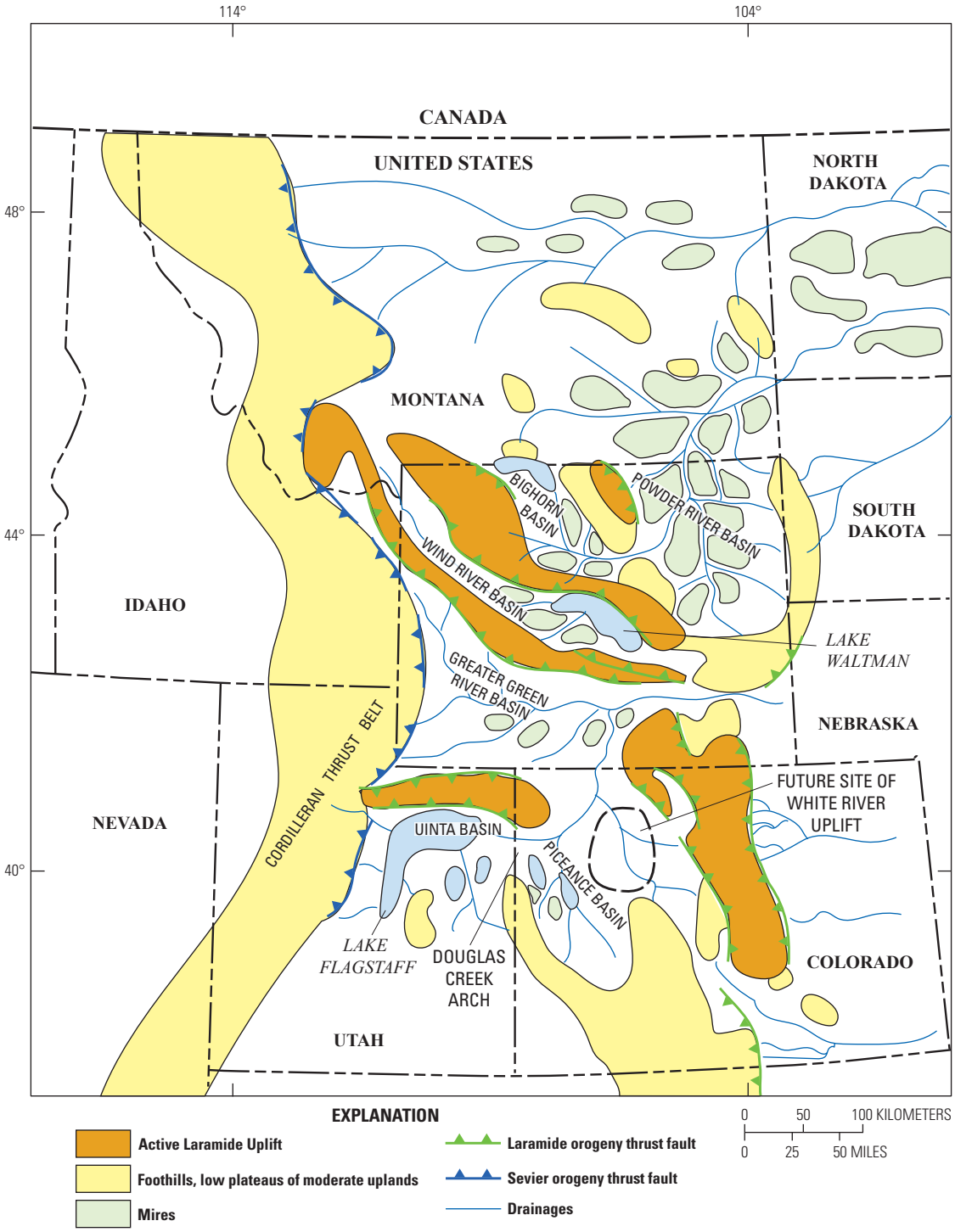


Figure 4. Paleographic map of the Rocky Mountain region during late Paleocene time. Modified from Flores and Nichols (1999).

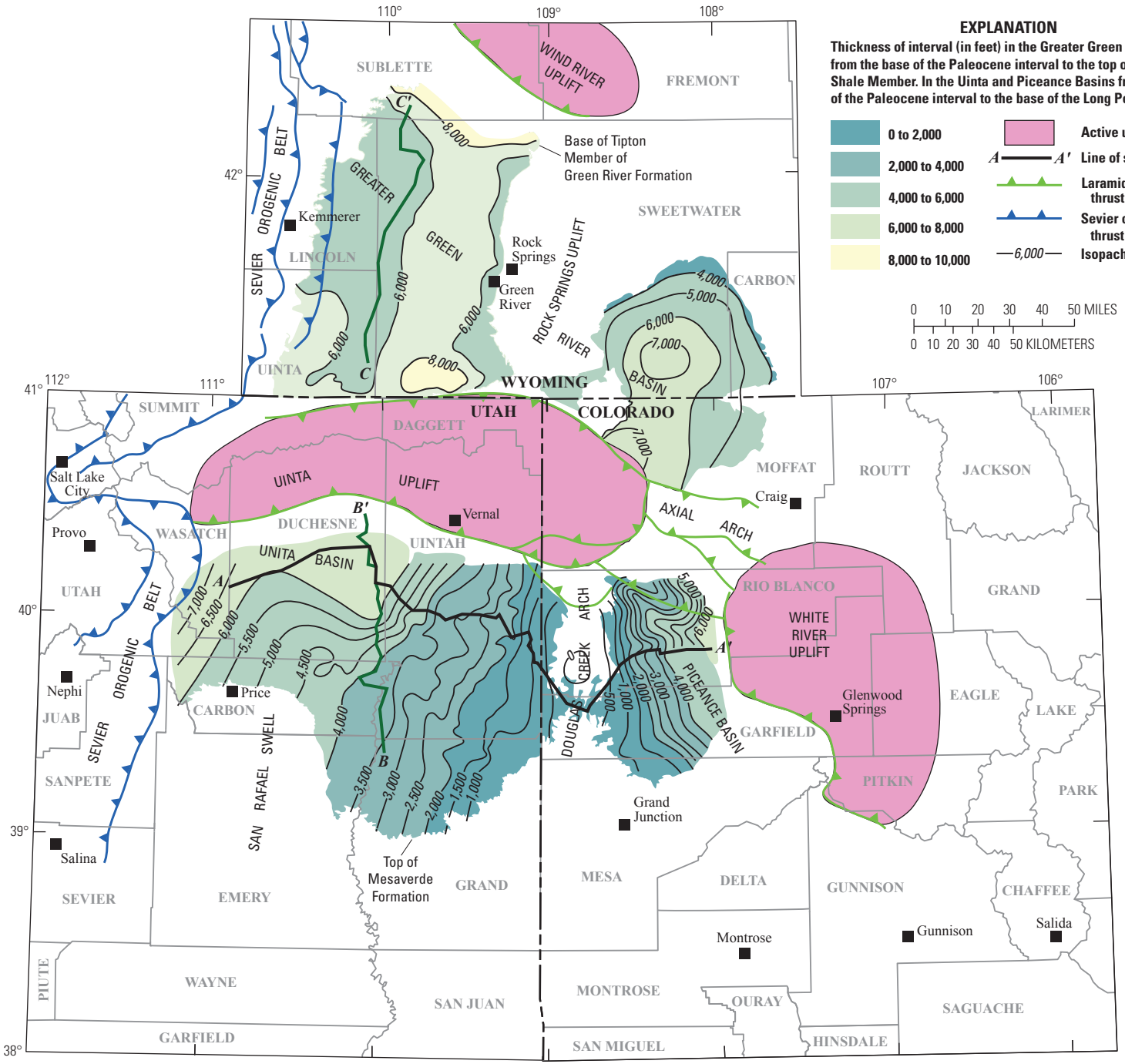


Figure 5. Isopach map from the base of Paleocene strata to the base of the Long Point Bed in the Uinta and Piceance Basins and from the base of Paleocene strata to the top of the Tipton Shale Member in the Greater Green River Basin. Isopach map in the Uinta Basin is from Johnson and Roberts (2003b), in the Piceance Basin from Johnson and Finn (1986), and in the Greater Green River Basin is new to this report. Lines of section for cross sections *A*–*A′* (fig. 2 in black), *B*–*B′* (fig. 8 in green), and *C*–*C′* (fig. 9 in green) are shown.

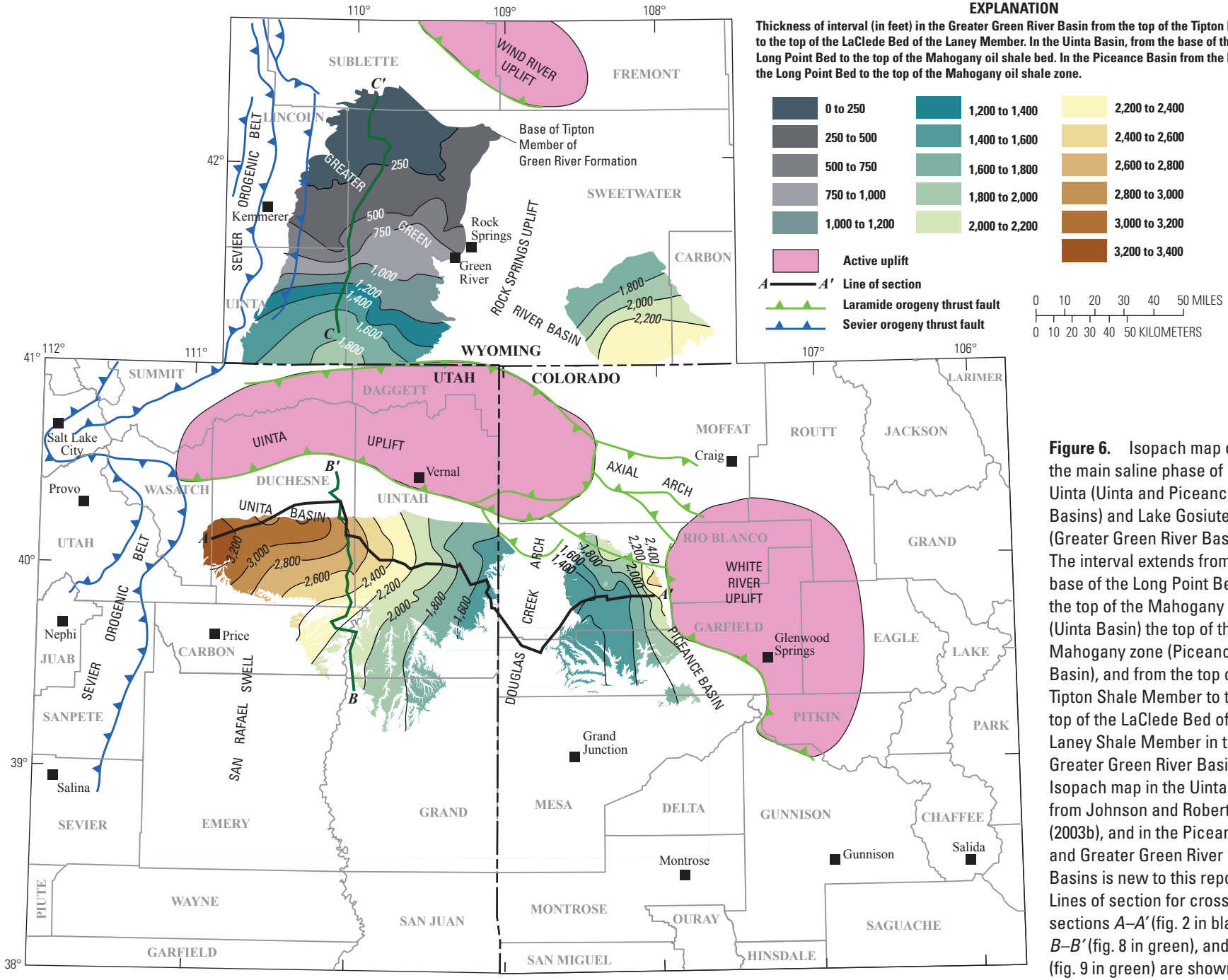


Figure 6. Isopach map of the main saline phase of Lake Uinta (Uinta and Piceance Basins) and Lake Gosiute (Greater Green River Basin). The interval extends from the base of the Long Point Bed to the top of the Mahogany bed (Uinta Basin) the top of the and Mahogany zone (Piceance Basin), and from the top of the Tipton Shale Member to the top of the LaClede Bed of the Laney Shale Member in the Greater Green River Basin. Isopach map in the Uinta Basin from Johnson and Roberts (2003b), and in the Piceance and Greater Green River Basins is new to this report. Lines of section for cross sections *A–A′* (fig. 2 in black), *B–B′* (fig. 8 in green), and *C–C′* (fig. 9 in green) are shown.

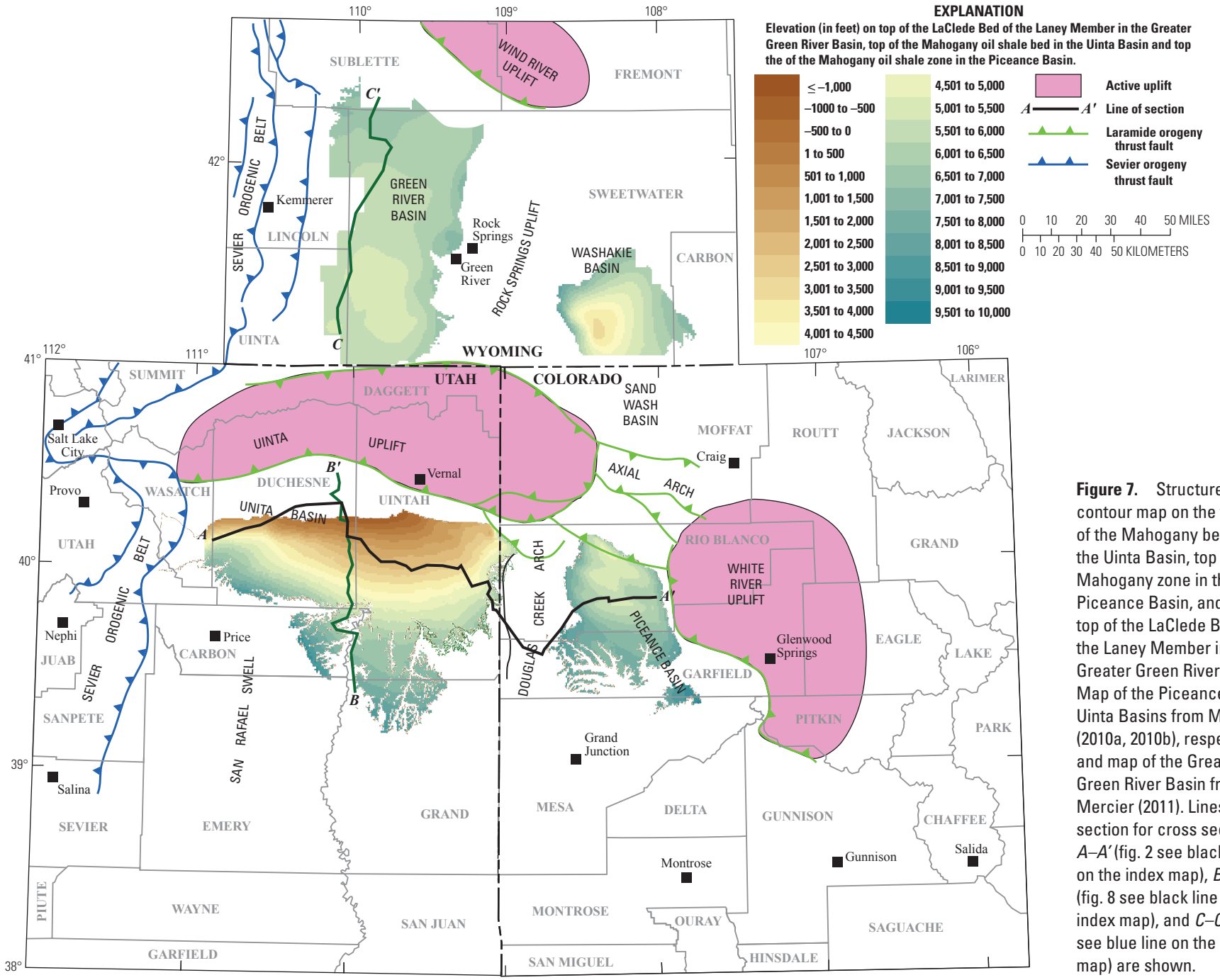


Figure 7. Structure contour map on the top of the Mahogany bed in the Uinta Basin, top of the Mahogany zone in the Piceance Basin, and on the top of the LaClede Bed of the Laney Member in the Greater Green River Basin. Map of the Piceance and Uinta Basins from Mercier (2010a, 2010b), respectively, and map of the Greater Green River Basin from Mercier (2011). Lines of section for cross sections *A–A′* (fig. 2 see black line on the index map), *B-B′* (fig. 8 see black line on the index map), and *C–C′* (fig. 9 see blue line on the index map) are shown.

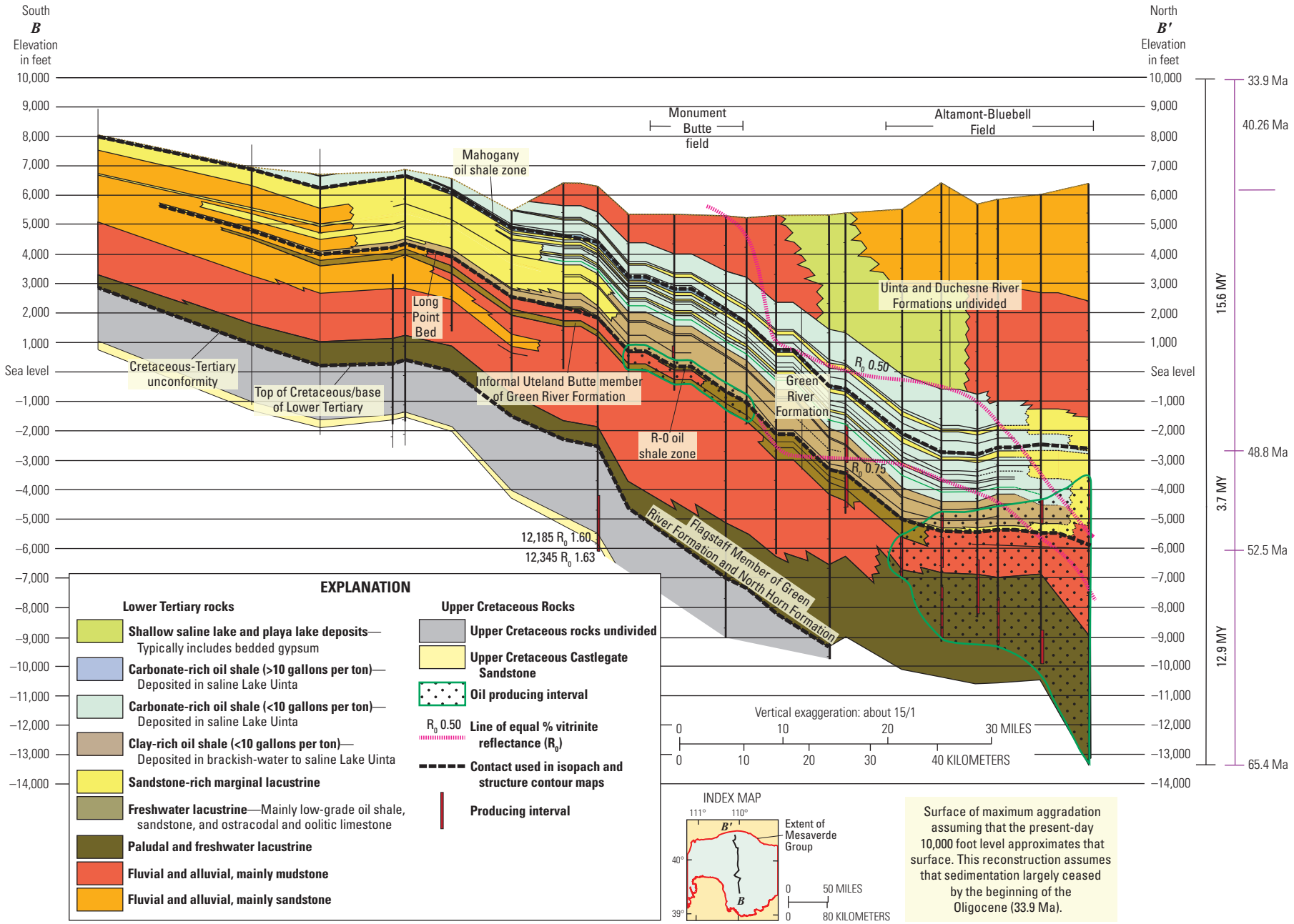


Figure 8. South-to-north cross section across the Uinta Basin showing (1) depositional settings, (2) thermal maturities using vitrinite reflectance, and (3) oil productive intervals. Datum is sea level. Cross section is simplified from Johnson (2014).

(3) variations in thermal maturities using vitrinite reflectance, ($\%R_0$) and (4) oil productive intervals. An unconformity is present between Late Cretaceous and early Tertiary strata throughout most if not all of the Uinta and Piceance Basins (figs. 2, 8). Oldest lower Tertiary strata above the unconformity varies from Paleocene near the basin troughs to lower Eocene over the crest of the Douglas Creek arch (fig. 2) (see, for example, Johnson and Johnson, 1991). The underlying Upper Cretaceous interval was intensely weathered during this long period of exposure and onlap, creating a distinctive interval in outcrop where sandstones are white due to kaolinization of feldspars (Johnson and May, 1980).

A south-to-north structural cross section in the Green River Basin almost due north of the Uinta Basin cross section simplified from Self and others (2010, their plate 1) is shown in figure 9, with the three units used to generate the two isopach maps and structure contour map in the Greater Green River Basin marked in heavy black lines in ascending order: (1) top of Cretaceous-base of lower Tertiary, (2) top of Tipton Member, and (3) top of LaClede Bed of the Laney Shale Member. For most of the Greater Green River Basin, the contour horizon is the top of the Rife Bed of the Tipton Member (fig. 3), but in the northern part of the Green River Basin, where that bed is missing, the contour horizon is the top of the stratigraphically lower Scheggs Bed of the Tipton Member (fig. 3). Similar to the Uinta and Piceance Basins, an unconformity is present between Upper Cretaceous and lower Tertiary rocks throughout most of the Greater Green River Basin (for example, see Hettinger and others, 1991; Hettinger and Kirschbaum, 1991) with Paleocene strata above (fig. 10). Age of the top of the Tipton is about 51.3 Ma and age of the top of the LaClede Bed is similar to that of the top of the Mahogany at about 48.7 Ma (Smith and others, 2008).

Isopach Map of the Interval from the Base of Lower Tertiary Strata to the End of Freshwater Lakes

The first isopached interval (fig. 5) extends, in the Uinta and Piceance Basin, from the base of lower Tertiary above the Upper Cretaceous Mesaverde Formation/Group to the base of the Long Point Bed (fig. 2) and, in the Greater Green River Basin, from the base of the Paleocene strata to the top of the Tipton Member of the Green River Formation (fig. 5). The interval covers an extended period of time, as much as 14 million years, but subsidence trends shown on figure 5 may offer some insights into the development of freshwater lakes in the three basins. The map was compiled mainly from published sources. The Uinta Basin portion of this map is from Johnson and Roberts (2003b, fig. 5), and the Piceance Basin portion is from Johnson and Finn (1986, their fig. 9). A published isopach map for this interval in the Greater Green River Basin was not available, and one was generated for this report by subtracting elevations on structure contour maps in ArcGIS to generate an isopach map. The top of the Cretaceous in the Washakie and Sand Wash Basins is the top of the Maastrichtian Lance Formation (fig. 10), and a structure contour map on the top of that formation published by Roberts (2005, his fig. 3) was used. In the Green River Basin, west of the Rock Springs uplift, much of the Upper Cretaceous Maastrichtian interval was eroded prior to deposition of the Paleocene section (fig. 10), and here a structure contour map on the top of the Mesaverde Group published by Johnson and others (2005, their fig. 1) was used. The westward thinning and ultimate truncation of the entire Maastrichtian section across the Washakie Basin was documented by Johnson and others (2004). The structure contour map on the top of the Tipton Member published by Johnson and others (2011) did not include the Sand Wash Basin, and the map was extended into that basin using available drillhole data.

Elevations on the two horizons were subtracted in ArcGIS and an isopach map was contoured from the resulting values. The geographic information system (GIS)-generated isopach map for the Green River Basin west of the Rock Springs uplift is shown on figure 5. The two structure contour maps for the Washakie and Sand Wash Basins, however, were too generalized to produce a reasonable isopach map in ArcGIS, and a generalized isopach map of the interval in those two basins was generated by hand. As such, the isopach map for the area east of the Rock Springs uplift is considered less reliable than that for the area west of the uplift.

In the Uinta Basin, the interval thickens from near zero along the crest of the Douglas Creek arch to as much as 7,000 feet (ft) in a trough that varies from east-west, south of the Uinta Mountains (indicated by the Uinta uplift), to nearly north-southeast of the Sevier orogenic belt (fig. 5). The San Rafael Swell, a minor uplift southwest of the Uinta Basin, does not appear to have been active at this time (Johnson and Roberts, 2003b). In the Piceance Basin, the interval thickens from near zero along the crest of the Douglas Creek arch to more than 6,000 ft along the basin trough just east of the White River uplift (fig. 5). In the Green River Basin, the interval thickens from less than 6,000 ft in the central part of the basin to more than 8,000 ft adjacent to the Wind River uplift and to about 8,000 ft adjacent to the Uinta uplift. In the Washakie Basin, the interval thickens from less than 4,000 ft around the basin margins to more than 7,000 ft in the basin center. In the Sand Wash Basin, the interval thickens slightly toward the Uinta Mountains. Thus, maximum thickness of rocks in the Greater Green River Basin deposited during this time period was somewhat more than in the Uinta-Piceance.

