Development, Evolution, and Destruction of the Saline Mineral Area of Eocene Lake Uinta, Piceance Basin, Western Colorado

Scientific Investigations Report 2013–5176

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

COVER. View of the Green River Formation at Anvil Points, west of Rifle, Colorado. Photo by Ronald C. Johnson, U.S. Geological Survey.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Development, Evolution, and Destruction of the Saline Mineral Area of Eocene Lake Uinta, Piceance Basin, Western Colorado

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Abstract

Halite and the sodium bicarbonate mineral nahcolite were deposited in Eocene-age saline Lake Uinta in the Piceance Basin, northwestern Colorado. Variations in the areal extent of saline mineral deposition through time were studied using descriptions of core and outcrop. Saline minerals have been extensively leached by groundwater, and the original extent of saline deposition was determined from the distribution of empty vugs and collapse breccias. Because vugs and breccias strongly influence groundwater movement, determining where leaching has occurred is an important consideration for in-situ oil shale extraction methods currently being developed.

Lake Uinta formed when two much smaller freshwater lakes, one in the Uinta Basin and the other in the Piceance Basin, expanded and coalesced across the Douglas Creek arch. Early Lake Uinta inherited much of the topography in the freshwater lake and surrounding alluvial plains that preceded it, and the deep central lake area of Lake Uinta developed largely over the offshore area of the freshwater lake. A prolonged period of infilling followed the formation of Lake Uinta, creating broad lake-margin shelves prior to the onset of saline mineral deposition. These shelves almost certainly played a critical role in the evolution of the brine layer that accumulated in the deep central lake area. Broad marginal shelves formed as well around the Uinta Basin part of Lake Uinta. Brines that formed on those shelves also probably migrated to the deep central lake area in the Piceance Basin, as no saline minerals were deposited in the Uinta Basin until late in the history of Lake Uinta.

Oil shale in the deep central lake consists of interbedded laminate oil shale beds that originated within the deep lake area, and blebby and streaked oil shale beds that were transported into the deep lake area by sediment gravity flows. Blebby and streaked oil shale beds contain carbonate clasts and siliciclastic clasts similar to lithologies found on the marginal shelves. It is possible that these clasts and the highly saline brines that evolved on the marginal shelves were incorporated into the same gravity flows.

Saline mineral deposition is informally subdivided into early, middle, and late phases. During the early phase, nahcolite and rich oil shale were deposited in the deep central lake area, and carbonate-rich sandstone, siltstone, and mudstone and ostracodal, oolitic, algal limestone were deposited on the marginal shelves. During the middle saline mineral phase, oil shale deposition gradually expanded across the marginal shelves, and by the end of that phase, oil shale deposition covered almost all of the former shelf areas. An increasing flow of water from Lake Gosiute to the north, as it was gradually filled in by volcaniclastics, may have caused this expansion. Saline mineral deposition also expanded during the middle saline mineral phase, reaching to near the former shelf break by the end of that phase. This suggests that the former shelf break remained a topographic feature that confined the deep saline brine layer throughout the middle phase.

By the beginning of the late saline mineral phase, Lake Gosiute had been completely filled in and volcaniclastic debris reached the northern shore of Lake Uinta. This initiated a north-to-south infilling of the Piceance Basin part of Lake Uinta that progressively pushed the saline mineral area southward and ultimately onto the former marginal shelf areas in the southern part of the basin. A saline mineral area formed for the first time in the eastern part of the Uinta Basin during this infilling and, for a time, saline minerals were deposited in both basins. By the end of the late saline phase, the Piceance Basin part of Lake Uinta was filled in and saline mineral deposition shifted entirely into the Uinta Basin.

Leaching of saline minerals began sometime after the Green River Formation was lithified enough to allow collapse breccias to form. Leaching is ongoing today, indicated by the discharge of highly saline water from a series of springs in the northern part of the basin. Groundwater invasion and saline mineral dissolution is commonly incomplete in areas that lack fractures, leaving behind pockets of unleached saline minerals in otherwise leached intervals. Today, the base of the leached zone slopes toward the north and toward the area where the brines are being discharged.

Introduction

The Eocene Green River Formation in Colorado, Wyoming, and Utah was deposited in two large lakes: (1) Lake Uinta in the Piceance Basin of western Colorado and the Uinta Basin of eastern Utah and westernmost Colorado, and (2) Lake Gosiute in the Greater Green River Basin in southwest Wyoming and northwest Colorado (fig. 1). The Green River Formation contains the largest in-place oil shale resource in the world, recently estimated at 1.53 trillion barrels of oil for the Piceance Basin (fig. 2) (Johnson and others, 2010a), 1.32 trillion barrels of oil for the Uinta Basin (Johnson and others, 2010b), and 1.44 trillion barrels of oil for the Greater Green River Basin (Johnson and others, 2011). It must be emphasized that only a small fraction of this in-place resource is of a thickness, grade, and depth favorable for extraction.

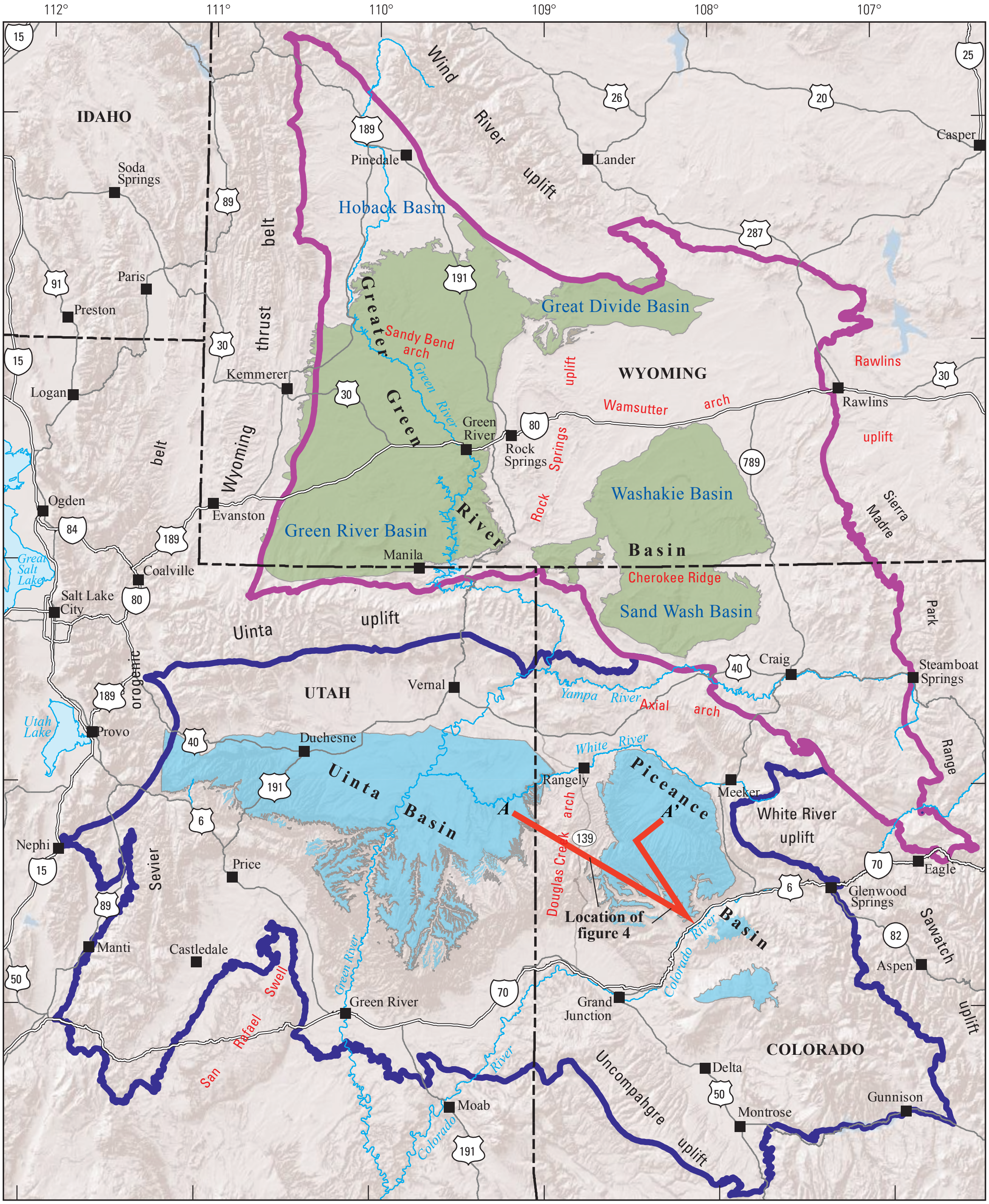
During the long history of Lake Uinta, as much as 8 million years in the Uinta Basin where the lake persisted the longest (Smith and others, 2008), the lake remained saline and did not have an outlet. Lake Gosiute, in contrast, evolved from a highly saline lake to a freshwater lake late in its history once drainage southward into Lake Uinta was established. Saline minerals were deposited in both lakes, with trona ($Na_3H(CO_3)_2 \cdot 2H_2O$) and halite (NaCl) deposited in Lake Gosiute and nahcolite ($NaHCO_3$) and halite deposited in Lake Uinta. Nahcolite resources in the Piceance Basin were recently estimated at 43.3 billion short tons (fig. 2) (Brownfield and others, 2010a). Several companies currently mine underground beds of trona in Wyoming, and one company solution mines a thick bed of nahcolite in Colorado. Saline minerals in the Uinta Basin were recently studied by Brownfield and others (2010b).