Isopach of the Highly Organic-Rich Brackish to Hypersaline Interval

The second isopached interval (fig. 6) extends from the base of the Long Point Bed to the top of the Mahogany bed/zone in the Uinta and Piceance Basins and from the top of the Tipton Member to the top of the Laclede Bed of the Laney Shale Member in the Greater Green River Basin. The LaClede Bed is approximately equivalent in age to the Mahogany zone (Smith and others, 2008). The Mahogany

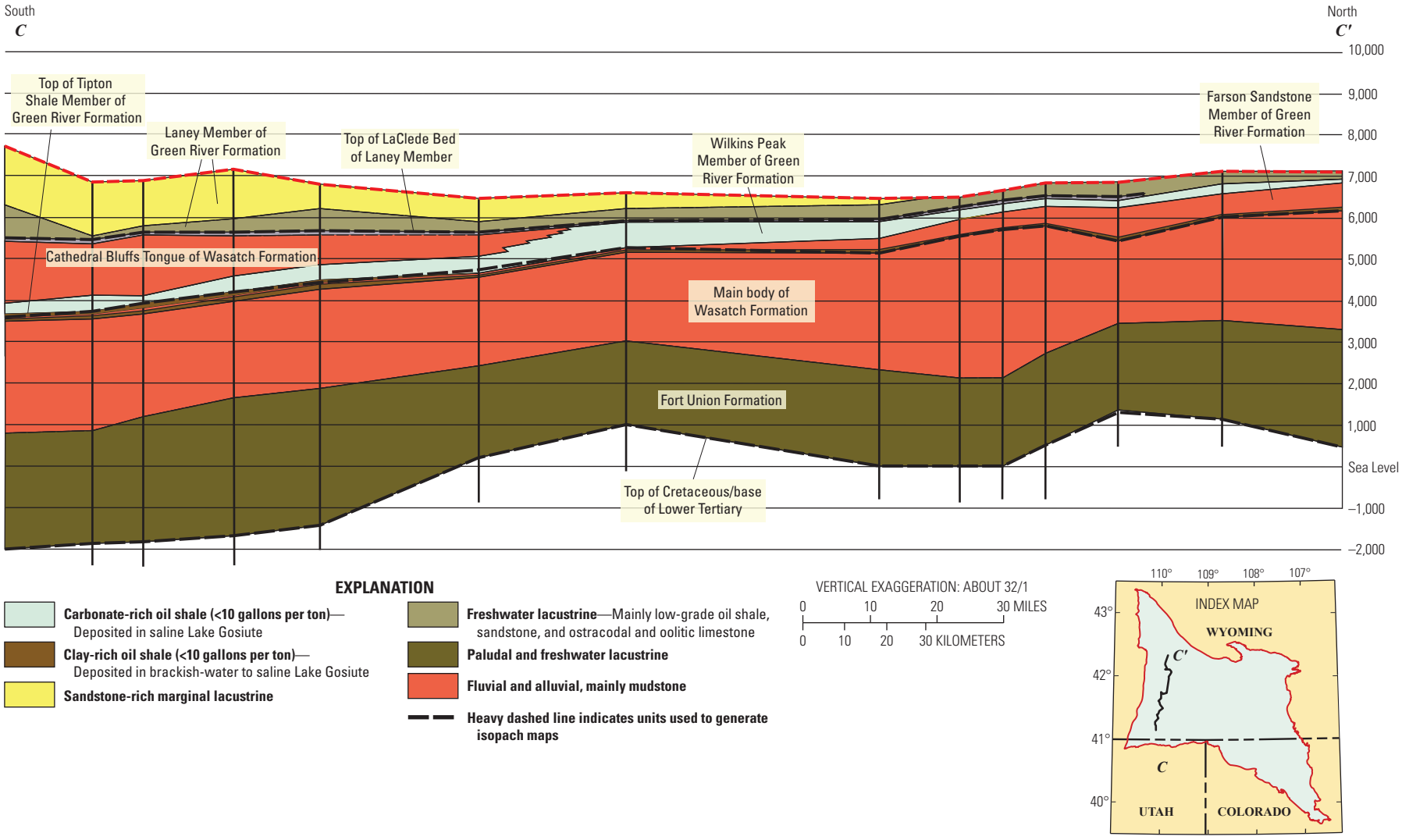


Figure 9. South-to-north cross section across the Green River Basin showing (1) depositional settings, (2) thermal maturities using vitrinite reflectance, and (3) the three time periods discussed here. The time intervals are: (1) base of Tertiary to the top of the Tipton Shale Member of the Green River Formation (65.4 to 52.5 Ma), (2) top of Tipton to top of LaClede Bed of Laney Member of Green River Formation (52.5 to 49.5 Ma), and (3) top of LaClede to maximum aggradation (about 33.9 Ma). Datum is sea level. Cross section is simplified from Self and others (2011).

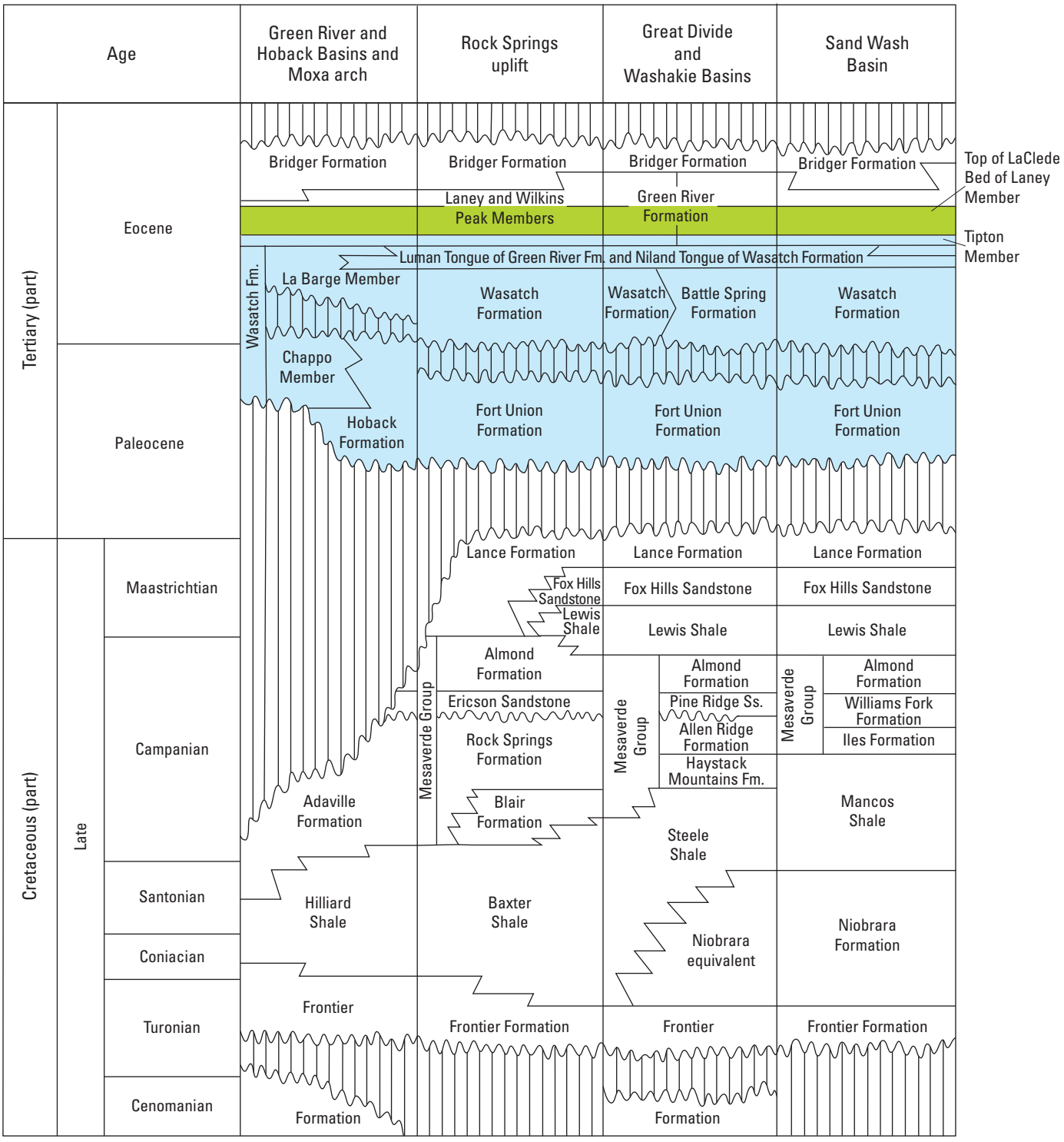


Figure 10. Generalized correlation chart for the Upper Cretaceous and lower Tertiary stratigraphic units in the Greater Green River Basin. Modified from Finn and others (2005) and Ryder (1988) to show more detail in the Green River Formation interval. Extent of first and second isopached intervals (figs. 5 and 6) shown in blue and green, respectively.

zone and LaClede Bed are widespread rich oil shale intervals deposited late in the saline histories of Lakes Uinta and Gosiute and are approximately time correlative (Smith and others, 2008). The top of the Mahogany zone is commonly used for structure contouring in the Piceance Basin (for example, see Pitman and Johnson, 1978); however, in the Uinta Basin, the top of the Mahogany zone is difficult to locate in some parts of that basin. As a result, the top of the Mahogany bed, the richest oil shale bed in the Mahogany zone, is generally used for contouring in the Uinta Basin (for example, see Cashion, 1967). Subsidence trends in the Uinta and Piceance Basins are similar to the previous period except as much as 1,400 ft of brackish-to-saline lacustrine rocks were deposited over the crest of the Douglas Creek arch. The interval thickens from less than 1,400 ft along the crest of the Douglas Creek arch to more than 3,200 ft in the western part of the Uinta Basin and more than 2,400 ft in the eastern part of the Piceance Basin along the basin trough (fig. 6). As with the previous time period, the San Rafael Swell was apparently not active at this time (Johnson and Roberts, 2003b).

A major realignment of subsidence trends in the Greater Green River Basin from the previous time period is indicated (figs. 5, 6). Thicknesses of rock deposited in the Greater Green River Basin during this time period are significantly less than for the Uinta-Piceance (maximum of 1,750 ft in the Greater Green River Basin as compared to a maximum of 3,200 ft for the Uinta-Piceance), whereas during the preceding time period, thicknesses were greater in the Greater Green River Basin. Thus, rates of subsidence in the Greater Green River Basin during this time period appear to be slowing when compared to rates in the Uinta and Piceance Basins. In addition, the interval thins markedly from south to north across the Green River Basin to less than 250 ft in the northern part of the basin adjacent to the Wind River uplift. The trough south of the Wind River uplift apparent on the previous isopached interval was replaced by regional southward tilting.

Late Laramide Subsidence Patterns

A structure contour map on the top of the LaClede Bed of the Laney Member in the Greater Green River Basin and on the top of the Mahogany oil shale bed in the Uinta Basin and Mahogany oil shale zone in the Piceance Basin is shown in figure 7. The structure contour map on the top of the LaClede Bed is from Mercier (2011), on the top of the Mahogany bed in the Uinta Basin is from Mercier (2010b), and on the top of the Mahogany oil shale zone in the Piceance Basin is from Mercier (2010a). Maximum elevations are from preserved outcrops of these units. No attempt was made to estimate maximum elevations prior to regional uplift and extensive erosion of the Green River Formation around the margins of the three basins. Maximum elevation on the top of the LaClede Bed varies from 7,200 ft in the Sand Wash Basin, to 7,440 ft in the Green River Basin, and to 8,000 in the Washakie Basin. Maximum elevation of the Mahogany oil shale bed/zone is 8,750 ft along the south margin of the Uinta Basin and 9,460 ft along the south margin of the Piceance Basin. Minimum elevations along the basin troughs are 5,100 ft in the Green River Basin; 3,750 ft in the Washakie Basin; 5,500 ft in the Sand Wash Basin; 4,900 in the Piceance Basin; and –3,000 ft in the Uinta Basin. Although the Sand Wash Basin was not studied in detail here, maximum and minimum elevations on the LaClede Bed are 7,200 ft and 5,500 ft, respectively. The most striking change indicated during this time period is the marked acceleration of subsidence rates in the Uinta Basin when compared to rates in the Piceance and Greater Green River Basins. This change created a major petroleum system in only the Uinta Basin.

Detailed Study of the Freshwater Lacustrine Interval in the Uinta, Piceance, and Greater Green River Basins

Lacustrine systems in the Green River lake basins expanded and contracted repeatedly throughout the Paleocene and Eocene, but three major lacustrine maximums and two major minimums are generally recognized. Generalized maps of these maximums and minimums are presented in this report, along with the previously discussed isopach maps to study relationships between subsidence trends and lake phases. It is not certain that these maximums and minimums occurred in all basins at the same time.

Late Paleocene Paludal-Lacustrine Maximum

By late Paleocene, poorly drained paludal and freshwater lacustrine settings covered large areas of the Laramide basins (fig. 4). A large freshwater lake, Lake Flagstaff, covered much of the Uinta Basin, while another large lake, Lake Waltman, formed along the trough of the Wind River Basin (fig. 4). Johnson (1985) compiled a map showing the maximum extent of Lake Flagstaff using subsurface and surface information that has been modified for this report using additional drillhole information (fig. 11). The largely paludal Fort Union Formation covered much of the Piceance Basin (Johnson and Flores, 2003) (fig. 11). Both the Flagstaff Member of the Green River Formation and the Fort Union Formation pinch out a few miles from the crest of the Douglas Creek arch (fig. 2).

The Flagstaff Member is the oldest lacustrine unit that has potential to be developed for tight oil in all the Green River lacustrine basins, and as such will be discussed in detail. The Flagstaff Member is considered to be late Paleocene to early Eocene in age based on its molluscan fauna (La Rocque, 1951; 1960) and palynomorpy assemblages (Newman, 1974). Organic-rich shale in the Flagstaff Member is thought to be one of the sources of oil at Altamont-Bluebell field (Morgan and others, 2003a), a deep, highly

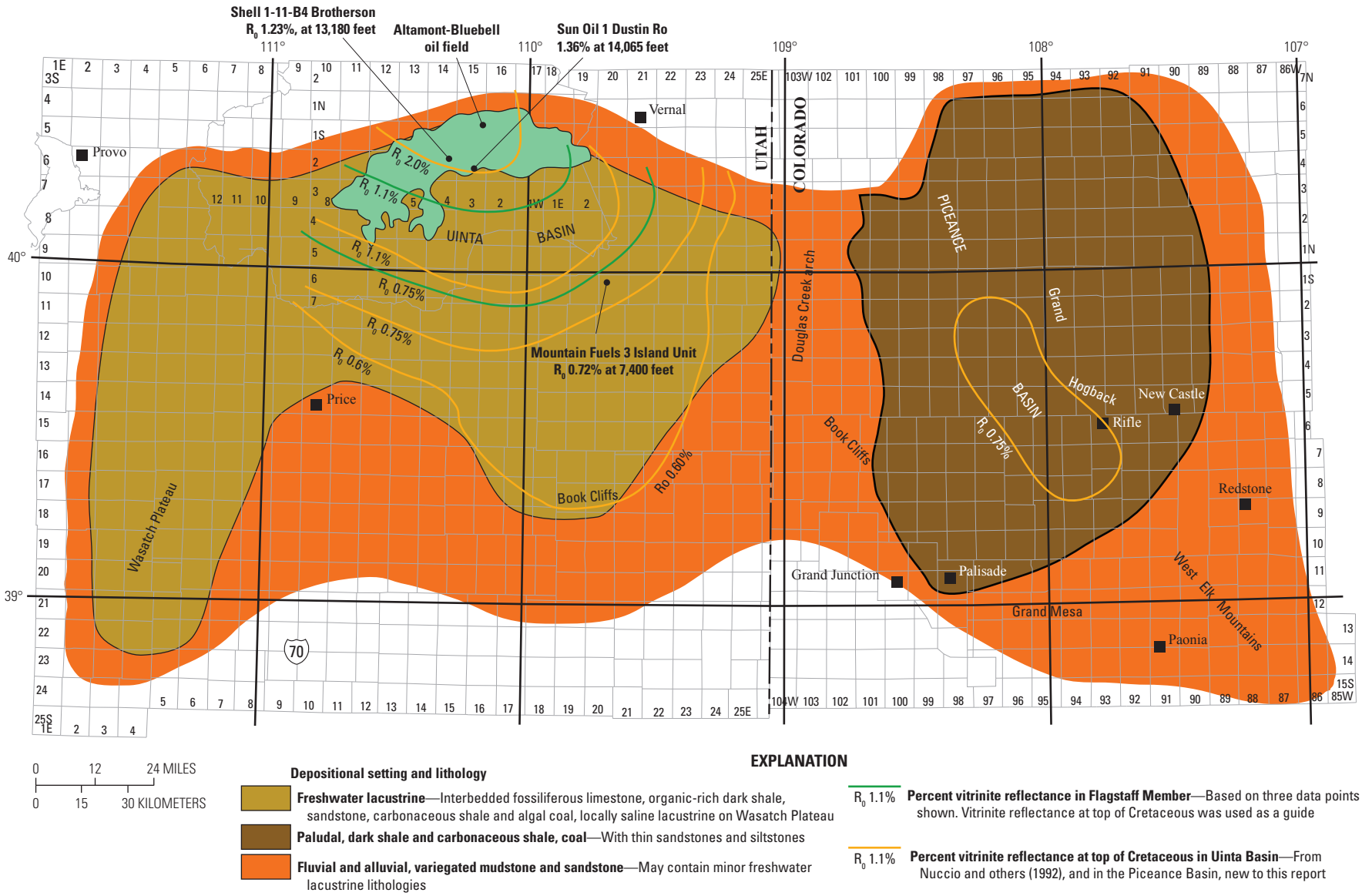


Figure 11. Map showing maximum extent of upper Paleocene lacustrine Flagstaff Member of the Green River Formation in the Uinta Basin and maximum extent of late Paleocene age paludal interval in the Fort Union and Wasatch Formations in the Piceance Basin. Maximum extent of Flagstaff Member new to this report. Extent of lacustrine deposition in the Piceance Basin modified from Johnson (1985) and Johnson and Flores (2003). Vitrinite reflectance values for the Flagstaff Member are from Anders and others (1992). Vitrinite reflectance contours at the top of the Cretaceous are from Nuccio and others (1992). Vitrinite reflectance values at the top of the Cretaceous in the Piceance Basin are estimated from thermal maturity cross sections by Johnson and Nuccio (1986). Vitrinite reflectance contours for the Flagstaff Member are new to this report. Outline of Altamont-Bluebell oil field encompasses all producing wells in IHS Global Inc. in the Altamont-Bluebell field area.

overpressured field near the trough of the Uinta Basin (Tissot and others, 1978; Fouch and others, 1994). The field produces mainly from marginal lacustrine rocks and adjacent alluvial rocks. Lake Flagstaff formed when isolated lakes in the underlying largely alluvial and paludal Upper Cretaceous and Paleocene North Horn Formation coalesced to form one large lake (Fouch, 1975). The Flagstaff Member was first described on the Wasatch Plateau by Spieker and Reeside (1925) and Spieker (1946, 1949) and traced along outcrop in the western part of the Uinta Basin by Spieker (1949). The Flagstaff Member was mapped in outcrop eastward to near where Upper Cretaceous and lower Tertiary strata crop out along the Green River by Fischer and others (1960, their plate 10). East of the Green River, the Flagstaff appears to grade into sandstone and shale. The Flagstaff Member was traced in the subsurface throughout much of the western part of the Uinta Basin by Ryder and others (1976), and in the subsurface in the eastern part of the basin by Johnson (1985). At maximum transgression, Lake Flagstaff extended to within a few miles of the crest of the Douglas Creek arch (fig. 11).

The Flagstaff Member was originally called the Flagstaff Limestone Member of the Wasatch Formation by Spieker and Reeside (1925) and was elevated to formation status by Spieker (1946). Fouch (1976) designated the unit as the Flagstaff Member of the Green River Formation because it joins the main body of the Green River Formation in the central part of the Uinta Basin. Stanley and Collinson (1979) retained the formation rank of Spieker (1946) and divided the Flagstaff Limestone on the Wasatch Plateau into the following ascending order: (1) Ferron Mountain Member, (2) Cove Mountain Member, and (3) Musinia Peak Member. The Ferron Mountain and Musinia Peak Members represent high stands of Lake Flagstaff and consist of highly fossiliferous limestone with abundant gastropod, ostracode, and charyophyte remains and some stromatolites indicating a shallow, well-oxygenated freshwater lacustrine environment. The Cove Mountain Member represents a more restricted phase of the lake and consists of nonfossiliferous dolomicrite, mudstone, sandstone, and bedded and nodular gypsum. In the western part of the Uinta Basin, the Flagstaff Member grades from lake-margin to lake-center from (1) interbedded sandstone, siltstone, gray calcareous claystone, algal coal, and oncolitic carbonate; (2) highly fossiliferous gray mud and grain-supported limestone; and (3) dark-gray mud-supported limestone (Ryder and others, 1976).

A detailed map showing depositional settings in the Greater Green River Basin during maximum extent of late Paleocene paludal period is not available, but considerable thicknesses of coal were deposited over large parts of the basin during this period (Tyler and others, 1995; Roberts, 2005).

Late Paleocene–Early Eocene Paludal-Lacustrine Minimum

Paludal-lacustrine systems retreated significantly during the latest Paleocene and early Eocene, being replaced for a prolonged period by well-drained fluvial and alluvial environments around the margins of the Uinta, Piceance, and Greater Green River Basins. This retreat has been attributed to renewed uplift on Laramide structures and climate change (for example, see Foreman and others, 2012). During this period, Lake Flagstaff retreated to the rapidly subsiding western part of the trough of the Uinta Basin (fig. 12), where the lake persisted for most if not all of this prolonged period when fluvial and alluvial deposition dominated the basin-margin areas (Fouch, 1975). The marginal lacustrine facies and the adjacent fluvial facies to the north are the main producing intervals in the Altamont-Bluebell field (fig. 12) with oil being sourced by the adjacent organic-rich offshore lacustrine facies (Lucas and Drexler, 1975).

In the Piceance Basin, widespread paludal conditions of the late Paleocene were replaced in the early Eocene by, first, a period of sandy fluvial deposition possibly signaling renewed uplift and reworking of Upper Cretaceous coastal plain sediments from nearby highlands, and then by the development of a permanent freshwater lake, Lake Cow Ridge or the Cow Ridge phase of Lake Uinta in the central part of the Piceance Basin (Johnson, 1985; Johnson and Flores, 2003). Climate change probably also played a role in these transitions because they occurred near the early Eocene climate maximum (Foreman and others, 2012). The freshwater lake formed considerably west of the rapidly subsiding trough of the Piceance Basin, adjacent to the actively rising White River uplift, possibly because of the abundance of sediments coming from that uplift (Johnson, 1985). With time, the lake expanded westward to within a few miles of the crest of the Douglas Creek arch (fig. 2). Expansions and contractions of Lake Cow Ridge to the north and south during this period were much more pronounced than to the east (Johnson, 1979a; 1979b), possibly because the slope of the fluvial and alluvial plain was more gradual in these directions.

The lower Eocene Ramsey Ranch Member of the Wasatch Formation, deposited in paludal and freshwater lacustrine settings, overlies the upper Paleocene part of the Fort Union Formation in the Greater Green River Basin and represents a shift from widespread paludal conditions to more restricted freshwater lakes and ponds. Similar to in the Piceance Basin, the freshwater lakes occupied only a fraction of the area of the former swamps. The Ramsey Ranch Member consists of carbonaceous shale and coal and freshwater limestone and oil shale deposited in small freshwater lakes and ponds (Roehler, 1992). The Ramsey Ranch Member is largely confined to the most rapidly subsiding areas of the Greater Green River Basin, the trough just north of the Uinta uplift and the central part of the Washakie Basin (figs. 1, 12), but does extend northward into the Great Divide Basin where rates of subsidence were lower. The Ramsey Ranch Member appears to have been the target of a recent unsuccessful horizontal test in the Washakie Basin discussed in a subsequent section (Freshwater Lacustrine Interval in the Greater Green River Basin).

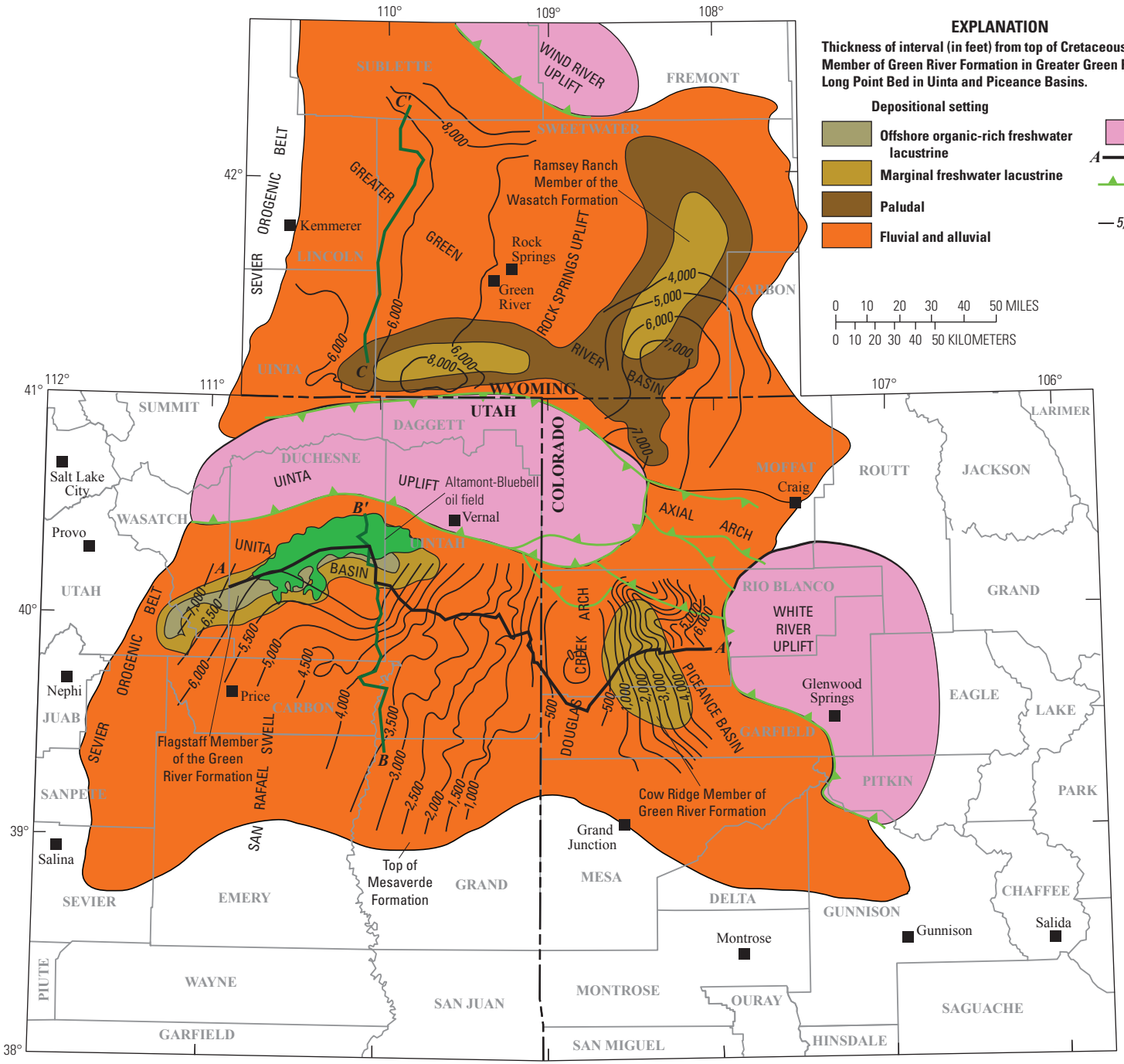


Figure 12. Map of the Uinta, Piceance, and Greater Green River Basins showing minimum extent of freshwater lakes during the latest Paleocene to earliest Eocene. Extent of Flagstaff Member of the Green River Formation in the Uinta Basin is modified from Ryder and others (1976). Extent of Cow Ridge Member of the Green River Formation in the Piceance Basin is new to this report. Extent of Ramsey Ranch Member of the Wasatch Formation in the Greater Green River Basin is modified from Roehler (1993). Included is the isopach map of the interval from the base of the Paleocene to the base of the Long Point Bed (Uinta and Piceance Basins) and top of the Tipton Shale Member (Greater Green River Basin).

Early Eocene Freshwater Lacustrine Maximum

After the early Eocene paludal-lacustrine minimum, freshwater lakes expanded out of the rapidly subsiding troughs of the Uinta, Piceance, and Greater Green River Basins to cover large areas of those basins (fig. 13). Included on figure 13 is the isopach map from the base of Paleocene to the base of the Long Point Bed in the Uinta and Piceance Basins and top of the Tipton Member. The freshwater lacustrine maximum is represented by the Uteland Butte member in the Uinta Basin, maximum transgression of the Cow Ridge Member in the Piceance Basin, and the Luman Tongue of the Green River Formation in the Greater Green River Basin (Roehler, 1993). During maximum transgression, the Uteland Butte and maximum Cow Ridge lake phases may have connected along the north part of the Douglas Creek arch where the Green River Formation is now eroded, because the two units can be traced to within a few miles of each other along the south part of the arch where the Green River Formation is still preserved. It is not known if the freshwater lacustrine maximums in the Uinta-Piceance and the Greater Green River Basins occurred at the same time.

Lithology of the Uteland Butte Member, Uinta Basin from Outcrop and Core

The primary target for recent horizontal tight oil drilling in the Uinta Basin is the Uteland Butte member (an informal name) of the Green River Formation. In the subsurface, the Uteland Butte member was originally referred to as the "Uteland Butte limestone" after the Uteland Butte field by Osmond (1992). In the subsurface, the Uteland Butte consists of limestone, dolostone, calcareous mudstone, and rare sandstone (Morgan and others, 2003b). Morgan and others (2003b) suggested that the lack of sandstone may have been caused by the rapid lake level rise resulting in the siliciclastic sediments being deposited in proximal stream channels. Morgan and others (2003b) describe a thin, widespread dolomitized zone with more than 20 percent porosity but low permeability near the top of the Uteland Butte. This dolostone bed is the target for horizontal drilling described by Anderson and Roesink (2013) and Vanden Berg and others (2014) and discussed in more detail later in this section.

Bradley (1931) was the first to study the freshwater lacustrine sequence (now known as the informal Uteland Butte member) when he measured and described a detailed section of these rocks where they are exposed in Indian Canyon in the western part of the Uinta Basin (fig. 14). Bradley (1931) applied the informal name "basal tongue of the Green River Formation" to this interval. At Indian Canyon, the basal tongue is about 200 ft thick; consists of mainly flaky shale and marlstone containing ostracodes, pelecypods, and gastropods; and is separated from overlying lacustrine rocks by 380 ft of fluvial rocks considered to be part of the Wasatch Formation by Bradley (1931). This fluvial interval has also been referred to as a tongue of the Colton Formation by Little (1988).

Overlying the Wasatch tongue is another lacustrine sequence, which Bradley (1931) referred to as the "second lacustrine phase of the Green River Formation." This sequence, according to Bradley (1931, p. 17), "is not greatly different from the basal unit but lacks the beds of carbonaceous shale, coal, and shell marl." An "algal reef" is shown on the plotted section in Bradley (1931), about 50 ft above the base of the second lacustrine phase. Stromatolites will generally not form in the presence of mollusks because they graze on the algal mats that create them. The second lacustrine phase is now recognized as largely equivalent to the R-0 zone (fig. 2), a brackish-to-saline lacustrine interval deposited early in the saline phase of Lake Uinta. Johnson (1985) noted that freshwater mollusks are extremely rare in the R-0 zone and above. The R-0 zone is discussed later in this section.

The basal tongue of Bradley (1931) was traced across the Uinta Basin to where it pinches out near the crest of the Douglas Creek arch by Johnson (1989) who determined that the basal tongue occupied about the same stratigraphic position as the most expansive period of the freshwater Cow Ridge phase of the lake in the Piceance Basin known as the "B marker" in the subsurface. Johnson and others (1988) referred to this interval, where it is exposed along the west margin of the Piceance Basin, as the "persistent ostracodal limestone zone" because it includes a minor amount of thin ostracodal limestone beds interbedded with organic- and clay-rich shale. In the subsurface, the "B marker" is 30 to 70 ft thick and is slightly more resistant on resistivity logs than the clay shale intervals above and below due to a small amount of carbonate being present. This increase in carbonate was relatively modest when compared with the increase in carbonate that accompanied deposition of the Uteland Butte.

Total thickness of the Uteland Butte member was studied in the subsurface using electric logs and some Amstrat logs (fig. 14). In electric logs, the Uteland Butte consists of two or three laterally persistent sequences with a resistant carbonate-rich bed at the base that grades up into less resistant, more clay-rich beds at the top. All resistant intervals on electric logs were considered to be carbonate-rich, because sandstones are rare in the Uteland Butte. The interval shown in figure 14 includes all lacustrine rocks that contain some carbonate-rich beds and is thicker than the main carbonate-rich interval of the Uteland Butte member isopached by Morgan and others (2003b, their plate 11). Thickness of the Uteland Butte using based on this assessment varies from less than 50 ft in the southeast part of the basin, where it consists of a single ostracodal and oolitic limestone, to more than 400 ft along the basin trough south of the Uinta uplift, where it consists of three to four carbonate cycles.

The Uteland Butte member and Cow Ridge Member were mapped to the limit of outcrop along the crest of the Douglas Creek arch in both basins. Post-depositional downcutting has produced a 12-mile gap in Green River Formation exposures along the northern part of the arch. Where Green River Formation exposures are continuous along the southern part of the crest, both the Uteland Butte and Cow Ridge grade into fluvial

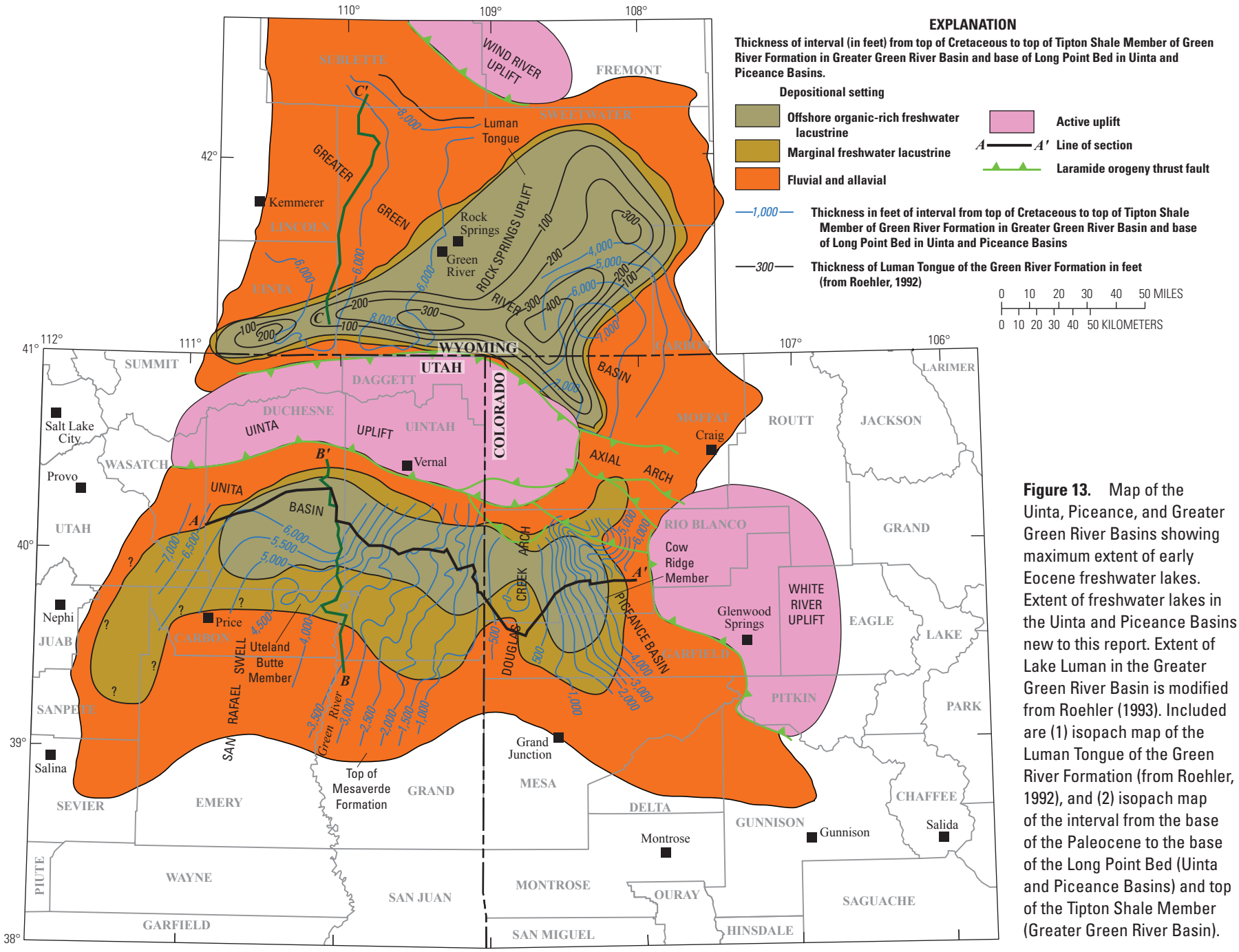


Figure 13. Map of the Uinta, Piceance, and Greater Green River Basins showing maximum extent of early Eocene freshwater lakes. Extent of freshwater lakes in the Uinta and Piceance Basins new to this report. Extent of Lake Luman in the Greater Green River Basin is modified from Roehler (1993). Included are (1) isopach map of the Luman Tongue of the Green River Formation (from Roehler, 1992), and (2) isopach map of the interval from the base of the Paleocene to the base of the Long Point Bed (Uinta and Piceance Basins) and top of the Tipton Shale Member (Greater Green River Basin).

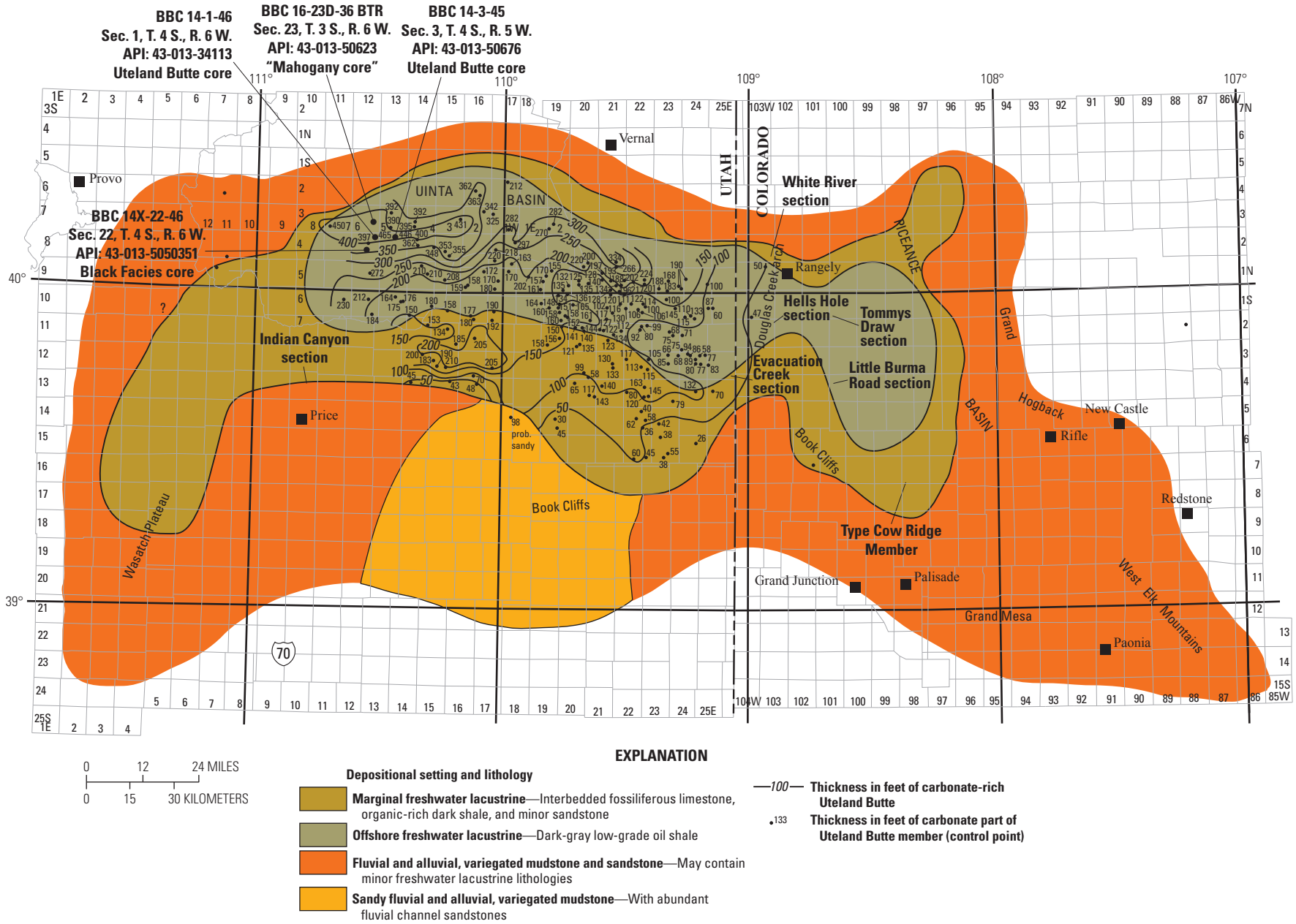


Figure 14. Map of the Uinta and Piceance Basins showing lithofacies of the informal Uteland Butte member of the Green River Formation in the Uinta Basin and the Cow Ridge Member of the Green River Formation in the Piceance Basin during their maximum extent, and thickness of the carbonate-rich part of the informal Uteland Butte member using electric logs and some Amstrat logs. Locations of surface sections and coreholes discussed are also shown.

and alluvial rocks of the Wasatch Formation. It is entirely possible that the two lakes may have connected from time to time across the northern part of the crest of the Douglas Creek arch in an area that is now eroded. The two lakes almost certainly were connected by a stream or river across the crest of the arch, because the arch was apparently not a significant topographic feature at this time.

The Uteland Butte member was described in detail at three localities in the Uinta Basin where it crops out just west of the crest of the Douglas Creek arch by Johnson and others (1988). Two of the sections, the Evacuation Creek section and the White River section (fig. 14), were revisited for this study. Both sections were also previously described by Cashion (1967). The White River section was revisited in 2014, and an outcrop that was better exposed than the one described by Johnson and others (1988) was discovered. This outcrop is described here. The lower 19.5 ft of the newly discovered Uteland Butte outcrop near the White River section (fig. 15) consists of dark organic-rich shale, white shell beds of freshwater mollusks, and one discontinuous stromatolite bed (figs. 16–19); these strata directly overlie variegated mudstones deposited in an alluvial plain environment. This lacustrine interval was not exposed at the original site described by Johnson and others (1988). Johnson (1985) noted that oolite and oncolite beds were common in the freshwater interval in the Uinta Basin, and occasionally stromatolite beds were observed in what is now called the Uteland Butte member, but that these lithologies were completely absent from the Cow Ridge Member in the Piceance Basin. It is possible that the shell beds represent periodic mortality events as the water in the lake during Uteland Butte time varied from fresh to slightly brackish. A model that attempts to explain these differences between the Uteland Butte member and Cow Ridge Member is presented later in this section.

From 19.5 ft to 76.5 ft, the section consists of mainly even-bedded ostracode and mollusk-rich limestone interbedded with laminated gray mudstone (fig. 15). A fine- to very-fine grained ripple-laminated sandstone of probable marginal lacustrine origin is present from 99 to 112 ft. A lenticular channel sandstone extends from 117.5 to 123.5 ft in the measured section. Above this sandstone, the section is mostly covered and consists of medium-gray nonlaminated mudstone and ostracode and mollusk-bearing limestone. The section was stopped at 230 ft at the top of a ridge where exposures ran out. Based on the description of the original White River section measured by Johnson and others (1988), this new section ended at or near the Long Point Bed, and it is possible that the two ostracodal limestones at the top of the new section constitute that bed. If true, then the overlying covered interval would be the R-0 zone. Clearly, the entire 230-ft interval contains some lacustrine rocks, but the carbonate-rich portion, from 19.5 ft to 76.5 ft, is probably equivalent to what is called Uteland Butte member in the subsurface. The 57-ft thickness of this interval is similar to thicknesses of the Uteland Butte in the nearby subsurface (fig. 14).

The Evacuation Creek section consists of interbedded limestone, dark shale, and thin fine- to very-fine grained sandstone beds (fig. 20). Limestone beds are commonly micritic and contain ostracodes, oolites, pizolites, gastropods, pelecypods, and turtle remains. The base of the Uteland Butte here consists of an interval of interbedded thin sandstone and dark shale beds that directly overly variegated mudstone of the Wasatch Formation. A 45-ft-thick sandstone with trough-cross beds to 4 ft high is in the overlying Wasatch tongue just below the Long Point Bed. The Long Point Bed is a 2-ft-thick ostracodal limestone with gastropods. The R-0 zone is 81.5 ft thick and consists mainly of dark-gray fissile shale with two thin ostracodal limestone beds and one 0.5-ft-thick stromatolite bed.

Bill Barrett Corp. cored the Uteland Butte member at three localities on their leased areas in the western part of the Uinta Basin (fig. 14). This core, along with a complete description and data from extensive geochemical, mineralogical, and mechanical studies, was donated to the Utah Geological Survey and can be viewed and sampled by the public. A complete discussion of these extensive analyses is beyond the scope of this paper. Only one core photograph and two micrographs (figs. 21–23) are presented here that generally depict the lithologies found in the core. Figure 21 is a photograph of core of the Uteland Butte member taken from the Bill Barrett Corp. 14-3-45 well in sec. 3, T. 4. S., R. 5 W. The core consists of interbedded calcareous shale (dark gray), limestone (light gray), and dolomite (tan). The target dolomitized bed for most, if not all, of the horizontal Uteland Butte wells in the basin extends from about 7,372 to 7,377 ft. Figure 22 is a photomicrograph of a typical micritic limestone of the Uteland Butte with numerous ostracode and mollusk shells. The location of the photomicrograph sample is marked with a yellow arrow on figure 21. Figure 23 is a photomicrograph of the complex, highly altered dolomitized bed that is the main target for horizontal drilling. Location of the photomicrograph is marked with a red arrow on figure 21.

Figure 15 (facing page). Detailed surface section of the informal Uteland Butte member of the Green River Formation and overlying tongue of Wasatch Formation along White River west of Rangely, Colorado. Descriptions of the Uteland Butte member in this area have been previously published by Cashion (1967) and Johnson and others (1988). The section was re-described for this study. Location is shown on figure 14. Sh, shale; Ost, ostracodes; lam, lamination; Gyp, gypsum; Carb, carbonate; sli, slightly.

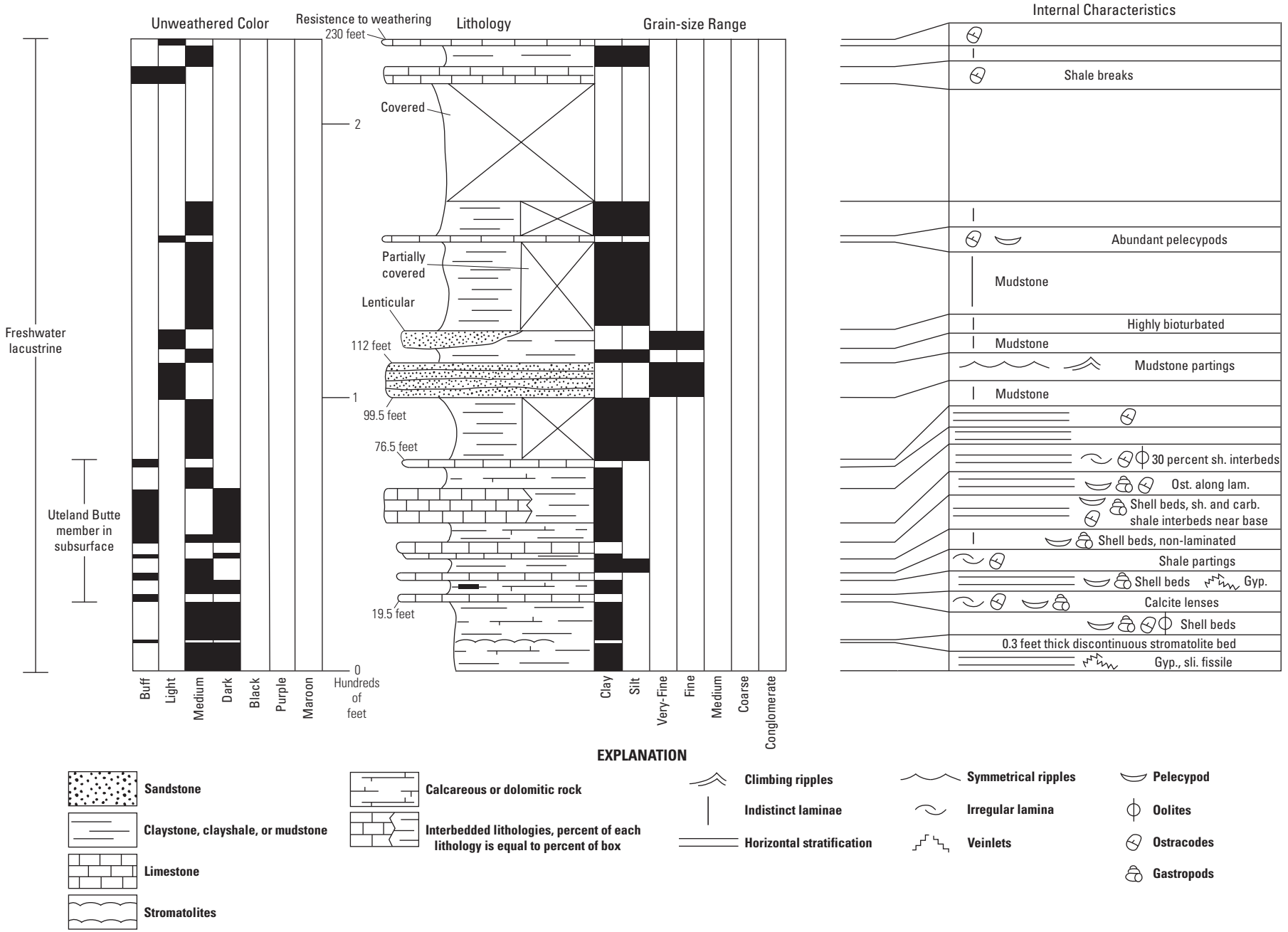

Unweathered Color
Resistence to weathering
Lithology
Grain-size Range
Internal Characteristics
230 feet
Covered
2
Partially covered
Lenticular
112 feet
1
99.5 feet
76.5 feet
19.5 feet
0
Hundreds of feet
Freshwater lacustrine
Uteland Butte member in subsurface
Buff
Light
Medium
Dark
Black
Purple
Maroon
Clay
Silt
Very-Fine
Fine
Medium
Coarse
Conglomerate
Shale breaks
Abundant pelecypods
Mudstone
Highly bioturbated
Mudstone
Mudstone partings
Mudstone
30 percent sh. interbeds
Ost. along lam.
Shell beds, sh. and carb. shale interbeds near base
Shell beds, non-laminated
Shale partings
Shell beds
Gyp.
Calcite lenses
Shell beds
0.3 feet thick discontinuous stromatolite bed
Gyp., sli. fissile
EXPLANATION
Sandstone
Claystone, clayshale, or mudstone
Limestone
Stromatolites
Calcareous or dolomitic rock
Interbedded lithologies, percent of each lithology is equal to percent of box
Climbing ripples
Indistinct laminae
Horizontal stratification
Symmetrical ripples
Irregular lamina
Veinlets
Pelecypod
Oolites
Ostracodes
Gastropods



Figure 16. Photograph of the informal Uteland Butte member of the Green River Formation at the White River section showing interbedded dark organic-rich shale, white shell beds (purple arrow), and one discontinuous stromatolites bed (blue arrow) overlain by ostracodal limestone. Location is shown on figure 14.