Nahcolite and halite deposits in the Green River Formation of the Piceance Basin were once much more extensive, both vertically and laterally, than they are today. The progressive penetration of groundwater into the Green River Formation has increasingly encroached upon the saline interval, leaving behind a leached zone estimated by Brownfield and others (2010a) to be as much as 580 feet (ft) thick. Evidence for leaching includes cavities, collapse breccias, and open fractures that form the main source of secondary porosity and permeability in the oil shale interval (Weeks and others, 1974). Groundwater moves freely though this highly porous and permeable zone, whereas groundwater has not yet reached intervals that still contain large amounts of intact nahcolite and halite. Understanding groundwater movement is critical to the in-situ methods for the extraction of oil from oil shale currently being developed. Some methods are designed to work only in oil shale intervals where groundwater movement is negligible (Day, 2011; Janicek, 2011, 2012), whereas others are designed to work within groundwater-bearing zones (Deeg and others, 2007, 2009). Nahcolite ($NaHCO_3$) decomposes to natrite (Na_2CO_3) or soda ash, carbon dioxide, and water at temperatures near 100 °C or significantly below retort temperatures; thus, large quantities of carbon dioxide, a greenhouse gas, would be released by any nahcolite in the retorted interval. Extracting nahcolite prior to in-situ retorting is thus critical (Janicek, 2012).

The oil shale section in the Piceance Basin is subdivided into 17 rich and lean oil shale zones (fig. 3) representing alternating periods of high and low organic productivity and (or) preservation and thus closely representing time-stratigraphic intervals (Donnell and Blair, 1970; Cashion and Donnell, 1972; Donnell, 2008). The recently completed assessment of in-place oil shale in the Piceance and Uinta Basins (Johnson and others, 2010 a, b) assessed each of these 17 zones separately. Thirteen of these zones in the Piceance Basin contain saline minerals or evidence that saline minerals were once present. A separate map was generated for each zone displaying where saline minerals are present and where there is evidence that saline minerals were once present. Three maps were generated for the uppermost oil shale zone, which is unusually thick and complex. The advantage of using the time-stratigraphic rich and lean zone stratigraphy is that it allows for the tracking of overall depositional changes in Lake Uinta through time. A disadvantage is that individual zones can be quite thick and thus represent a considerable period of time. Thus, important events that occurred within an individual zone, such as a short-term expansion or contraction of the lake, are not captured, although they may be very important to understanding the evolution of the saline zone. In addition, two detailed structural cross sections that use sea level as a datum were constructed to better track the penetration of groundwater into the oil shale interval. The focus of this paper is thus twofold: (1) to describe the development and evolution of the saline mineral facies in the Piceance Basin through time, and (2) to delineate the extent of the leaching of this saline interval in order to better understand groundwater movement in the basin.

The Development of Eocene Lake Uinta and Contemporary Lake Gosiute

The Eocene Green River Formation of the Piceance Basin was deposited in lower to middle Eocene time in Lake Uinta, a large saline lake that extended across the Piceance Basin, the Uinta Basin to the west, and the intervening Douglas Creek arch. The Uinta and Piceance Basins are structural and sedimentary basins formed during the Laramide orogeny, a major tectonic event that affected the central Rocky Mountain region from Late Cretaceous through Eocene time. The Douglas Creek arch was an area with relatively low subsidence rates throughout the Paleocene and Eocene prior to the development of Lake Uinta, as pre–Lake Uinta lower Tertiary strata thin and largely wedge out on both flanks of the arch. Lake Uinta strata, in contrast, extend across the arch unbroken (fig. 4). To the north, Lake Gosiute occupied much of the Greater Green River Basin of southwest Wyoming and part of northwest Colorado in lower to middle Eocene time (fig. 1). The two lakes may have been connected across the intervening Axial arch (fig. 1) for a



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 Southwesten Wyoming Province boundary

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

Figure 1. (Caption on following page.)