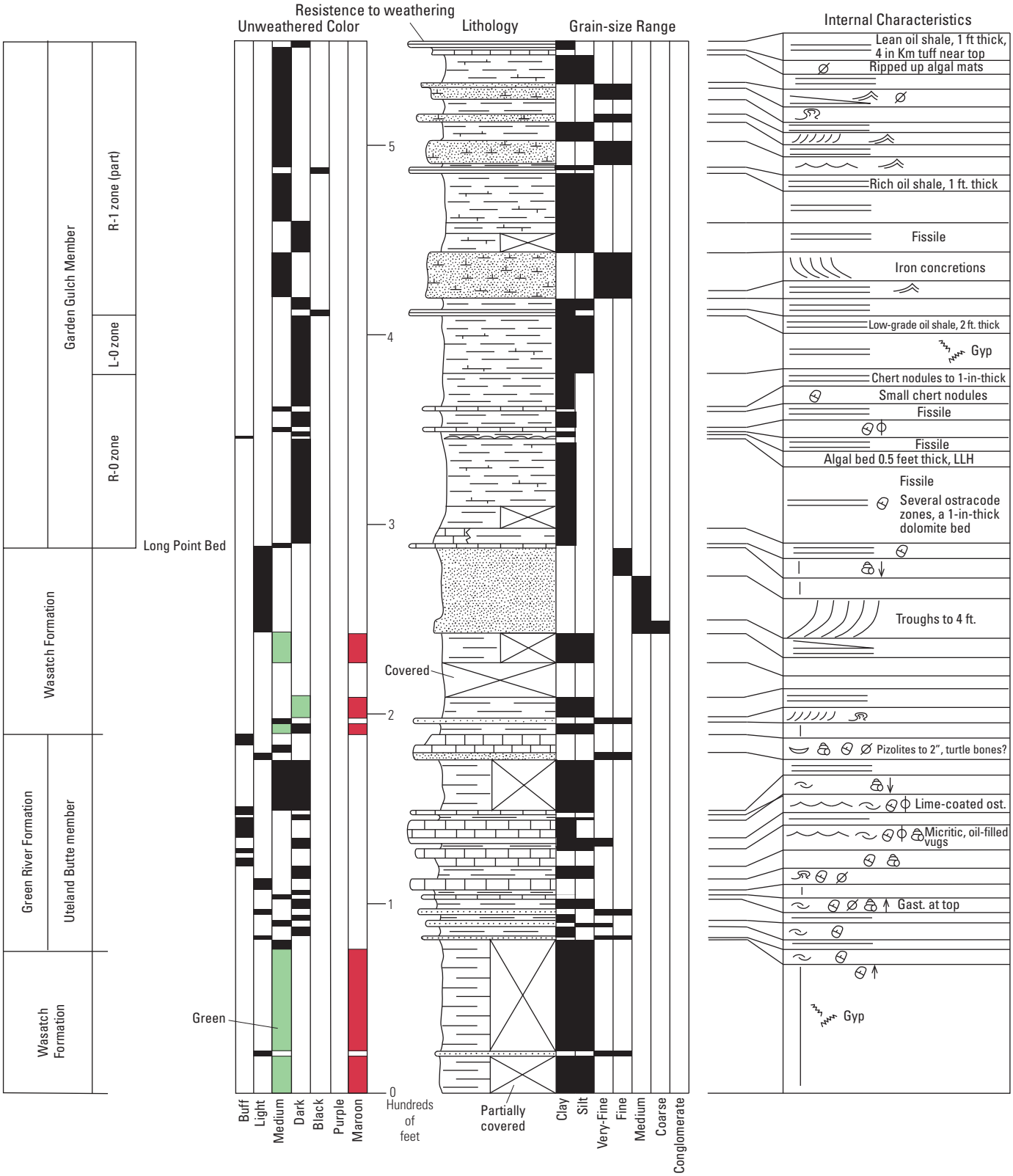
Figure 17. Photograph of interbedded shell beds and organic-rich shale in the informal Uteland Butte member of the Green River Formation at the White River section. Location is shown on figure 14.



Figure 18. Photograph of discontinuous stromatolites bed in the informal Uteland Butte member of the Green River Formation at the White River section. Location is shown on figure 14.



Figure 19. Photograph of ostracodal limestone interbedded with gray shale in the informal Uteland Butte member of the Green River Formation at the White River section. Location is shown on figure 14.


Resistence to weathering
Unweathered Color
Lithology
Grain-size Range
Internal Characteristics
Wasatch Formation
Green River Formation
Uteland Butte member
Garden Gulch Member
R-1 zone (part)
L-0 zone
R-0 zone
Wasatch Formation
Long Point Bed
Green
Covered
Partially covered
5
4
3
2
1
0
Hundreds of feet
Buff
Light
Medium
Dark
Black
Purple
Maroon
Clay
Silt
Very-Fine
Fine
Medium
Coarse
Conglomerate
Lean oil shale, 1 ft thick, 4 in Km tuff near top
Ripped up algal mats
Rich oil shale, 1 ft. thick
Fissile
Iron concretions
Low-grade oil shale, 2 ft. thick
Gyp
Chert nodules to 1-in-thick
Small chert nodules
Fissile
Fissile
Algal bed 0.5 feet thick, LLH
Fissile
Several ostracode zones, a 1-in-thick dolomite bed
Troughs to 4 ft.
Pizolites to 2", turtle bones?
Lime-coated ost.
Micritic, oil-filled vugs
Gast. at top
Gyp

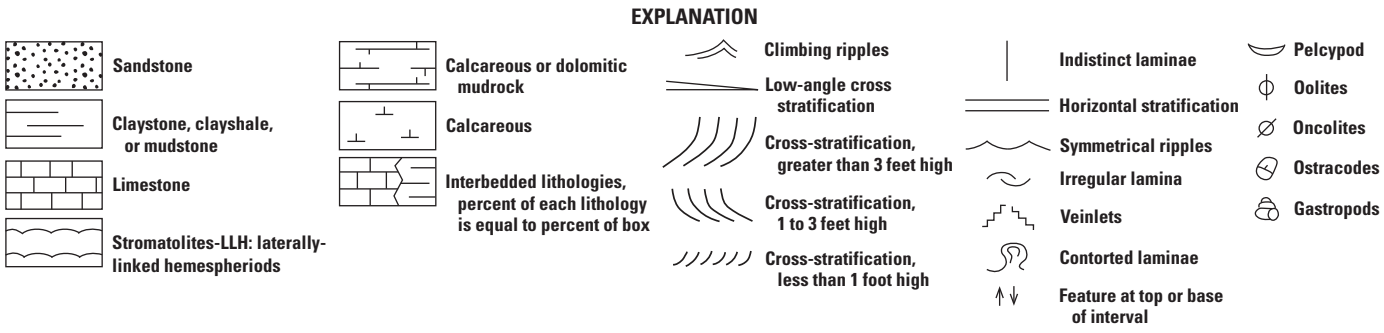


Figure 20 (above and facing page). Detailed surface section extending from the upper part of the Wasatch Formation below the informal Uteland Butte member of the Green River Formation to the R-1 oil shale zone along Evacuation Creek in eastern Utah. Modified from Johnson and others (1988). Location shown on figure 14. Gyp, gypsum; gast, gastropods.

Figure 24 shows (1) the total thickness of dolomite beds in the Uteland Butte member modified from Anderson and Roesink (2013), and (2) the thickness of the carbonate-rich interval of the Uteland Butte from this study. Maximum thickness of dolomite beds is about 45 ft in the area where the carbonate-rich part of the Uteland Butte is thickest. More recent work by M.D. Vanden Berg (Utah Geological Survey, written commun., March 2015) using core data suggests that the area of thickest dolomite is somewhat south of that determined by Anderson and Roesink (2013). According to Anderson and Roesink (2013), the total thickness of dolomite beds drops off rapidly to the north reaching a total of less than 10 ft north of the dashed red line. The northern boundary of the Uteland Butte horizontal oil play defined by Anderson and Roesink (2013) generally corresponds to this significant drop in total dolomite thickness represented by the less than 10 ft total dolomite line.

Hydrocarbon Production from the Uteland Butte Member

Figure 25 shows (1) all wells listed in the IHS Global Inc. database (2015) within the "Uteland Butte play," (2) wells listed in the IHS database as targeting the Uteland Butte, (3) total production in barrels of oil equivalent (BOE) for the first full 3 months of production for 84 horizontal producers identified as completed in the Uteland Butte by M.D. Vanden Berg (Utah Geological Survey, written commun., January 2015), and (4) oil fields that produce some oil from vertical wells completed in the Uteland Butte. It is not clear how many of the wells listed as within the Uteland Butte play or targeting the Uteland Butte actually produce out of the Uteland Butte member. Laterals that are approximately 4,000 ft are shown in yellow and 11,000 ft laterals are shown in pink. Production varies from 253 to 97,776 BOE for the first full 3 months of production with the most productive wells being the 11,000-ft laterals. Note that the Uteland Butte horizontal tight oil play is largely developing in a sparsely drilled area between Monument Butte and Altamont-Bluebell fields.

Lithology of the Cow Ridge Member, Piceance Basin from Outcrop

Johnson (1984) named the freshwater phase of the Lake Uinta in the Piceance Basin the Cow Ridge Member, and the member has been extensively mapped throughout the Piceance Basin. The name Cow Ridge Member was also originally applied to the Uteland Butte interval where it crops out in the easternmost part of the Uinta Basin by Pantea (1987; 1993) and Scott and Pantea (1990). The lake was confined for much of its history to the central part of the Piceance Basin, where the Cow Ridge Member reaches a maximum thickness of more than 2,200 ft, but expanded to occupy much of the basin during a comparatively short period of time (figs. 2, 13). The Cow Ridge Member type section is in the southern part of the Piceance Basin (fig. 14) and was deposited during this expansive period. The Cow Ridge Member at the type locality is about 205 ft thick and consists of interbedded ostracodal limestone, sandstone, siltstone, dark shale, carbonaceous shale, and thin coal beds (figs. 26, 27).

Two detailed measured sections of the Cow Ridge Member along the western boundary of the Piceance Basin adjacent to the crest of the Douglas Creek arch are also presented here: (1) Tommys Draw section (figs. 14, 28, and 29), and (2) Little Burma Road section (figs. 14, 30). For more detailed sections of the Cow Ridge Member, see Johnson and others (1988) and Johnson (1984). A tongue of Wasatch Formation separates the Cow Ridge Member from the R-0 zone of the Garden Gulch Member throughout much of the marginal areas of the Piceance Basin; however, along the northwest margin of the basin, where these two sections were measured, the R-0 zone directly overlies the Cow Ridge Member. In these two sections, the transition upward from freshwater lacustrine to brackish-to-saline lacustrine is marked by a shift from low-grade lacustrine oil shale and sandstone and limestone containing freshwater mollusks to somewhat higher-grade clay-rich oil shale and minor limestone devoid of freshwater mollusks (Johnson and others, 1988). The base of the R-0 zone represents a major expansion of the lake and

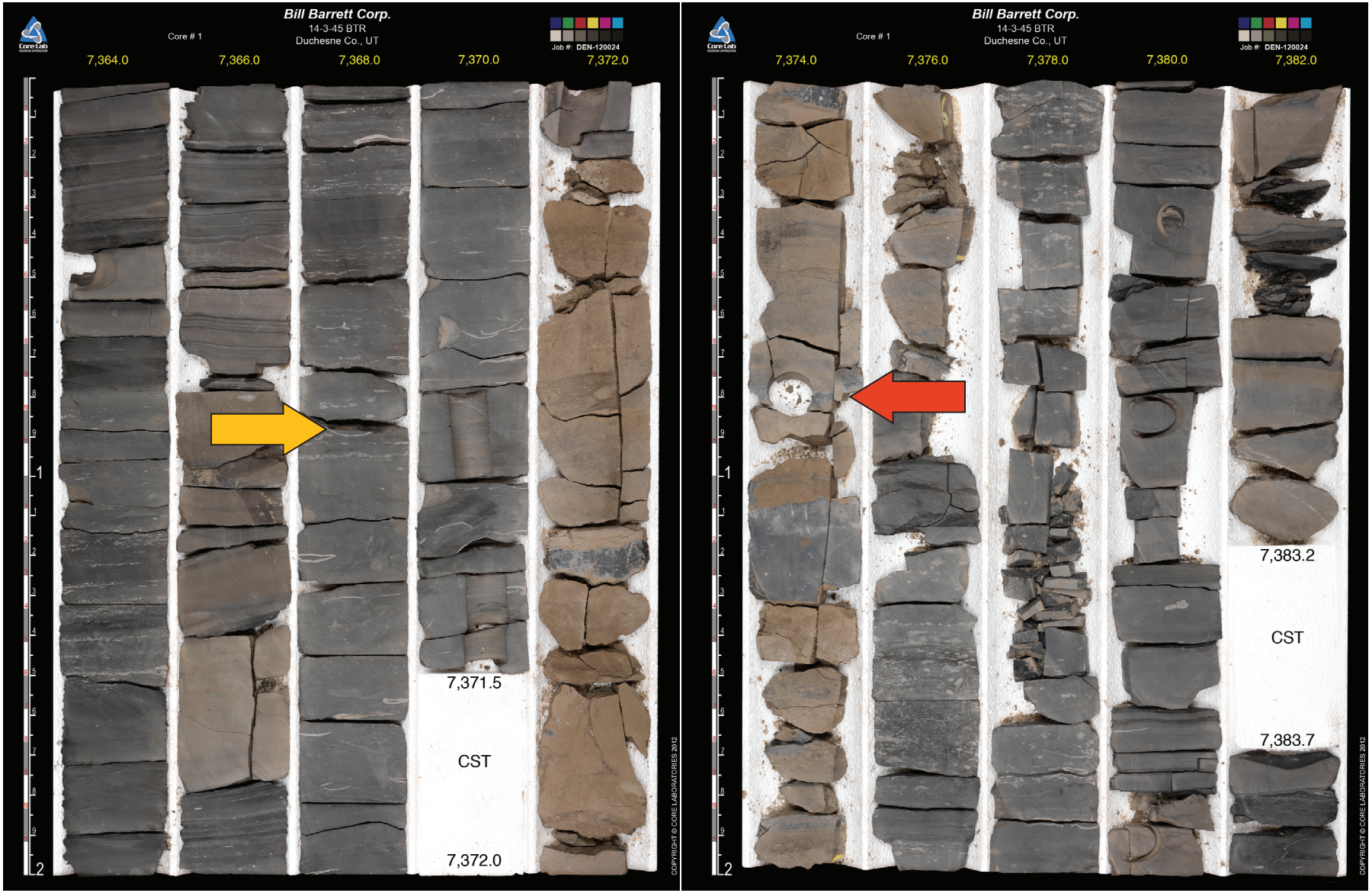


Figure 21. Core of informal Uteland Butte member of the Green River Formation from the Bill Barrett Corp. Bill Barrett Corp. 14-3-45 well in sec. 3, T. 4 S., R. 5 W. Location shown on figure 14. The thickest dolomite bed near the middle of the core is the target for horizontal drilling. The dolomitic limestone bed has an average porosity of 20 percent and an average permeability of 0.076 millidarcies based on core plugs (Anderson and Roesink, 2013). Photograph courtesy of Bill Barrett Corp.

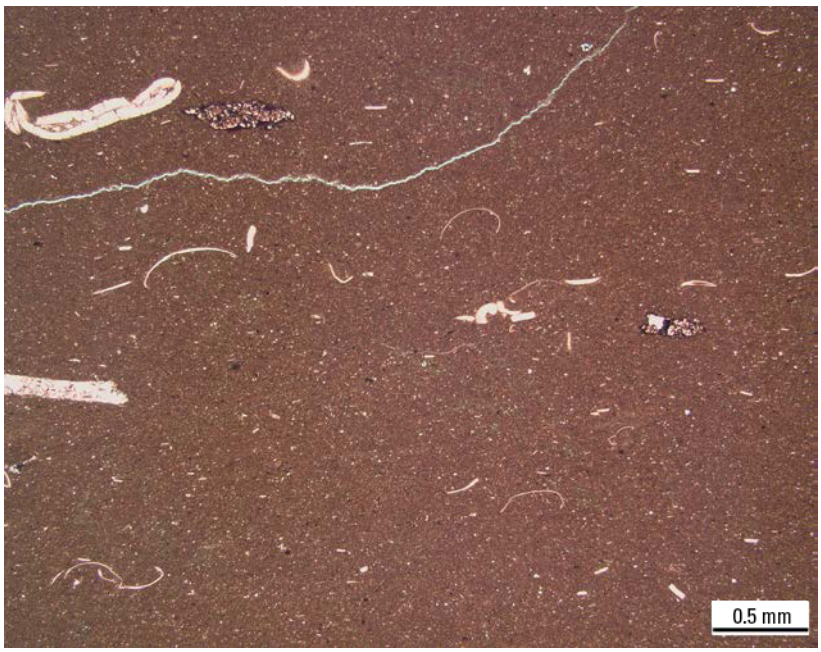


Figure 22. Photomicrograph of limestone at a depth of 7,368.70 feet in the Bill Barrett Corp. 14-3-45 well in sec. 3, T. 4 S., R. 5 W. Location shown on figure 14. The rock is a homogeneous lime mud with sparse shell fragments. Photograph courtesy of Bill Barrett Corp.

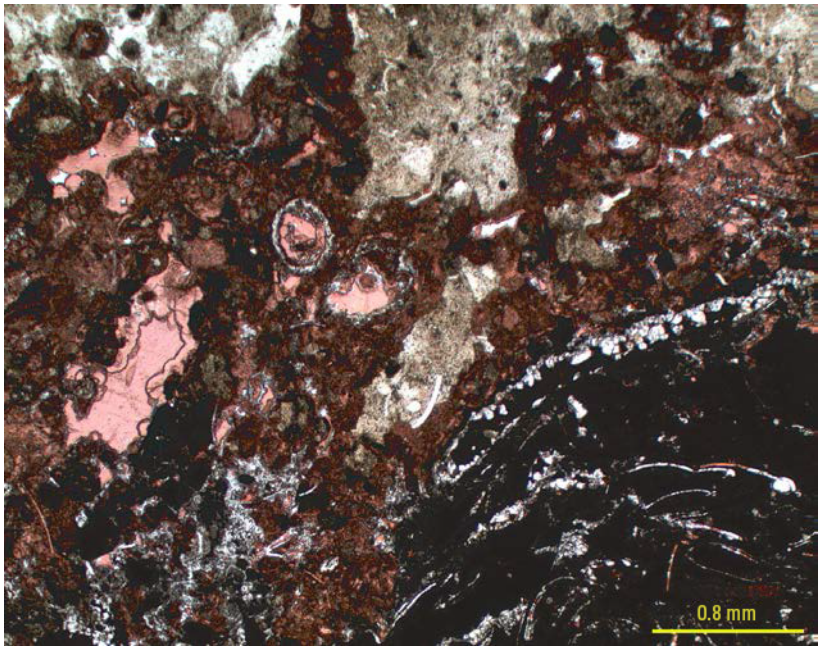


Figure 23. Photomicrograph at a depth of 7,374.5 feet from the cherty dolomitic limestone bed that is the target for horizontal drilling in the Bill Barrett Corp. Bill Barrett Corp. 14-3-45 well in sec. 3, T. 4 S., R. 5 W. Location shown on figure 14. Note the authigenic quartz and replacement calcite (pink) and chert. Photograph courtesy of Bill Barrett Corp.

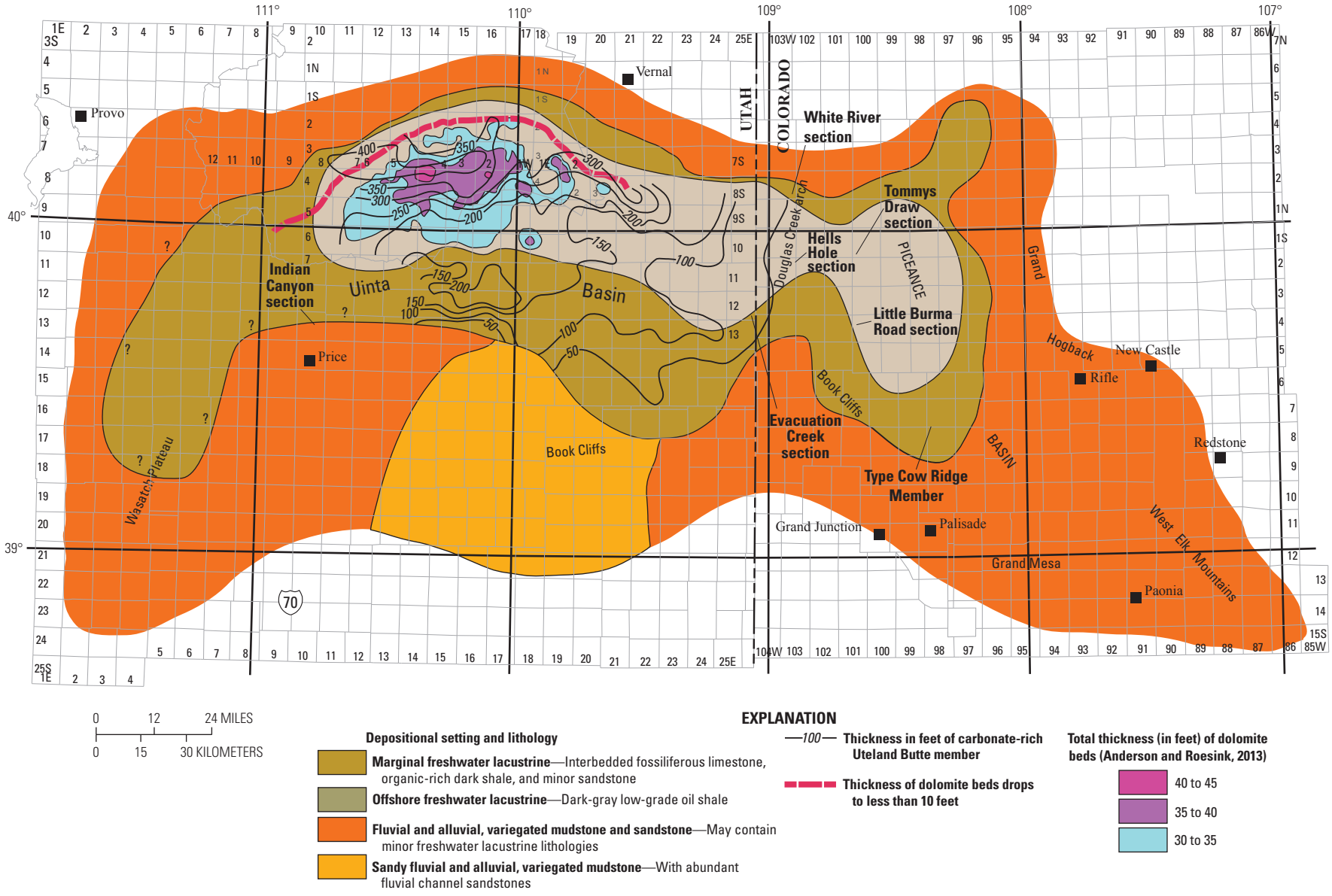


Figure 24. Map of the Uinta and Piceance Basins showing total thickness of dolomite beds in the informal Uteland Butte member of the Green River Formation (modified from Anderson and Roesink, 2013). There is less than 10 total feet of dolomite beds north of the dashed red line. Lithofacies of the Uteland Butte member in the Uinta Basin and the Cow Ridge Member of the Green River Formation in the Piceance Basin during their maximum extent, and thickness of the carbonate-rich part of the Uteland Butte member are also shown.

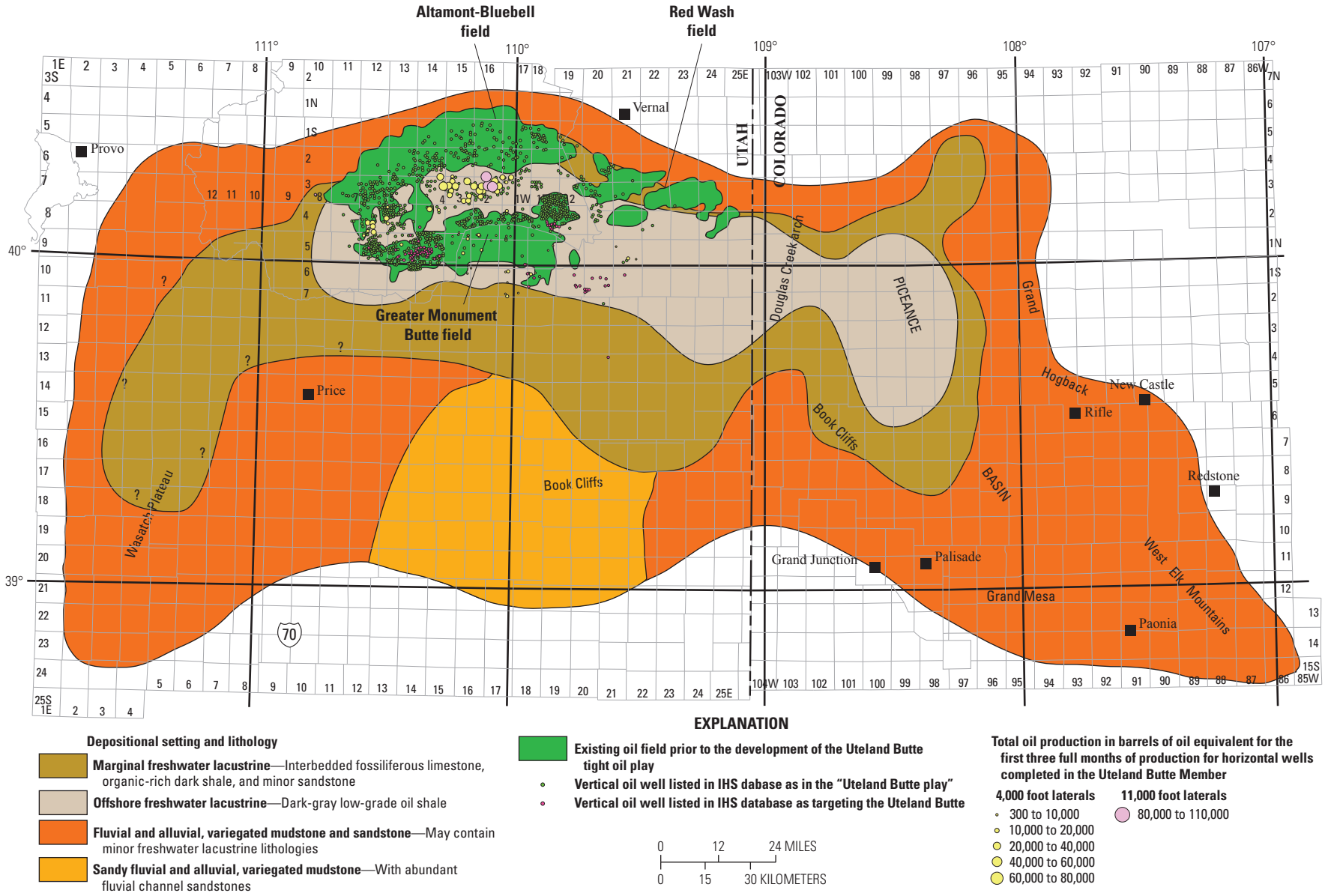


Figure 25. Map of the Uinta and Piceance Basins showing (1) all wells listed in the IHS Global Inc. database within the "Uteland Butte play," (2) wells listed in the IHS database as targeting the Uteland Butte, (3) total production in barrels of oil equivalent (BOE) for the first full 3 months of production for 84 horizontal producers identified as completed in the Uteland Butte by M.D. Vanden Berg (Utah Geological Survey, written commun., January 2015), and (4) oil fields that produce some oil from vertical wells completed in the Uteland Butte. Lithofacies of the informal Uteland Butte member in the Uinta Basin and the Cow Ridge Member of the Green River Formation in the Piceance Basin during their maximum extent are also shown. Field outlines were generated using data from IHS Global, Inc.



Figure 26. Photograph of the type section of the Cow Ridge Member of the Green River Formation in the southwest part of the Piceance Basin (sec. 31, T. 7 S., R. 98 W.). The unit consists of interbedded ostracodal limestone, sandstone, siltstone, dark shale, carbonaceous shale, and thin coal beds. No stromatolites have been found in the Cow Ridge Member.



Figure 27. Photograph of thin coal beds in the type section of the Cow Ridge Member of the Green River Formation in the southwest part of the Piceance Basin (sec. 31, T. 7 S., R. 98 W.). Thin coal beds have also been found in the informal Uteland Butte member of the Green River Formation.



Figure 28. Photograph of Cow Ridge Member of the Green River Formation at Tommys Draw along the west margin of the Piceance Basin (brown slope at base, sec. 10, T. 3 S., R. 100 W.). The most distal facies of the Cow Ridge Member can be examined in outcrop and consists of dark, ostracodal shale; low-grade oil shale with minor ostracode and mollusk-rich limestone; and sandstone.

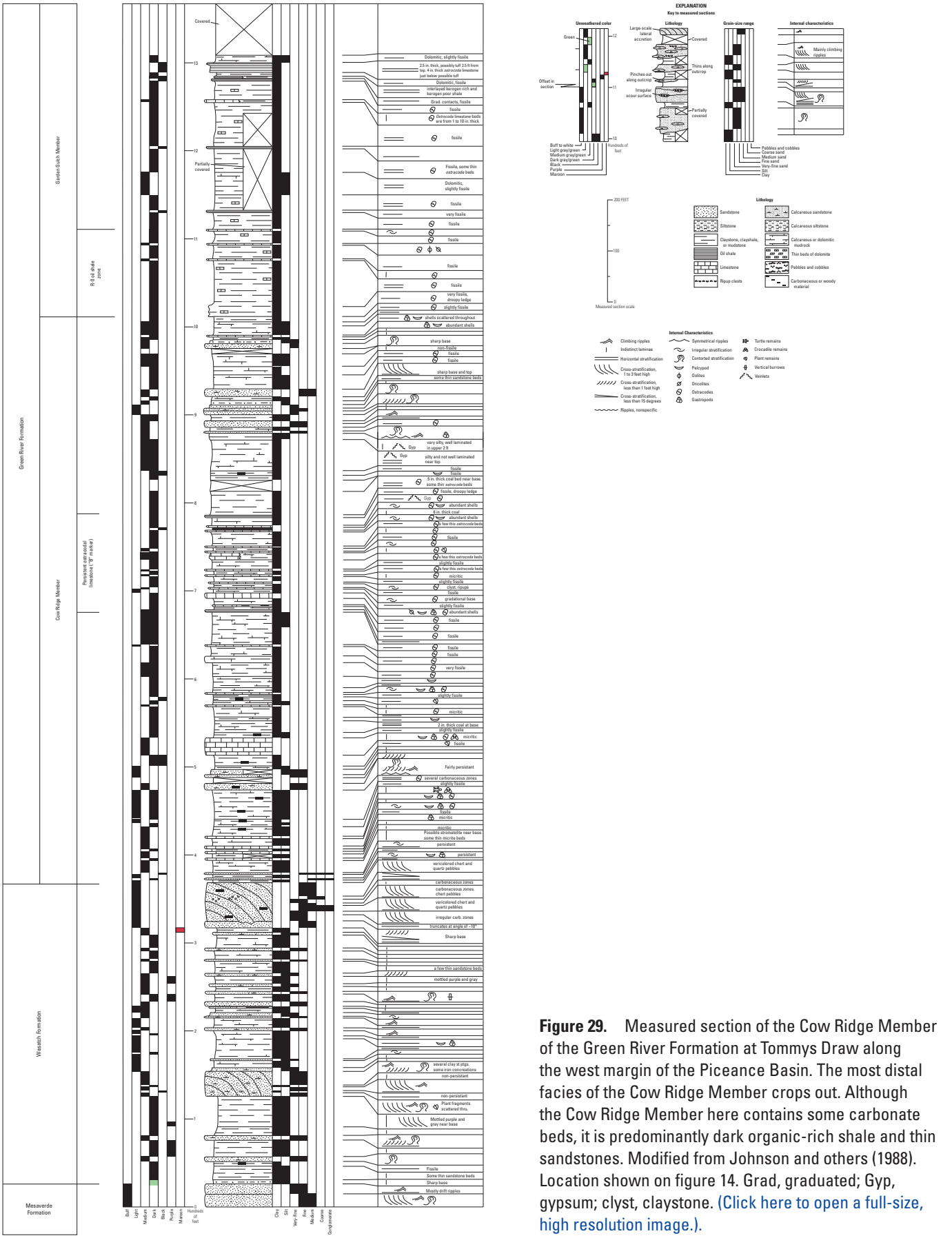
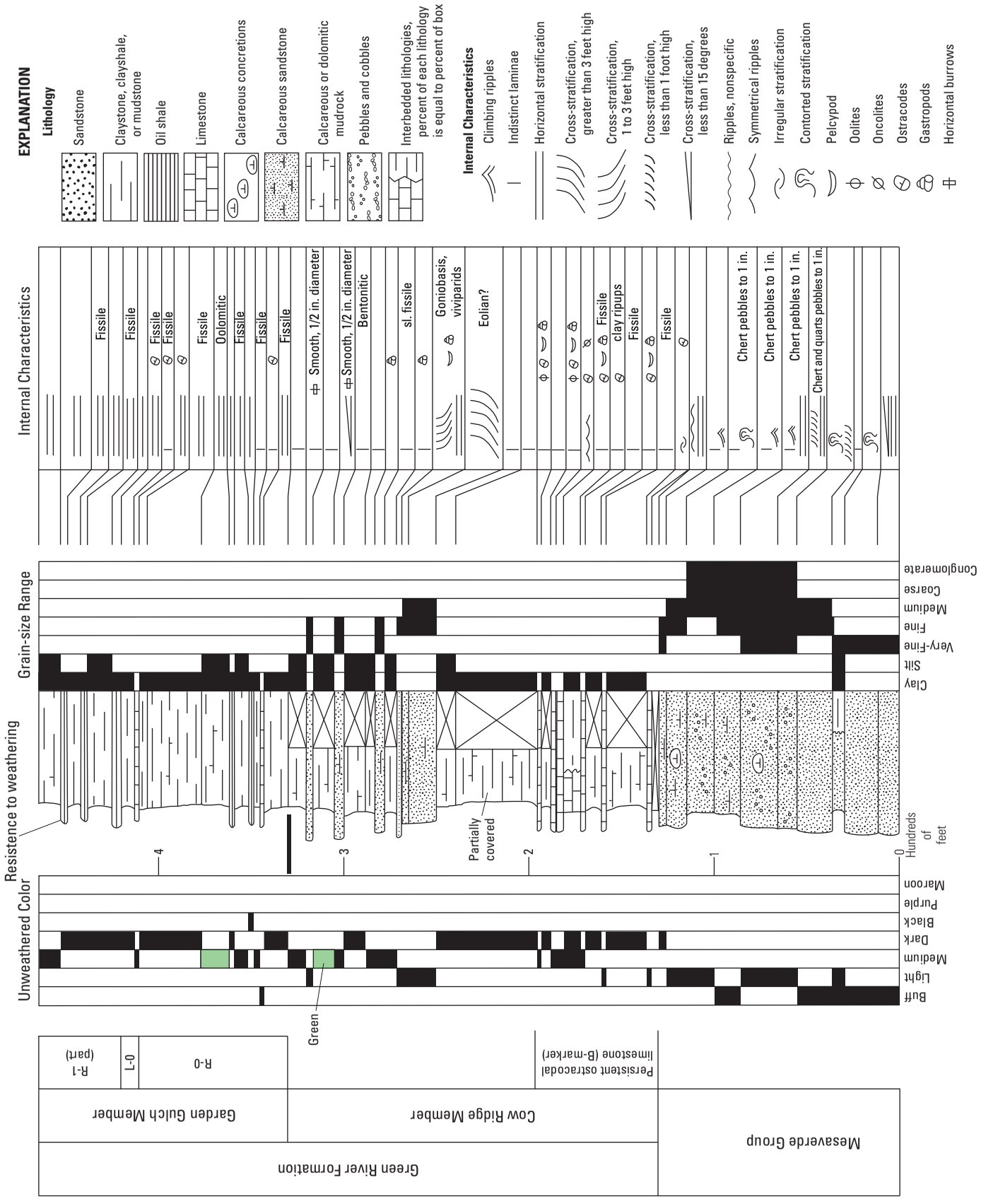


Figure 29. Measured section of the Cow Ridge Member of the Green River Formation at Tommys Draw along the west margin of the Piceance Basin. The most distal facies of the Cow Ridge Member crops out. Although the Cow Ridge Member here contains some carbonate beds, it is predominantly dark organic-rich shale and thin sandstones. Modified from Johnson and others (1988). Location shown on figure 14. Grad, graduated; Gyp, gypsum; clyst, claystone. (Click here to open a full-size, high resolution image.).


EXPLANATION
Lithology
Sandstone
Claystone, clayshale, or mudstone
Oil shale
Limestone
Calcareous concretions
Calcareous sandstone
Calcareous or dolomitic mudrock
Pebbles and cobbles
Interbedded lithologies, percent of each lithology is equal to percent of box
Internal Characteristics
Climbing ripples
Indistinct laminae
Horizontal stratification
Cross-stratification, greater than 3 feet high
Cross-stratification, 1 to 3 feet high
Cross-stratification, less than 1 foot high
Cross-stratification, less than 15 degrees
Ripples, nonspecific
Symmetrical ripples
Irregular stratification
Contorted stratification
Pelcypod
Oolites
Oncolites
Ostracodes
Gastropods
Horizontal burrows
Internal Characteristics
Fissile
Fissile
Fissile
Fissile
Fissile
Oolomitic
Fissile
Fissile
Fissile
Smooth, 1/2 in. diameter
Smooth, 1/2 in. diameter
Bentonitic
sl. fissile
Goniobasis, viviparids
Eolian?
Fissile
clay ripups
Fissile
Fissile
Chert pebbles to 1 in.
Chert pebbles to 1 in.
Chert pebbles to 1 in.
Chert and quarts pebbles to 1 in.
Grain-size Range
Clay
Silt
Very-Fine
Fine
Medium
Coarse
Conglomerate
Resistence to weathering
Unweathered Color
Buff
Light
Medium
Dark
Black
Purple
Maroon
Partially covered
Green
Hundreds of feet
0
1
2
3
4
Green River Formation
Mesaverde Group
Cow Ridge Member
Garden Gulch Member
Persistent ostracodal limestone (B-marker)
R-0
O-1
R-1 (part)

a shift from freshwater to brackish and finally saline conditions and is discussed in detail later in this section. At the Little Burma Road section, the Cow Ridge Member directly overlies an undated 78.5-ft-thick conglomeratic sandstone that in turn overlies the Upper Cretaceous Mesaverde Group. This conglomeratic sandstone may be similar to the Dark Canyon of Fouch and others (1983) of the Wasatch Formation, an upper lower Paleocene interval described farther to the west along the south margin of the Uinta Basin (Franczyk and others, 1990). If so, then there are no rocks preserved at this locality above the conglomeratic sandstone until maximum transgression of the Cow Ridge stage of Lake Uinta during the Eocene. At the Tommys Draw section, the Cow Ridge Member is separated from the Mesaverde Group by about 340 ft of the fluvial and alluvial Wasatch Formation, and the conglomeratic sandstone is missing.

At Tommys Draw (fig. 29), the Cow Ridge Member is about 640 ft thick and consists mainly of dark organic-rich shale with minor limestone and sandstone. The "persistent ostracodal limestone zone" of Johnson and others (1988) represents the most expansive period of the lake and is equivalent to the "B marker" in the subsurface. It extends from 675 to 785 ft in the measured section (fig. 29) and is probably largely equivalent to the Uteland Butte member. It consists of dark shale, oil shale, and thin limestone. A 22-ft-thick micritic limestone with ostracode and mollusk shells near the base of the Cow Ridge is the thickest limestone at Tommys Draw. At Little Burma Road (fig. 30), the Cow Ridge Member is about 195 ft thick and, similar to the Cow Ridge at Tommys Draw, and consists of mainly dark shale with minor limestone and sandstone. Sandstone is somewhat more abundant than at Tommys Draw, and the thickest limestone is only 8 ft. The "persistent ostracodal limestone (B-marker)" interval is the 61.5 ft interval at the base of the Cow Ridge that directly overlies the conglomeratic sandstone interval.

Model to Explain Differences Between the Uteland Butte and Cow Ridge Members

The Uteland Butte member is far more carbonate-rich than the Cow Ridge Member and includes oolites, oncolites, and rare stromatolites, lithologies that are lacking in the Cow Ridge Member. These differences were noted by Johnson (1985). Although both the Uteland Butte and Cow Ridge contain a similar freshwater mollusk assemblage (for example, see Johnson and others, 1988), the presence of oolites and oncolites suggest more alkaline conditions in the Uinta Basin than in the Piceance Basin, and the rare occurrence of stromatolites suggest that on occasion, the water became brackish enough to have killed off the freshwater mollusk assemblage. In addition, the Uteland Butte member includes substantial limestone and dolomite throughout its extent, whereas the Cow Ridge Member includes only scattered carbonate beds in a predominantly organic-rich and clay-rich shale interval in the central part of the Piceance Basin.

Here we propose a model to explain these differences that is based on the premise that the Douglas Creek arch acted as a modest topographic barrier between the two lakes throughout the freshwater period (fig. 31). During lake high stands, a single unbroken lake existed across the crest of the arch (fig. 31*A*), whereas a river across the crest of the arch connected the two lake basins during periods of lower water level (fig. 31*B*). In this scenario, the river flowed from the Uinta Basin into the Piceance Basin which in turn drained north across the Axial arch (fig. 1) and into the Greater Green River Basin. During periods of extreme drought (fig. 31*C*), the model proposes that the lake level in the Uinta Basin temporarily dropped below the elevation of the crest of the arch, creating an internally drained lake with increasingly alkaline water favorable to the deposition of oolites, oncolites, and thick limestone beds. Lake water chemistry periodically became toxic enough to the freshwater mollusk assemblage to cause mass mortality events represented by the shell hashes exposed at the White River section, allowing stromatolites to grow. The Uinta Basin side of the lake could not have remained brackish for very long as freshwater mollusks are scattered throughout the Uteland Butte member.

Luman Tongue of the Green River Formation, Greater Green River Basin

The Luman Tongue of the Green River Formation represents the most expansive period of freshwater lacustrine deposition in the Greater Green River Basin. It may be time equivalent to the Uteland Butte member in the Uinta Basin and the Cow Ridge Member in the Piceance Basin, but radiometric dates for all three units are lacking (Smith and others, 2008). The freshwater lakes and ponds represented by the Ramsey Ranch Member of the Wasatch Formation expanded and coalesced to form one large freshwater lake represented by the Luman Tongue of the Green River Formation (figs. 3, 13) (Roehler 1992). The Luman stage of Lake Gosiute, at its maximum extent, covered about 6,650 square miles 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. 13) (Roehler, 1992). The Luman Tongue reaches a thickness of more than 300 ft along the trough north of the Uinta Mountains; more than 400 ft in the Washakie Basin; and more than 300 ft in the Great Divide Basin (fig. 13) (Roehler 1992). Based on surface sections from throughout the Greater Green River Basin (Pipiringos, 1961; Roehler, 1981; 1989a; 1989b), the Luman Tongue consists of clay-rich, low-grade oil shale; mollusk-bearing sandstone and limestone; carbonaceous shale with thin coal beds; and siltstone (Pipiringos, 1961;

Figure 30 (facing page). Measured section of Cow Ridge. Here the Cow Ridge directly overlies the Mesaverde Group and consists mainly of dark shale and sandstone with minor thin ostracodal limestone. Modified from Johnson and others (1988). Location shown on figure 14.

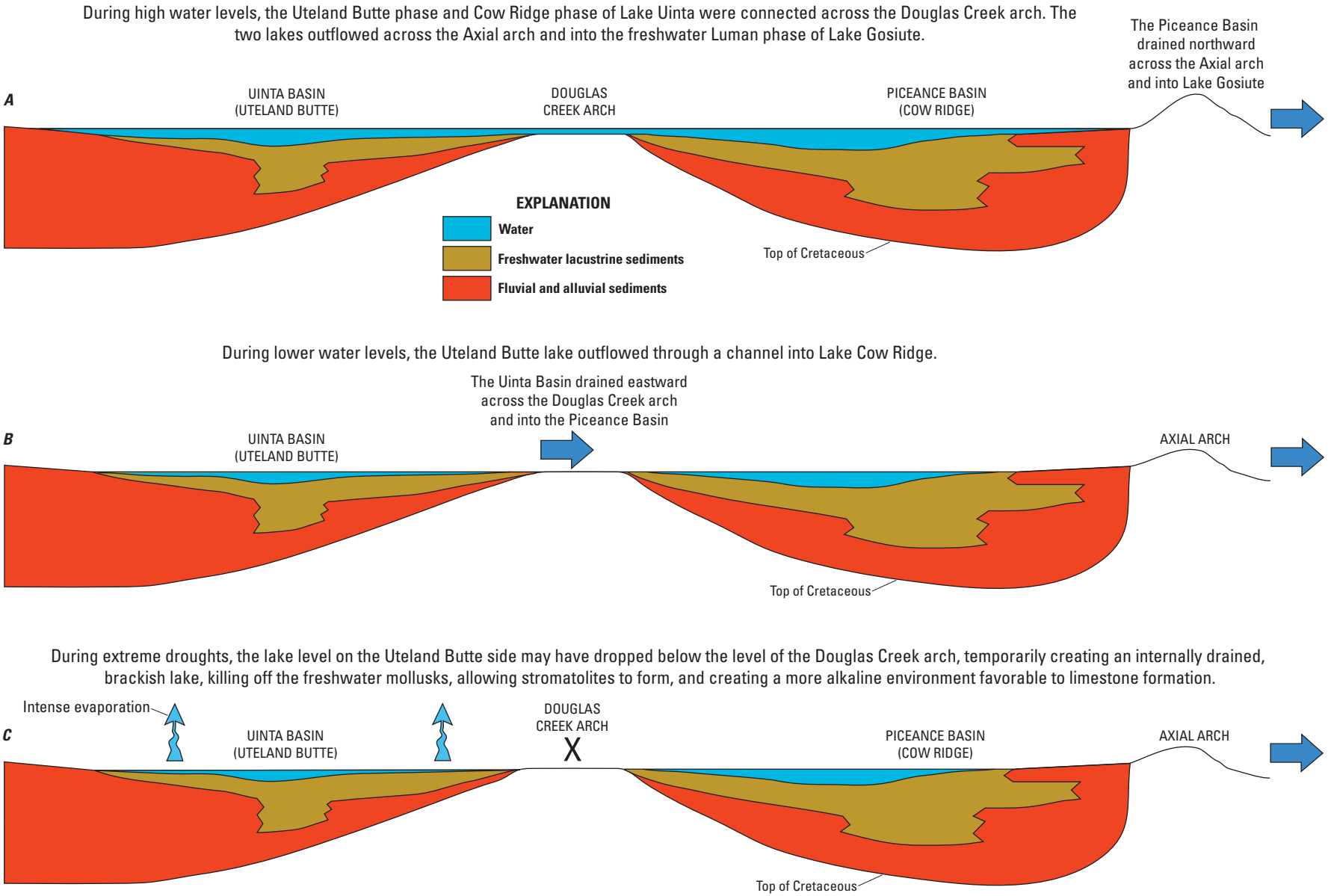


Figure 31. Proposed model to explain the periodic shift to more brackish and alkaline conditions during the overall freshwater phase of Lake Uinta in the Uinta Basin (informal Uteland Butte member of Green River Formation). The model suggests that the lake dropped from a high stand *A*, to below the crest of the Douglas Creek arch from time to time *B*, producing an internally drained brackish-alkaline lake that killed off the freshwater mollusks and favored carbonate precipitation *C*, Evidence for brackish conditions in the freshwater lake phase in the Piceance Basin (Cow Ridge Member of the Green River Formation) are lacking, and the Cow Ridge Member contains far less carbonate than the Uteland Butte.

Roehler, 1992). Mollusks are freshwater types, consisting mainly of the gastropods *Elimia tenera* (formerly known as *Goniobasis tenera*) and *Viviparus* sp. and the *pelecypod Lampsilis* sp. believed that Lake Gosiute during the Luman stage drained southward near the east end of the Uinta Mountains and into the Piceance Basin.

Organic Richness of the Uteland Butte and Cow Ridge Members Using Fischer Assay

From the late 1940s to the early 1980s, the former U.S. Bureau of Mines (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. The Fischer assay method is a standardized laboratory test for determining the oil yield from oil shale and has been almost universally used to determine oil yields for Green River Formation oil shales (Stanfield and Frost, 1949; American Society for Testing Materials, 1984). It is a much simpler, less rigorous analytical procedure than programmed pyrolysis methods, like Rock-Eval (Espitalie and others, 1986). The Fischer assay method consists of heating a crushed and screened (–8 mesh, or less than 2.38-millimeter [mm]) 100-gram (g) sample in a small aluminum retort to 500 degrees Celsius (°C) at a rate of 12 °C per minute and then held at that temperature for 40 minutes (fig. 32). The volatile vapors of pyrolysate oil, gas, and water pass through a condenser cooled with ice water (about 5 °C) and are collected in a graduated centrifuge tube. The oil and water are then separated by centrifugation and weighed. The quantities reported in the original sample are the weight percentages of oil, water, shale residue (containing carbon char), and "gas plus loss" (non-condensable gas yield). The specific gravity of the oil is measured and used to calculate the oil yield in gallons per ton. The Fischer assay method does not distinguish between hydrocarbons originally present in the sample (S1 peak of Rock-Eval analysis) and hydrocarbons generated from kerogen during pyrolysis (S2 peak) (Tissot and Welte, 1984). The method measures the amount of gases released during retorting, but in general the gases are not collected for compositional analysis. These gases—chiefly light hydrocarbons, hydrogen, and carbon dioxide (Miknis, 1992)—are reported as the "gas plus loss." Percent total organic carbon (TOC) measured by combustion after carbonate removal or programmed pyrolysis is equal to about one-half the value of oil generated in gallons per ton measured by Fischer assay. Thus a Fischer assay oil yield of 4 gallons per ton (GPT) would be roughly equivalent to 2 weight percent total organic carbon using other methods.