Figure 1 (previous page). Map showing extent of Uinta, Piceance, and Greater Green River Basins and approximate extent of oil shale in the Green River Formation. Location of cross section *A-A'* (see fig. 3) is shown in red. Subbasins in the Greater Green River Basin are 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 (USGS Uinta-Piceance Assessment Team, 2003). Extent of the Greater Green River Basin is the same as the Southwestern Wyoming Province boundary (USGS 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 was 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 basin, the top of the Mahogany bed 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 using a structure contour map of the top of the Mahogany oil shale bed compiled by Johnson and Roberts (2003). For the Sand Wash, Washakie, and Great Divide Basins, and the 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 was used, and for the northern part of the Green River Basin, the base of the Laney Shale Member of the Green River Formation was used, both as mapped by Love and Christiansen (1985).

relatively brief time shortly after they formed (Johnson, 1985, p. 272; Roehler, 1993, figs. 50, 52), but this is uncertain. There is, however, considerable evidence that Lake Gosiute drained southward into Lake Uinta late in its history (Roehler, 1974; Surdam and Stanley, 1979, 1980; Johnson, 1985, 2007; Smith and others, 2008). This southward drainage had a profound impact on Lake Uinta.

Lake Uinta formed when two much smaller freshwater lakes, one each in the Uinta and Piceance Basins, expanded and coalesced across the intervening Douglas Creek arch (figs. 1, 4) (Johnson, 1984, 1985). Freshwater mollusks, found throughout strata deposited during the earlier freshwater lacustrine phase, are abundant in the Long Point Bed of the Green River Formation (fig. 4), the basal transgressive bed of Lake Uinta. Mollusks, however, are absent or nearly absent in strata above, suggesting that salinity began to increase in Lake Uinta shortly after maximum transgression was reached. Stromatolites appear for the first time immediately above the Long Point Bed (Johnson and others, 1988, measured sections 6 and 9). Stromatolites will generally not form in the presence of mollusks, as they graze on the algal mats that create them. The abundance of freshwater mollusks in the Long Point Bed suggests a mass mortality event, possibly triggered by a slight increase in salinity. Freshwater mollusks never returned to Lake Uinta, and stromatolites remained common in marginal facies throughout the history of the lake, indicating that Lake Uinta remained internally drained and saline. Freshwater mollusks, however, do reappear late in the history of Lake Gosiute, indicating that it evolved from an internally drained lake to an externally drained lake as southward drainage into Lake Uinta was established.

The creation of a large internally drained or closed saline lake from much smaller, externally draining freshwater lakes is unusual and is not fully understood. Recent examples of freshwater lakes evolving into saline lakes, such as Pleistocene Lake Bonneville, did so after a period of contraction caused the lake level to drop below the spill point, thus eliminating its outlet. Johnson (1985, p. 271–272) suggested there was one spill point for the freshwater lakes in the Piceance and Uinta Basins and that this spill point gradually rose, possibly because of tectonic uplift, causing the lakes to expand and coalesce. The expansion was ultimately halted by the increased evaporation from the newly enlarged surface area of the lake. The outlet of the lake could have subsequently been lost if the spill point continued to rise once maximum expansion was reached. This hypothesis could also explain how a thick interval of Lake Uinta sediments could have been deposited over the Douglas Creek arch (fig. 4), a hinge line that had previously accumulated very little sediment during early Tertiary time, as subsidence would no longer be required to produce accommodation space. Lake level could rise freely in the basin provided a spill point was not reached.

Subdividing the Green River Formation into Members, Rich and Lean Zones, and Stages

The Green River Formation has been divided variously into (1) members, based on lithology; (2) stages, based on the evolution of the lake; and (3) “rich” and “lean” oil shale zones, representing approximately time-stratigraphic intervals of alternating high and low organic productivity and (or) preservation (figs. 3–5). These various schemes will be discussed only briefly here. For more complete summaries see Johnson and others (2010 a, b), Johnson (2012), and Mercier and Johnson (2012).