During the 1970s and 1980s, the USBM and the U.S. Geological Survey (USGS) each prepared digital databases of Fischer assay yields from Green River oil shale deposits, and these data were made available to the public through the National Technical Information Service (NTIS) (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).

The Fischer assay databases were used in the recent assessment of oil shale resources in the Uinta Basin by Johnson and others (2010b) for all oil shale zones from R-0 zone and above in the Uinta and Piceance Basins, and for the Tipton, Wilkins Peak, and Laney Members of the Green River Formation in the Greater Green River Basin. Although Fischer assay data were available for the freshwater lacustrine intervals in all three basins, they were not included in the recent assessments. The low oil yields and great depth of these intervals made it unlikely that they would ever be developed as an oil shale resource.

Twenty-four of these drill holes included Fischer assay analysis for the Uteland Butte interval in the Uinta Basin and 13 included Fischer assay analysis the "B-marker" interval

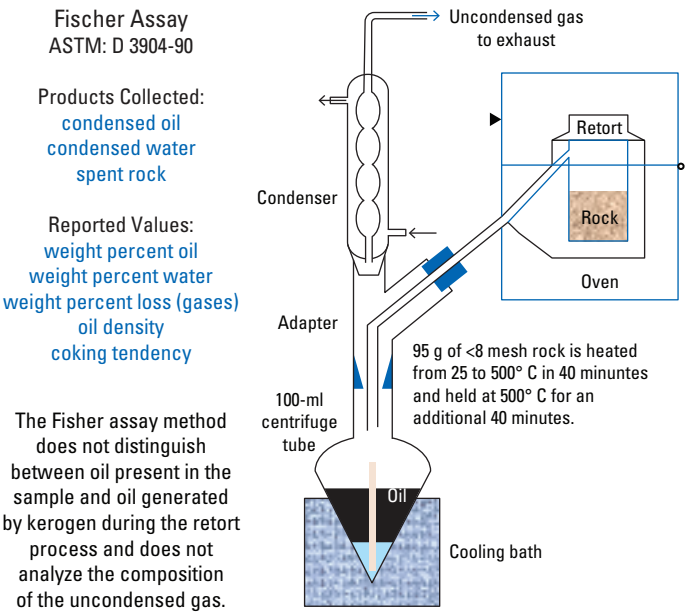


Figure 32. Schematic diagram of a Fischer assay retort, the standard method to measure oil content in oil shale. The Fisher assay method does not distinguish between oil present in the sample and oil generated by kerogen during the retort process and does not analyze the composition of the uncondensed gas.

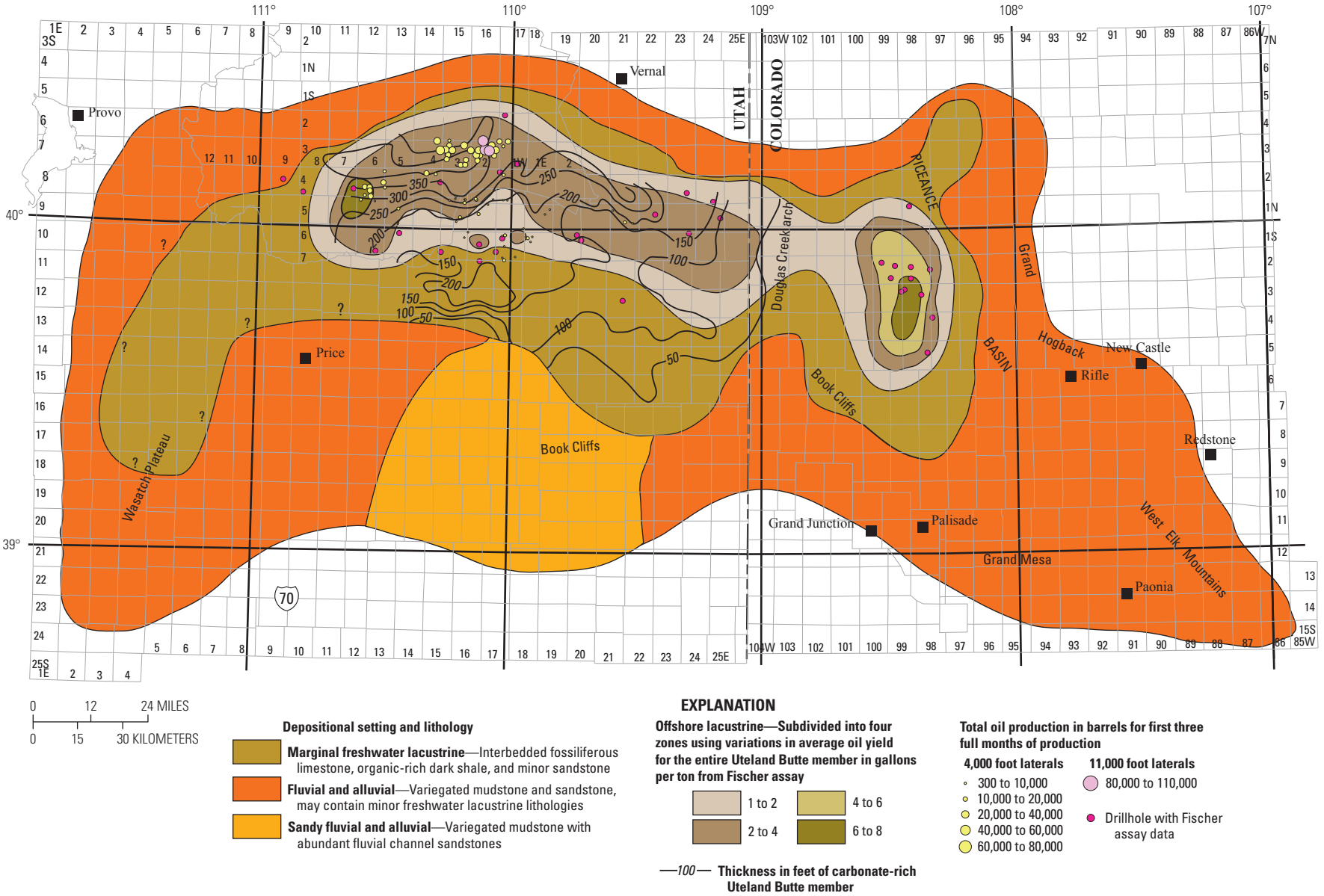


Figure 33. Map of the Uinta and Piceance Basins showing average oil yield in gallons per ton using Fischer assay for the entire informal Uteland Butte member of the Green River Formation in the Uinta Basin and for the B-marker interval in the Cow Ridge Member of the Green River Formation in the Piceance Basin. The assessed interval in the Uteland Butte varies from 80 feet in the eastern part of the Uinta Basin to as much as 550 feet along the basin trough. Maximum yield was 4.1 gallons per ton for a small area in the western part of the basin. The B-marker varies from 38 to 60 feet with average oil yields varying from 1 to 8.9 gallons per ton. Lithofacies of the informal Uteland Butte member in the Uinta Basin and the Cow Ridge Member in the Piceance Basin during their maximum extent and thickness of the carbonate-rich part of the Uteland Butte member are also shown.

of the Cow Ridge in the Piceance Basin (table 1). The results are contoured on figure 33. Fischer assay analyses for the Luman Tongue in the Greater Green River Basin are also presented in the Uinta Basin Fischer assay database (Dyni and others, 2006). Because of time constraints and complexity of the Luman Tongue, this information was not examined in detail for this study. Thickness of the assessed interval that contained significant oil yield and average oil yields in gallons per ton for those intervals are included in table 1. Because the sampling interval for cuttings is typically 10 ft or greater, thin rich zones would not be detected. The intervals listed do not always correspond exactly to the top and base of the Uteland Butte member as indicated by geophysical logs. Also, geologists are not always able to accurately compensate for the time it takes cuttings to reach the surface. In such cases, the interval with the highest Fischer assay values was assumed to be the Uteland Butte. In addition, errors in oil yield estimates using Fischer assay in low oil yield samples are significant (Stanfield and Frost, 1949). Thus, the average oil yields shown on figure 33 should be considered very approximate. Oil yields for the Uteland Butte member are within the 1–4 GPT range throughout the central part of the area where the Uteland Butte is present. Maximum oil yield for the Uteland Butte member is 3.6 GPT for a 280-ft-thick interval. Oil yields for the B-marker are much higher than for the Uteland Butte (to almost 8 GPT). The approximate limits of the offshore organic-rich facies of the Uteland Butte member and Cow Ridge Member are defined here using the greater than 1 GPT line. The remaining area is considered marginal lacustrine. Total production for horizontal Uteland Butte wells during the first full 3 months is also plotted on figure 33. Eighty-four of the 86 of the horizontal tests of the Uteland Butte are within the area of greater than 1 GPT oil yield by Fischer assay, defined here as the offshore organic-rich facies. Two of the horizontal tests completed in the marginal lacustrine facies just south of the 1 GPT line are reported to be producing from sandstones and not source rocks, suggesting that using the greater than 1 GPT line to define the limits of the offshore facies may have some merit.

Overpressure in the Uteland Butte Member

Continuous or basin-centered hydrocarbon accumulations in Rocky Mountain basins, such as the one in the Uteland Butte member, are nearly always abnormally overpressured or underpressured (Law and Spencer, 1998). Overpressure has been cited as one of the factors contributing to high production rates in the Uteland Butte horizontal play (Anderson and Roesink, 2013; Vanden Berg and others, 2014). Overpressure commonly occurs in lithologic units isolated by impermeable barriers in subsiding basins as the lithologic column is compacted, preventing fluids from migrating out; however, in Rocky Mountain basins, overpressure is generally attributed to hydrocarbon generation, because there are significant volume increases when oil and gas are generated from kerogen (Gies, 1984; Spencer, 1987; Law and Spencer, 1998). Pressure gradients in formations are measured in pounds per square inch per foot with normal formation pressure equal to the weight of freshwater, which is 0.433 pounds per square inch per foot (psi/ft). Normal pressure generally indicates that a formation is in communication with the regional groundwater system. Overpressure can also occur in regional groundwater systems if recharge areas are significantly above the basin floor creating an artesian system. Spencer (1987) considers reservoirs in Rocky Mountain basins to be significantly overpressured if the pressure gradient exceeds 0.50 psi/ft, and that value is used to define significant overpressure here.

Drill-stem tests measure the downhole pressure within the wellbore rather than directly measuring pressure within the formation itself, but the drill-stem test is considered one of the more reliable methods of estimating formation pressure (Holm, 1998). Drill-stem tests from 42 intervals in or near the Uteland Butte were deemed sufficiently reliable to use (fig. 34). A drill-stem test was considered reliable if the initial shut-in pressure was similar to the final shut-in pressure, suggesting that the test was run for a sufficiently long period of time for the pressure in the wellbore to equilibrate with formation pressures. Six wells indicated pressure gradients of 0.50 psi/ft or greater, defined here as significant overpressure, and these are shown as pink on figures 34 and 35.

Variations in mudweights used while drilling can also be used to define overpressure, although mudweights are not as reliable or as precise for defining overpressure as drill-stem tests. Drillers can overcompensate and use mudweights that are higher than formation pressures required or undercompensate while drilling through very tight intervals where excessive pressures are difficult to detect. A mudweight of about 0.43 psi/ft is typically used to drill through normally pressured formations, whereas a mudweight of over 0.50 psi/ft is commonly used to define significant overpressure. Mudweights used in five drillholes are used here to help define overpressure in areas where drill-stem tests were unavailable (fig. 34). Four indicated significant overpressure and one indicated normal pressure.

The area encompassing all drill-stem tests and mudweights that indicate significant overpressure is shown in pink on figure 34. Not all drill-stem tests within the pink area indicate significant overpressure, but most of them do. Tests that do not indicate overpressure in the pink area may be the result of a poorly run drill-stem test in an overpressured area or may indicate that some normally pressured zones exist in an overall overpressured area. The area of overpressure shown is similar to that defined by Anderson and Roesink (2013) using only mudweights (fig. 34).

Some tests in the Uteland Butte member marginal to the overpressured area indicate possible underpressure (fig. 34). Underpressure is more difficult to identify than overpressure because drill-stem tests that failed to reach true formation pressure cannot be easily distinguished from ones that measured true underpressure. Nelson (2002) identified a probable zone of underpressure in the shallower portions of Altamont-Bluebell

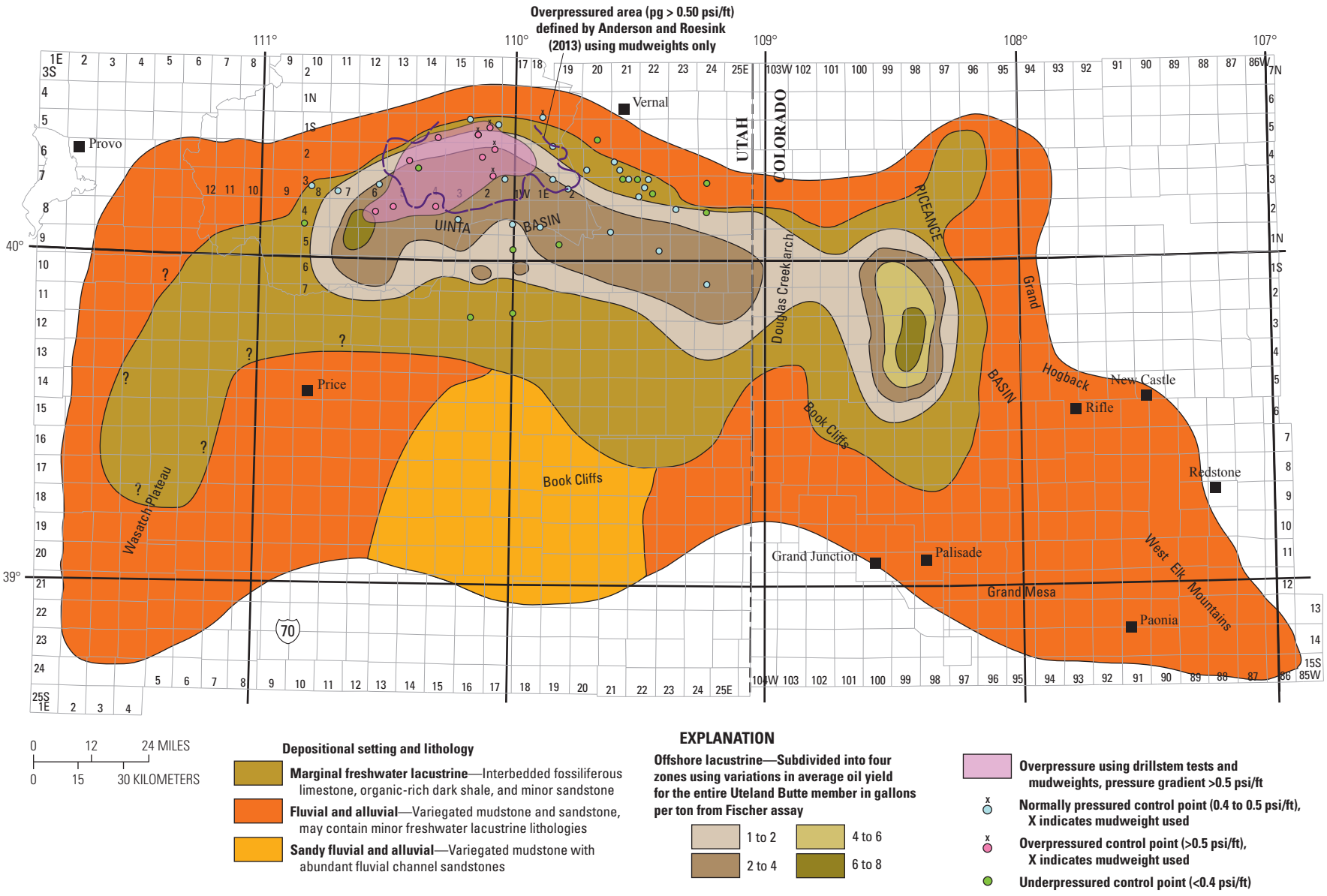


Figure 34. Map of the Uinta and Piceance Basins showing area of overpressure in the informal Uteland Butte member of the Green River Formation, defined here as a pressure gradient of greater than 0.5 pounds per square inch per foot. Pressure data from Utah Geological Survey Web site (http://oilgas.ogm.utah.gov/). Overpressure was defined using drill-stem tests and some mudweights. Drill-stem tests are from Utah Geological Survey Web site ,and mudweights are from geophysical log headers. Wells that indicate overpressure are shown in pink, whereas normally pressured or underpressured wells shown in blue. The area where overpressure occurs is shown in pink. Lithofacies of the Uteland Butte member in the Uinta Basin and the Cow Ridge Member of the Green River Formation in the Piceance Basin during their maximum extent are shown.

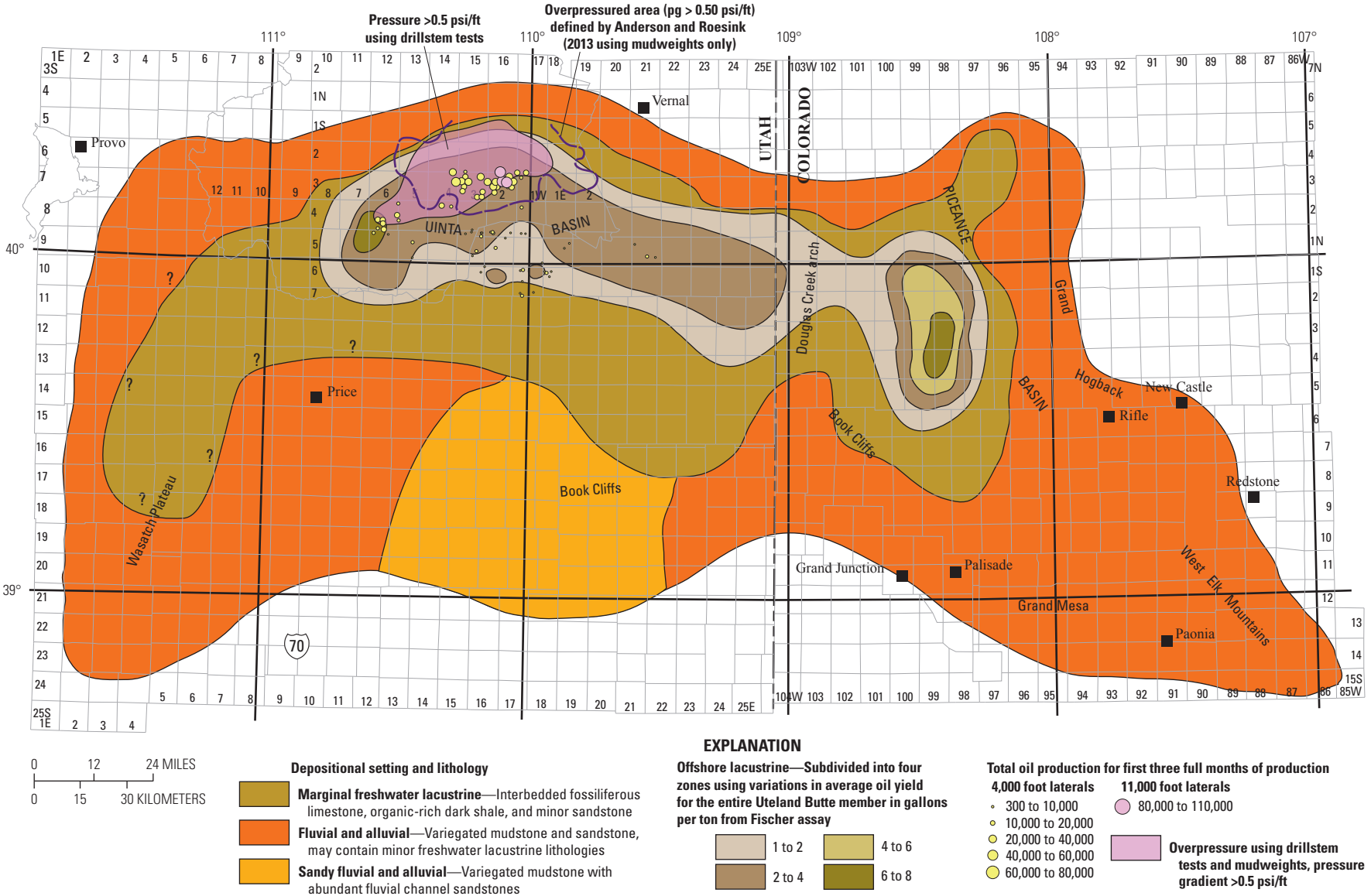


Figure 35. Map of the Uinta and Piceance Basins showing areas of overpressure in the informal Uteland Butte member of the Green River Formation, defined here as a pressure gradient of greater than 0.5 pounds per square inch per foot, and total oil production for the first full 3 months of production for all horizontal producers identified as completed in the Uteland Butte member. Lithofacies of the Uteland Butte member in the Uinta Basin and the Cow Ridge Member of the Green River Formation in the Piceance Basin during their maximum extent are also shown.

oil field near the trough of the Uinta Basin (fig. 12). This potential underpressured area was not studied in detail here. Figure 35 plots the total production for the first full 3 months of production for the horizontal wells on the area of overpressure defined here. The area of overpressure includes the majority of the most productive wells as Anderson and Roesink (2013) and Vanden Berg and others (2014) had indicated.

Variations in Thermal Maturity of the Freshwater Lacustrine Interval Using Vitrinite Reflectance and Rock-Eval

Variations in thermal maturity of the freshwater lacustrine interval in the Uinta, Piceance, and Greater Green River Basins have not been systematically studied in the past, largely because these members were only recently primary targets for oil and gas drilling. Here we have assembled the limited published thermal maturity information for these units in order to evaluate the potential for tight oil development. Two different methods for measuring variations in thermal maturity are commonly used: (1) Rock-Eval pyrolysis (for a summary, see Tissot and Welte, 1984) and (2) vitrinite reflectance. There are far more data points for vitrinite reflectance than for Rock-Eval, so vitrinite reflectance will be the primary method used here to study variations in thermal maturity.

In Rock-Eval programmed pyrolysis, the sample is heated at 300 °C for 3–5 minutes, at which point bitumen less than C33 and other volatile compounds that were originally present in the sample are released and measured (S1 peak, Tissot and Welte, 1984). The sample is then heated at a rate of 25 °C per minute to between 550–600 °C (depending on the instrument), distilling heavy bitumen and releasing hydrocarbons generated by the cracking of kerogen (S2 peak, Tissot and Welte, 1984). The ratio of S1/(S1+ S2) is called the transformation ratio or production index. For any given kerogen type, the transformation ratio generally increases with increasing thermal maturity. Anders and Gerrild (1984) determined that for Type I kerogen in the Uinta Basin, a transformation ratio of greater than about 0.1 indicated that the sample was mature with respect to oil generation. Tmax represents the temperature at which the S2 peak reaches a maximum (corresponds to maximum hydrocarbon generation from kerogen), and it has been used as a thermal maturity indicator (Tissot and Welte, 1984); however, Tmax for Type I kerogen, such as that present in the Green River Formation, appears to be relatively insensitive to increasing thermal maturity (Espitalie and others, 1986; Anders and others, 1992). The hydrogen to carbon ratio (H/C ratio) is an important parameter in determining both the hydrocarbon generating potential of kerogen and thermal maturity (Waples, 1981; Hunt, 1996; Baskin, 1997). For Type I kerogen present in the Green River Formation in the Uinta Basin, Anders and others (1992, their fig. 6) determined that there was a close relationship between H/C ratio and thermal maturity as measured by vitrinite reflectance.

Vitrinite reflectance (percent R_0) is a measurement of the percentage of light reflected by the vitrinite maceral at 500× magnification in oil immersion and is commonly used as a measure of thermal maturity in organic-rich rocks. The vitrinite maceral is formed from woody plant tissue, whereas most kerogen present in the Green River Formation in the Uinta Basin is derived from algal material. Thus, studying variations in vitrinite reflectance is an indirect measurement of thermal maturity of the largely Type I kerogen in the Green River Formation of the Uinta Basin. For Type I kerogens, the onset of oil generation is thought to correspond to a vitrinite reflectance of between 0.6 and 0.7 percent, with oil generation complete at R_0 values between of 1.2 and 1.3 percent (Baskin and Peters, 1992; Ruble and others, 2001). Vitrinite measurements on samples rich in Type I kerogen can be difficult to obtain, because the terrestrially sourced vitrinite maceral will be mixed with and diluted by the more prominent algal organic matter; therefore, variations in vitrinite reflectance only indirectly indicate thermal maturity of the largely amorphous Type I kerogen in Green River Formation rocks.

The detailed south-to-north cross section across from the south flank of the Uinta Basin to the deep basin trough published by Johnson (2014) included two vitrinite reflectance levels: (1) R_0 0.5 percent and (2) R_0 0.75 percent. The positions of these two vitrinite reflectance levels are included on the simplified version of the cross section shown in figure 8. The isolines representing the two vitrinite reflectance levels dip to the north, which was previously documented by Nuccio and others (1992) who suggested that this relationship could, in part, be explained by uplift of the margins of the basin, bringing rocks with higher maturities to shallower levels while the trough of the basin was still subsiding and receiving sediments. The decrease in thermal gradients toward the axis of the Uinta Basin, noted by Chapman and others (1984) and Anders and others (1992), also probably played a role. These low thermal gradients near the basin axis are thought to be the result of cold meteoric water penetrating faults along the basin's north margin and (or) due to heat being carried away by the thick, highly conductive quartzites of the Precambrian Uinta Mountain Group that was brought in contact with basin sediments by this faulting (Chapman and others, 1984; Anders and others, 1992).

Flagstaff Member

Anders and others (1992), in their study of variations in thermal maturities in the Uinta Basin, published the results from three vitrinite reflectance samples in the Flagstaff Member, and those results are plotted on figure 11. These limited samples are not by themselves sufficient to contour variations in thermal maturities at the Flagstaff level; however, Nuccio and others (1992) published a map contouring variations in levels of vitrinite reflectance at the top of the Upper Cretaceous Mesaverde Group, beneath the Flagstaff Member, and those contours are also shown on figure 11. Using these three values, and following the trends of the contours on the top of

the Mesaverde Group, rough contours showing variations in vitrinite reflectance at the Flagstaff level were generated and are shown on figure 11.

Uteland Butte and Cow Ridge Members

Variations in thermal maturity of the Uteland Butte/Cow Ridge interval using vitrinite reflectance have not been the focus of any previous studies. Nuccio and Roberts (2003) published a map showing variations in thermal maturity at a horizon in the lower part of the Green River, which is reproduced here (fig. 36*A)*. Timing of the onset of hydrocarbon generation is shown in figure 36*B*. An examination of the wells used by Nuccio and Roberts (2003) suggests that they may not have used a consistent horizon in the Uinta Basin, and thus the map is of limited use. Only two data points in the Piceance Basin appear to be from the Cow Ridge Member. These had vitrinite reflectance values of 0.24 and 0.45 percent, suggesting that the Cow Ridge is immature for oil generation. Organic-rich freshwater lacustrine rocks of the Cow Ridge Member extend as much as 2,500 ft below the Garden Gulch Member, and it is possible that maturities in the lower part of the Cow Ridge Member are sufficient to have generated liquid hydrocarbons. As of 2015, there is no commercial oil produced from the Green River Formation in the Piceance Basin. A minor amount of waxy oil is produced from the lower part of the Green River Formation along with gas sourced predominantly from the underlying Mesaverde Group (Johnson and Rice, 1990; Dubiel, 2003). The oil is considered a nuisance because it plugs up gas wells requiring them to be maintained on a regular basis (R.E. Chancellor, oral commun., 1977). The source of the oil is unknown. Dubiel (2003) suggested the oil came from marginally mature source rocks in the Cow Ridge Member, but it could also have migrated from deeper, more mature source rocks along with the gas. In addition, immature bitumen commonly fills fractures and forms blebs in the Garden Gulch Member of the Green River Formation based on unpublished core descriptions from the former USBM.

Eleven vitrinite reflectance readings published by Anders and others (1992) are from stratigraphically within or near the Uteland Butte member and had R_0 values ranging from 0.55 to 1.1 percent (fig. 37). The previously defined overpressured area is plotted with information from the vitrinite reflectance measurements in figure 37. Three isoreflectance values were contoured: (1) R_0 of 0.55 percent, (2) R_0 of 0.75 percent or approximately the onset of oil generation for Type I organic matter, and (3) R_0 of 1.1 percent or greater (fig. 37). The area of highest thermal maturity generally corresponds to the overpressured area. Anders and others (1992) listed Rock-Eval results for two samples in the Uteland Butte member in the Sun Oil No. 1 Daniel Uresk well in sec. 6, T. 4 S., R. 1 W. (fig. 37). One sample had a vitrinite reflectance value of 0.67 percent and a production index of 0.43, whereas the other sample had a vitrinite reflectance of 0.71 and a production index of 0.12. According to Anders and Gerrild (1984), both samples are mature enough to have generated oil.

Freshwater Lacustrine Interval in the Greater Green River Basin

Burial history plots generated by Roberts and others (2005) for four wells in the Green River Basin are shown on figures 38–40. Of all the basins that constitute the Greater Green River Basin, maturities based on vitrinite reflectance are highest at the Adobe Town location in the Washakie Basin (figs. 38, 39*A*). In the Washakie Basin, the deepest Eocene interval that may contain a continuous oil accumulation is the Ramsey Ranch Member of the Wasatch Formation, a sequence of carbonaceous shale, coal, freshwater limestone, and oil shale deposited in small freshwater lakes and ponds. Maximum thermal maturity for the Ramsey Ranch Member in the Adobe Town well near the deepest part of the Washakie Basin has a vitrinite value somewhat higher than a R_0 of 0.8 percent, or within the oil window. The other three burial reconstructions (from Green River and Great Divide Basins) indicate thermal maturities in the Green River Formation of less than 0.5 percent R_0, which indicates it is immature for oil generation. At present, there are no wells in the Washakie Basin that produce hydrocarbons from the Green River Formation. In 2012, Shell Oil drilled the No. 4-36BH well in sec. 36, T. 14 N., R. 98 W. as a horizontal test of Eocene lacustrine rocks in the deepest part of the Washakie Basin, about 3 miles southwest of the Adobe Town well (fig. 38). The well appears to have bottomed in the Ramsey Ranch Member of the Wasatch Formation in what was described as “a mixed lithology interval with rich, laminated, continuous oil shale unit and a unit of fine grained, moderately sorted, discontinuous arkosic arenite with carbonaceous laminae.” (Mountain Oil Journal, Inc., 2012). The well is now listed as dry and abandoned.

Early Eocene Freshwater Lacustrine Minimum

After maximum transgression of the freshwater lakes in all three basins, the lakes retreated once again to occupy areas roughly comparable to the lakes prior to the transgression (fig. 41). The lake in the Piceance Basin remained freshwater during this contraction indicated by the freshwater mollusk assemblage present in this interval where it is exposed along the east flank of the Douglas Creek arch (Johnson and others, 1988; see for example, the Tommys Draw section, fig. 29). The interval is still considered part of the Cow Ridge Member. The interval is present at the White River measured section in the northeast part of the Uinta Basin where it consists of gray mudstone with one 1.5-ft-thick ostracodal limestone with abundant pelcypods (fig. 15). The Niland Tongue of the Wasatch Formation represents this interval in the Greater Green River Basin (fig. 41). Roehler (1993, p. F40) described the Niland Tongue as deposited in “freshwater lacustrine, swamp, pond, and flood-plain” environments.

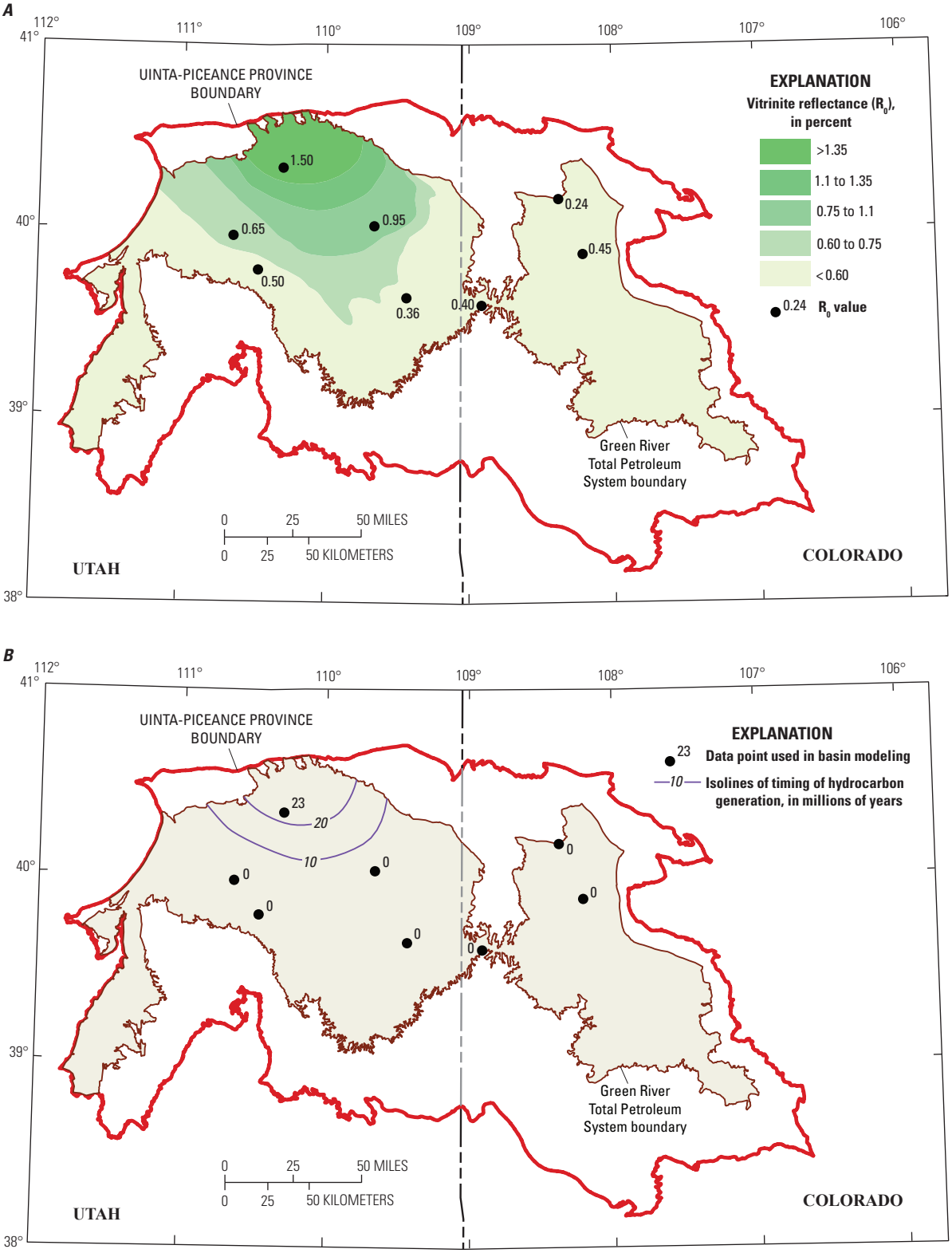


Figure 36. Map of the Uinta and Piceance Basins showing variations in thermal maturity using vitrinite reflectance and when significant oil and gas generation began for source rocks at a horizon in the lower part of the Green River Formation (modified from Nuccio and Roberts, 2003). Thermal maturities are too low in the Piceance Basin for hydrocarbons to have been generated in the Green River Formation.

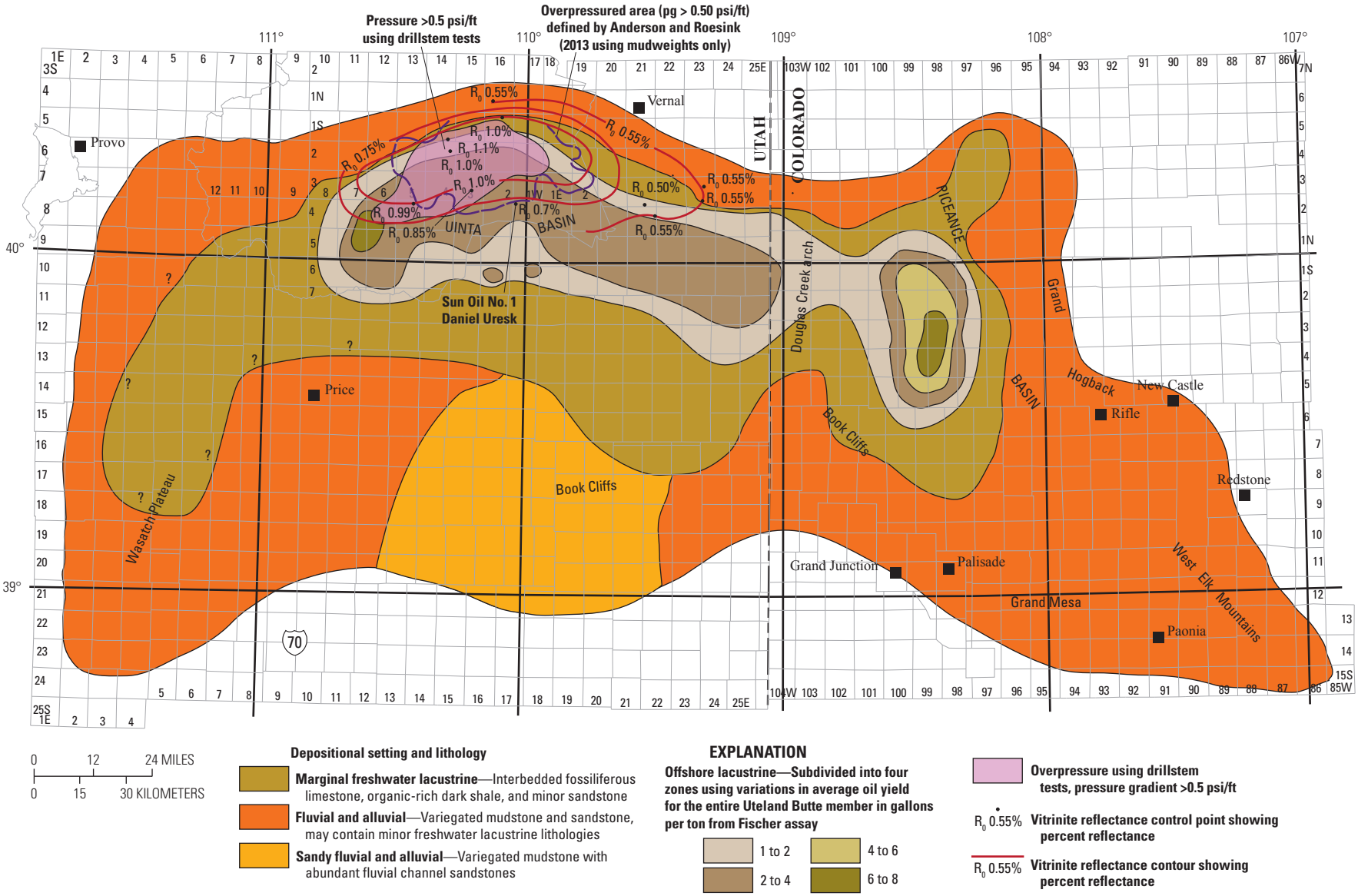


Figure 37. Map of the Uinta and Piceance Basins showing variations in percent vitrinite reflectance for the informal Uteland Butte member of the Green River Formation and intervals near the Uteland Butte (from Anders and others, 1992). Lithofacies of the informal Uteland Butte member in the Uinta Basin and the Cow Ridge Member of the Green River Formation in the Piceance Basin during their maximum extent are also shown.

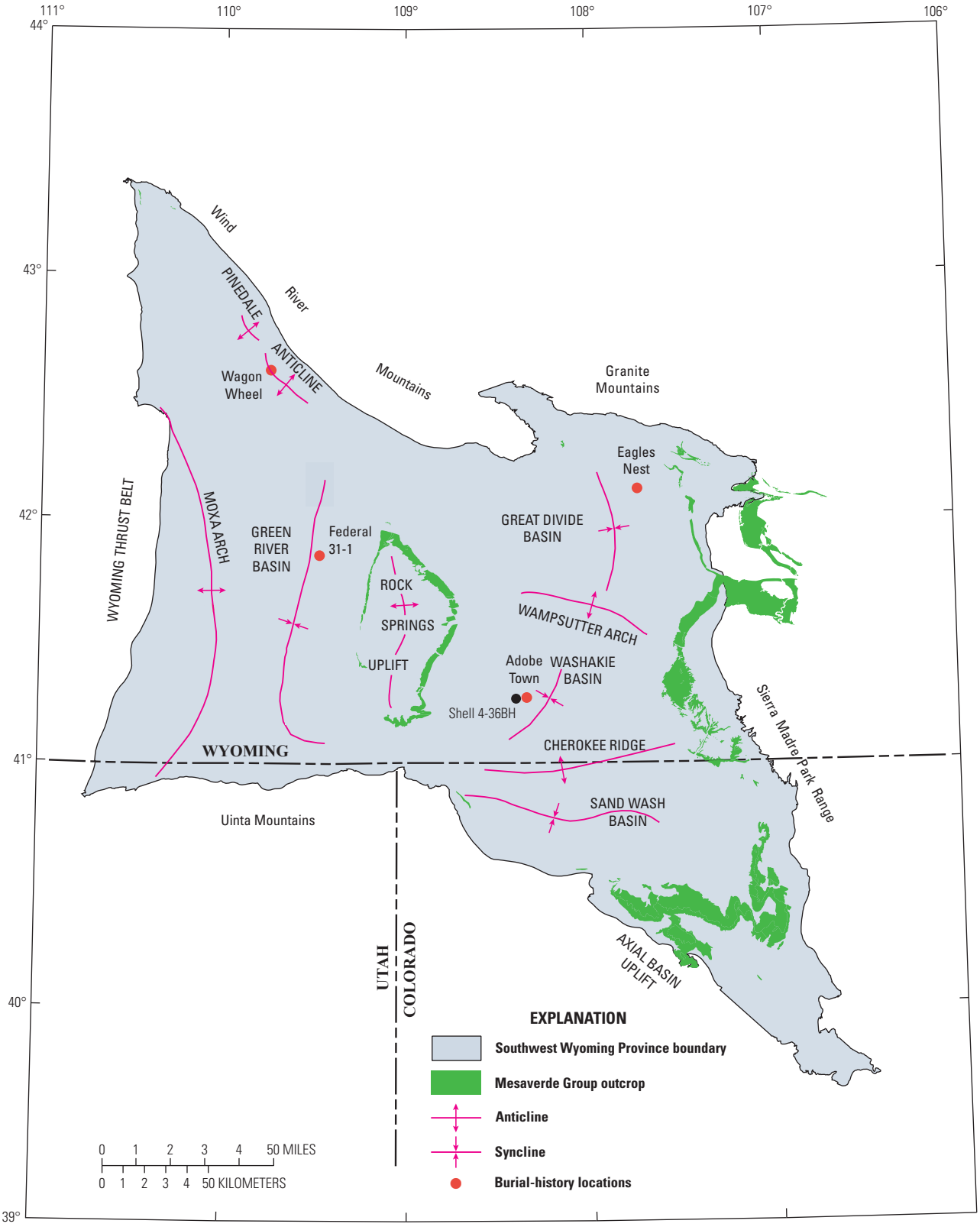


Figure 38. Index map of the Greater Green River Basin showing major geologic and geographic features and burial history locations shown in figures 40 and 41 (from Roberts and others, 2005).

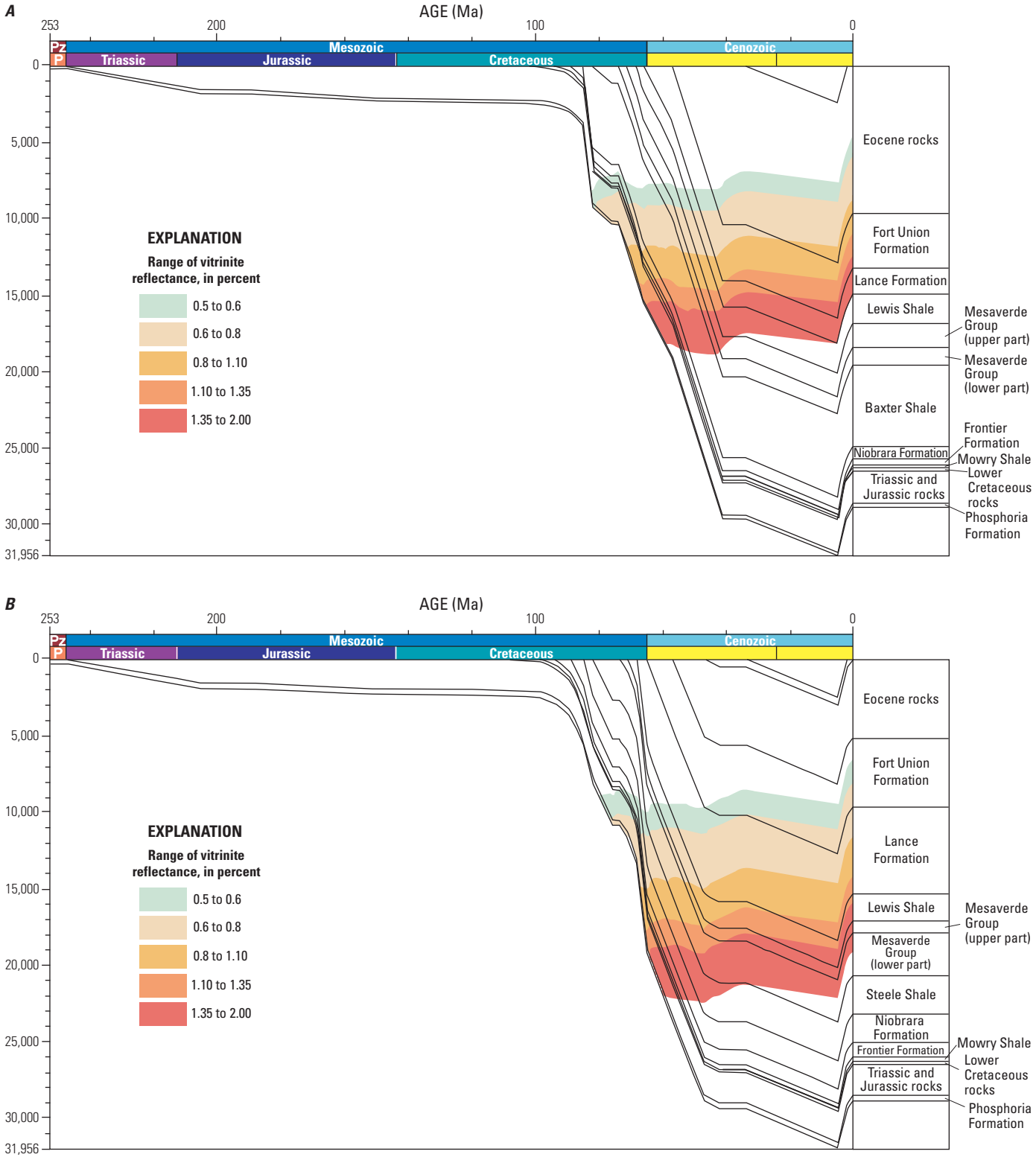


Figure 39. Burial-history curves for *A*, the Adobe Town location, sec. 20, T. 15 N., R. 97 W. Washakie Basin and *B*, the Eagles Nest location, sec. 29, T. 25 N., R. 91 W., Great Divide location (from Roberts and others, 2005). Maximum thermal maturity at the base of Eocene strata at the Adobe Town location is slightly above 0.8 percent vitrinite reflectance or in the early stages of oil generation. Maximum thermal maturity at the base of Eocene strata at the Eagles Nest location is less than a vitrinite reflectance of 0.5 percent or well below the onset of oil generation.

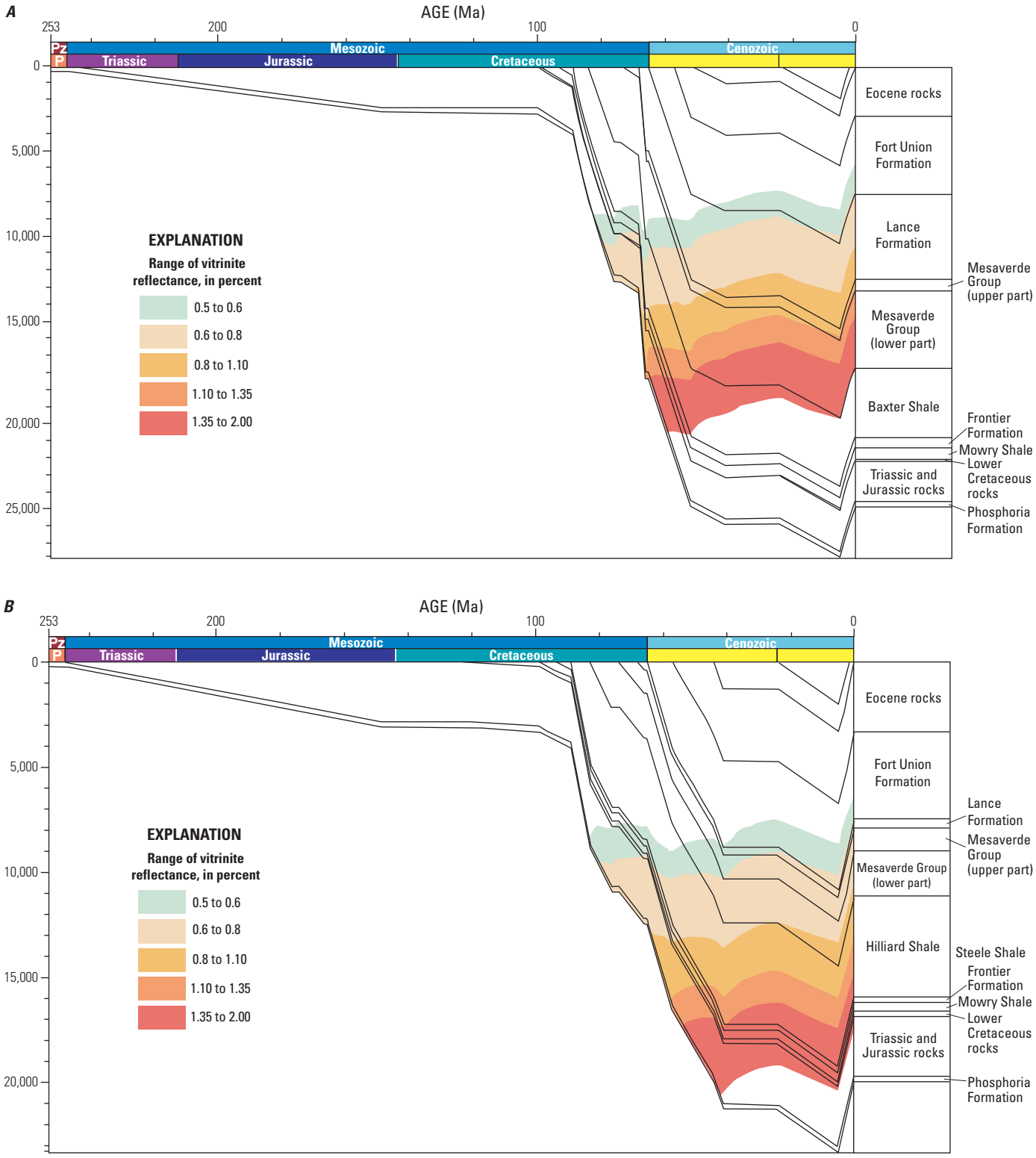


Figure 40. Burial reconstructions for *A*, the Wagon Wheel well in sec. 5, T. 30 N., R. 108 W. and *B*, the Federal 31-1 in sec. 31, T. 22 N., R. 106 W. Green River Basin (from Roberts and others, 2005). Maximum thermal maturity at the base of Eocene strata of well are below a vitrinite reflectance of 0.5 percent, or well below the onset of oil generation.

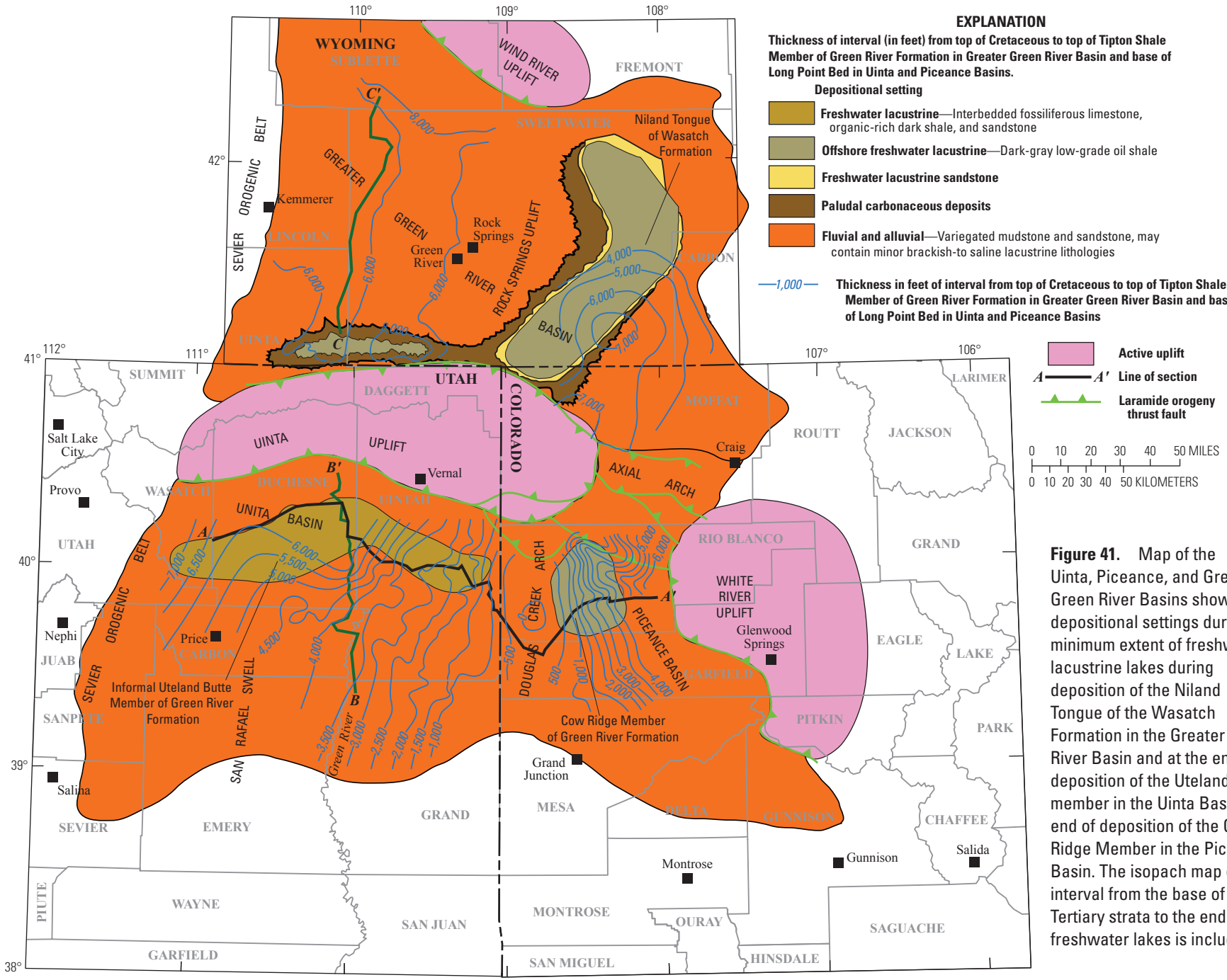


Figure 41. Map of the Uinta, Piceance, and Greater Green River Basins showing depositional settings during minimum extent of freshwater lacustrine lakes during deposition of the Niland Tongue of the Wasatch Formation in the Greater Green River Basin and at the end of deposition of the Uteland Butte member in the Uinta Basin and end of deposition of the Cow Ridge Member in the Piceance Basin. The isopach map of the interval from the base of lower Tertiary strata to the end of freshwater lakes is included.

Early Eocene Brackish-to-Saline Lacustrine Maximum

The prolonged freshwater phases of Lake Uinta and Lake Gosiute ended when both lakes transitioned first into brackish water and ultimately into hypersaline lakes because external drainages were lost. For Lake Uinta, the transition from fresh-to-brackish was preceded by a major expansion of the lake during the Long Point transgression (Johnson, 1985). For Lake Gosiute, the transition occurred during deposition of the transgressive Tipton Member of the Green River Formation (Roehler, 1991). Figure 42 shows extents of Lake Uinta and Lake Gosiute after maximum transgression represented by the lacustrine marginal sandstones (shown in yellow). As with the Uteland Butte and Cow Ridge Members, the extent of the offshore organic-rich lacustrine facies is defined here as that area that yielded more than 1 GPT with Fischer assay analysis.

The Long Point Bed, and overlying R-0 zone can be traced in nearly continuous outcrops across the south part of the Douglas Creek arch (Johnson, 2012), demonstrating unequivocally that Lake Uinta formed a single lake between the Uinta and Piceance Basin at this time. The R-0 zone varies from about 100 to 200 ft thick across most of the Uinta and Piceance Basins, thickening to more than 500 ft along the east margin of the Piceance Basin (fig. 43) where it grades into mainly sandstone of the Anvil Points Member (see, for example, Johnson, 1989, sheet 2). The Long Point Bed, a distinctive oolitic, ostracodal, and gastropod-rich bed, is generally the highest bed stratigraphically in both basins that contains large numbers of freshwater mollusks (Johnson, 1984). Stromatolites appear in the strata immediately above the Long Point Bed in some of the sections published by Johnson and others (1988), indicating that the lake became increasingly saline once maximum transgression was reached, killing off the freshwater-grazing mollusk population, which allowed stromatolites to grow. Johnson (1985) suggested that the transgression occurred rapidly because the Long Point Bed did not appear to climb stratigraphically toward the margins of the Uinta and Piceance Basins. Recently published cross sections in the Piceance Basin by Self and others (2010) and Johnson (2014) also failed to detect any noticeable stratigraphic climb of the Long Point Bed toward the margins of the Piceance Basin. It is thus possible that external drainage was lost quite rapidly, possibly by a catastrophic event.

The name Garden Gulch Member is generally applied to the clay-rich (mainly illite) oil shale interval in the eastern part of the Uinta Basin and throughout the Piceance Basin that was deposited in offshore areas after the Long Point transgression Uinta (Bradley, 1931). The R-0 zone constitutes the lowermost part of this illitic oil shale interval and is one of the most widespread oil shale zones in the Uinta and Piceance Basins. It is stratigraphically the highest interval discussed here, because it is probably the youngest interval that may have potential as a tight oil play. The R-0 zone extends from the Long Point Bed and its equivalent at the base to the top of the carbonate marker in the Uinta Basin (Ryder and others, 1976; Johnson, 1985) and the orange marker in the Piceance Basin (Johnson, 1985). It was the oldest oil shale zone assessed in the recently published oil shale assessments of the Uinta and Piceance Basins (Johnson and others, 2010a; 2010b). The carbonate marker and orange marker are equivalent shale units and are slightly more calcareous than shale intervals above and below. The markers form distinctive resistant units on electric logs.

The entire spectrum of offshore to nearshore environments in the R-0 zone is exposed along the west margin of the Piceance Basin and the east margin of the Uinta Basin, adjacent to the crest of the Douglas Creek arch (Johnson and others, 1988). Along the west margin of the Piceance Basin, at Tommys Draw (fig. 29) and Little Burma Road (fig. 30), the R-0 zone consists of low-grade oil shale with a few thin carbonate beds. Farther to the south along the west margin of the basin, oolitic, ostracodal, and stromatolitic limestone; sandstone; and siltstone become increasingly abundant (Johnson and others, 1988). Similarly, along the east margin of the Uinta Basin, the R-0 zone consists mainly of clay-rich, low-grade oil shale with minor sandstone and ostracodal, oolitic, and stromatolitic limestone.

A transgression, similar to the Long Point transgression in the Uinta and Piceance Basins, is represented by the base of the Scheggs Bed of the Tipton Shale Member in the Greater Green River Basin, when Lake Gosiute expanded to cover much of the Greater Green River Basin (fig. 42). Roehler (1993), however, suggests that Lake Gosiute remained freshwater throughout deposition of the Scheggs Bed, only becoming brackish at the beginning of deposition of the overlying Rife Bed of the Tipton Shale Member. If Roehler (1993) is correct, then the transition from fresh-to-brackish water in Lake Gosiute occurred significantly after maximum transgression was achieved. As with the maximum and minimum lake periods discussed earlier, it is uncertain if the maximum transgression in the Uinta and Piceance Basins, represented by the R-0 zone, is time-equivalent to maximum transgression represented by the Scheggs Bed in the Greater Green River Basin. The Scheggs Bed (fig. 42) consists mainly of low-grade clay-rich oil shale in the central parts of the Green River, Washakie, and Sand Wash Basins, becoming sandier toward the margins of the lake.

Variations in oil yield for the R-0 zone, which overlies the Long Point Bed in the Uinta and Piceance Basins (modified from Mercier and Johnson, 2012), and for the Tipton Shale Member are shown on figure 42 (modified from Johnson and others, 2011). In the Uinta Basin, oil yields for the R-0 zone vary from less than 1 GPT to a maximum of 10 GPT in the easternmost part of the basin. In the Piceance Basin, oil yields vary from less than 1 GPT to more than 14 GPT in the central part of the basin.

Oil yields for the Tipton Shale Member vary from less than 1 GPT to more than 20 GPT in the south-central part of the Green River Basin. Thus, oil yields are significantly higher in the Greater Green River Basin than in either the Uinta or Piceance Basins during and shortly after the

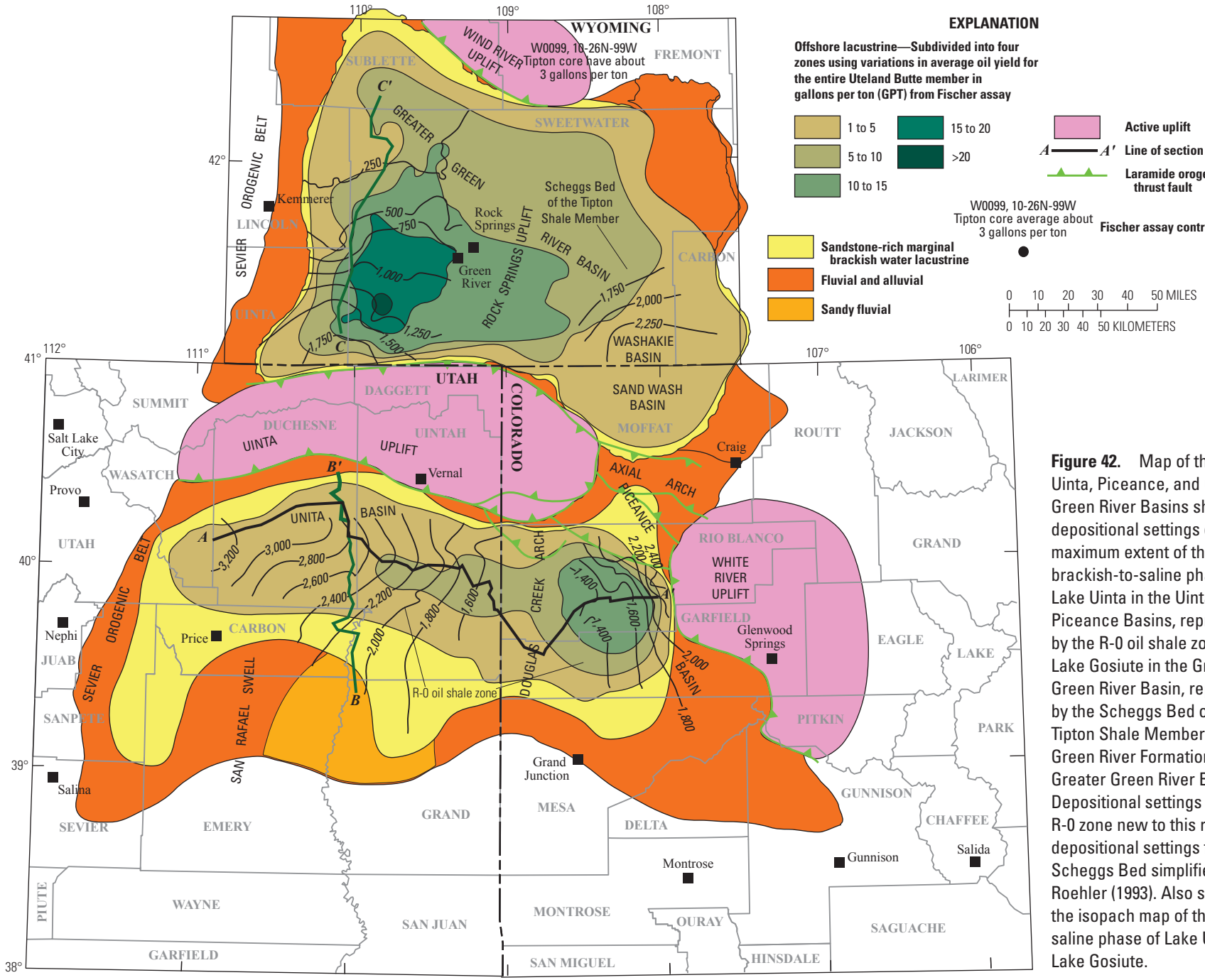


Figure 42. Map of the Uinta, Piceance, and Greater Green River Basins showing depositional settings during maximum extent of the brackish-to-saline phase of Lake Uinta in the Uinta and Piceance Basins, represented by the R-0 oil shale zone, and Lake Gosiute in the Greater Green River Basin, represented by the Scheggs Bed of the Tipton Shale Member of the Green River Formation in the Greater Green River Basin. Depositional settings for the R-0 zone new to this report, depositional settings for the Scheggs Bed simplified from Roehler (1993). Also shown is the isopach map of the main saline phase of Lake Uinta and Lake Gosiute.

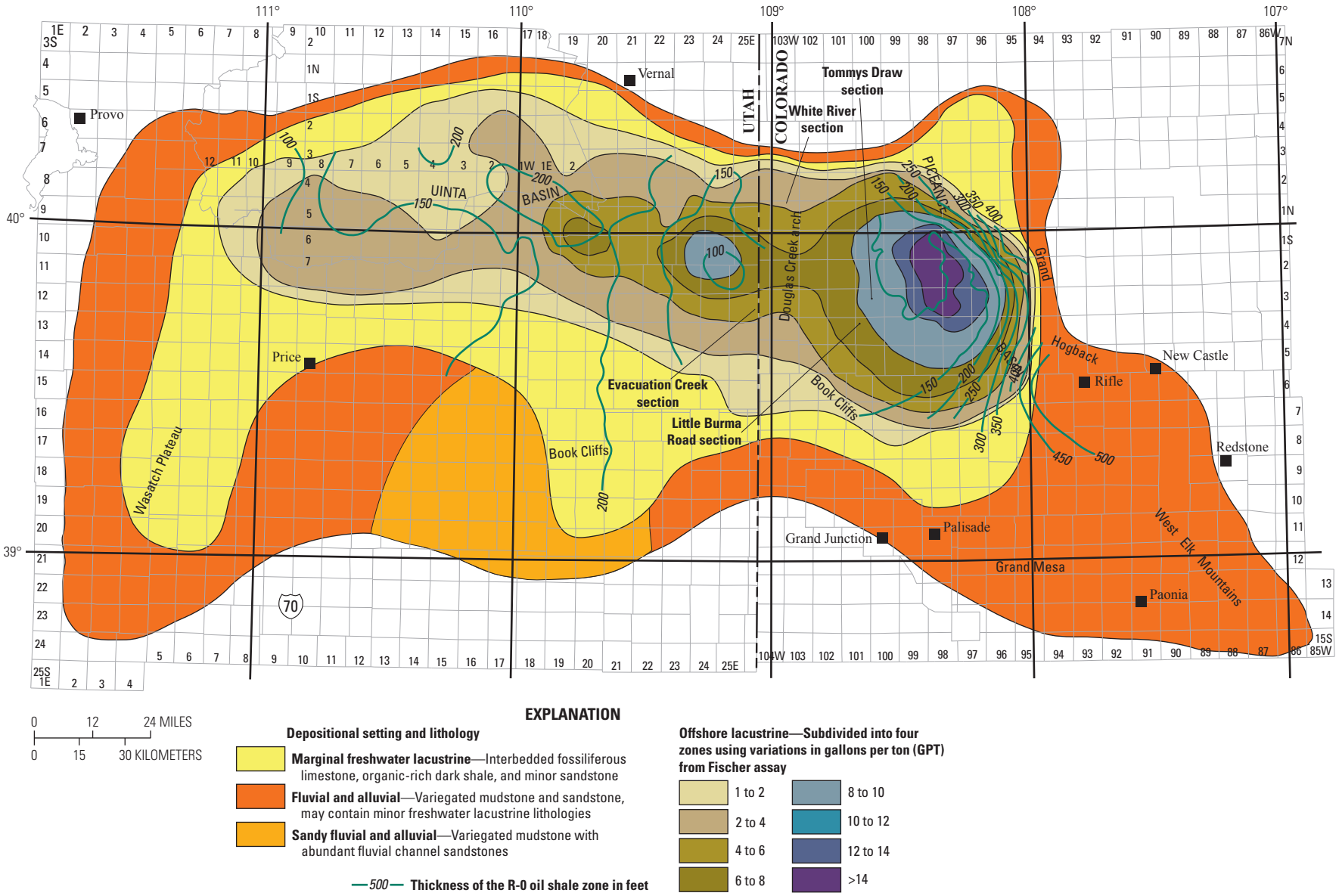


Figure 43. Map of the Uinta and Piceance Basins showing depositional settings at maximum transgression after the Long Point transgression and variations in oil yield using Fischer assay for the R-0 oil shale zone.

transition from fresh-to-brackish water. The Great Divide Basin was not assessed during the recent assessment of the Greater Green River Basin; however, oil yields for the Tipton Shale in that basin appear to be generally low based on a single corehole through the Tipton Member, C0099 in sec. 10, T. 26 N., R. 99 W. (fig. 42), that averaged 1.09 GPT over the entire 117.7-ft cored interval of the Tipton Shale Member and 2.98 GPT for the richest 38.4 ft of that interval. Oil yields for the Tipton Shale Member in the Sand Wash Basin are unknown but are hypothesized to be similar to that of the adjacent southern part of the Washakie Basin or in the 1–5 GPT range (fig. 42).

The isopach map of the preceding freshwater phase in all three basins is included on figure 42. Assuming that variations in rates of subsidence during deposition of the R-0 zone and Tipton Shale Member were similar to the preceding freshwater period, there appears to be little relationship between subsidence and organic richness. In the Piceance Basin, the richest oil shale is considerably east of the axis of the basin trough near the east margin of the basin where the R-0 zone grades into largely sandstone. In the Uinta Basin, the richest oil shale was deposited in the eastern part of the basin on the west flank of the Douglas Creek arch where rates of subsidence were comparatively low. In the Greater Green River Basin, oil yields are greatest in the southern part of the Green River Basin considerably north of the axis of the basin trough. In the Washakie Basin, there appears to be little relationship between rates of subsidence and organic richness, which suggests that variations in the rate of sediment supplied to the basins may have been more important in determining where the offshore organic-rich facies was than rates of subsidence.

The R-0 zone generally lacks the dolomite and limestone beds that make the Uteland Butte member a viable tight oil play in the Uinta Basin. It is conceivable that the R-0 zone could contribute some oil to the horizontal wells if vertical fractures are long enough. More importantly, the R-0 zone may act as a regional seal inhibiting the vertical migration of hydrocarbons in both the Uinta and Piceance Basins. Similarly, the Scheggs Bed of the Tipton Shale Member of the Green River Formation in the Greater Green River Basin may act as a regional seal because it consists mainly of low-grade, clay-rich oil shale.

Summary

This report examines the tight oil potential of the intervals deposited during the early fresh-to-brackish-water period of Eocene Lake Uinta in the Uinta and Piceance Basins and Eocene Lake Gosiute in the Greater Green River Basin. Rocks deposited during this period are generally not as organic-rich as the world-class oil shale intervals deposited during the mainly saline to hypersaline stages of the two lakes that followed but contain sufficient organic matter to be considered potential source rocks. A generalized history of the structural development of these basins is incorporated into this investigation to study relationships between lake development and subsidence and to better understand variations in post-depositional subsidence and burial that led to the development of a major petroleum system in only the Uinta Basin.

In general, the freshwater lakes were confined to the rapidly subsiding basin troughs during restricted lake phases (figs. 12, 41), expanding into slower subsiding areas including slowly subsiding structural arches such as the Douglas Creek arch between the Uinta and Piceance Basins and the Rock Springs uplift between the Green River and Washakie Basins only during high lake phases (figs. 13, 42). The decreasing rates of subsidence toward the north part of the Green River Basin through time (figs. 5, 6) may have played a role in confining the freshwater lake to the southern part of that basin even during maximum transgression (fig. 13). Variations in sediment supply, however, also influenced lake development. In the Piceance Basin, the locus of freshwater lacustrine deposition was shifted significantly to the west of the rapidly subsiding basin trough by sediments being shed from the nearby rising White River uplift to the east. Similarly, freshwater lake phases in the Washakie Basin appear to be shifted to the central and western parts of the basin trough (figs. 12, 13, and 41), possibly due to a significant sediment source from the east.

The presence of brittle calcareous beds and porous dolomite beds appears to be very important to tight oil production from the Uteland Butte member in the Uinta Basin. The existing evidence shows that the freshwater Cow Ridge Member in the Piceance Basin is much less calcareous than the Uteland Butte member and does not have thick dolomite beds (Johnson, 1985). The freshwater Luman Tongue in the Greater Green River Basin was not studied in detail but also appears to contain much less carbonate than the Uteland Butte. Additionally, the Uteland Butte member contains oolite and oncolite beds that are lacking in the Cow Ridge Member, suggesting more alkaline conditions, and rare stromatolites beds, suggesting that the lake during deposition of the Uteland Butte occasionally became sufficiently brackish to kill off the freshwater mollusk population allowing stromatolites to form. It is suggested that these differences were caused by the Douglas Creek arch. Rates of subsidence along the crest of the arch were very low throughout the freshwater lacustrine period, because there are few if any rocks from that period preserved along the crest of the arch. It is suggested that the Uinta Basin drained eastward across the crest of the arch and into the Piceance Basin during the freshwater period. During exceptionally low flow periods, flow to the Piceance Basin ceased, the lake in the Uinta Basin became internally drained, and salinity increased sufficiently to kill off the freshwater mollusk population.

In the Green River Basin north of the Uinta uplift, subsidence rates after deposition of the lacustrine oil shale intervals decreased markedly, whereas subsidence accelerated in the Uinta Basin south of that uplift (fig. 7). The cause of this asymmetry in subsidence rates is unknown, but it led to the development of a major petroleum system in the Uinta Basin, whereas the organic-rich interval in the Green River Basin was never buried deeply enough to have generated significant hydrocarbons. Subsidence

and burial after deposition of the organic-rich interval in the Washakie Basin (fig. 39) and in the Piceance Basin (fig. 11) may have been sufficient for hydrocarbons to have been generated in the Paleocene-age paludal interval, but it is unlikely that significant amounts of hydrocarbons were generated by the Eocene freshwater lacustrine rocks in those basins.

Rates of production for horizontal tests in the freshwater Uteland Butte member of the Green River Formation in the Uinta Basin generally increase toward the basin trough (fig. 33). Similarly, total organic matter (fig. 34), formation pressures (fig. 35), thermal maturities (fig. 38), and total thicknesses of calcareous-rich intervals (fig. 14) and dolomite-rich intervals (fig. 24) all generally increase toward the basin trough, and it is unclear how much of a role each of these factors plays individually in this increased production.

The shift from fresh-to-brackish water in the Uinta, Piceance, and Greater Green River Basins was preceded by major transgressive events, suggesting the outlet or outlets were lost at this time. Low-grade oil shale of the R-0 zone in the Uinta and Piceance Basins and the Tipton Shale Member of the Green River Formation was deposited over much of these three basins after maximum transgression was reached (figs. 42, 43), but this interval is only thermally mature enough in the Uinta Basin to have generated significant hydrocarbons. Additionally, these low-grade oil shale intervals in all three basins appear to lack significant carbonate, which may be an essential component for tight oil production. The low-grade oil shale intervals may, however, act as good seals inhibiting the vertical migration of gas.

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