Five major members of the Green River Formation are now widely used (figs. 4, 5): (1) Cow Ridge Member (Johnson, 1984), applied to the freshwater lacustrine interval that

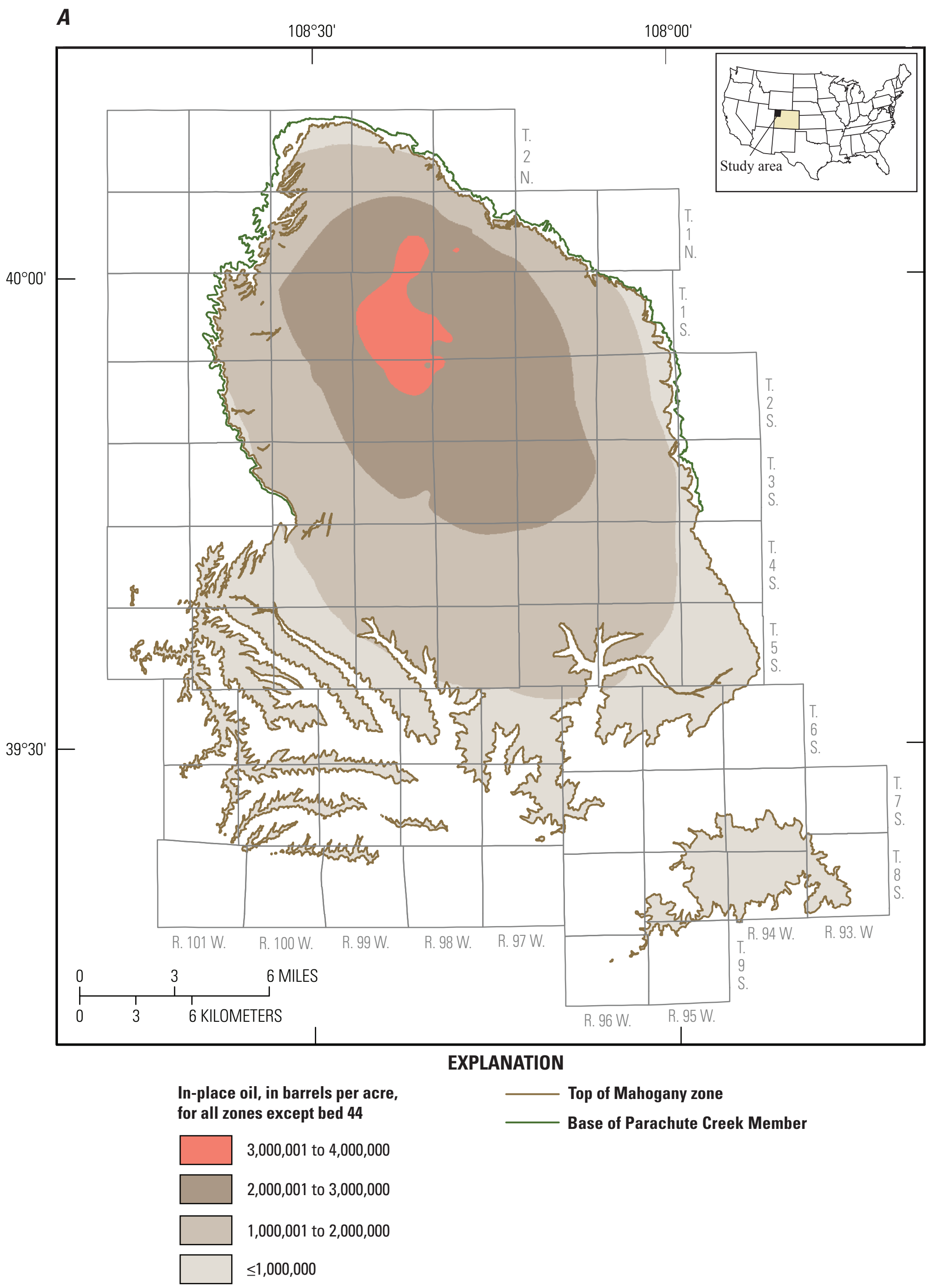


Figure 2. Maps showing (*A*) total in-place oil in barrels per acre (from Johnson, 2012) and (*B*) total in-place nahcolite in tons per acre (modified from Brownfield and others, 2010a) for all oil shale zones in the Piceance Basin. Location of highly saline springs (red circles) and zone of faulting and fracturing (blue area) in the northern part of the basin are also shown (modified from Weeks and others, 1974; Robson and Saulnier, 1981). Location of cross section *D-D′* (see fig. 9) is shown in black. (Continued on next page.)

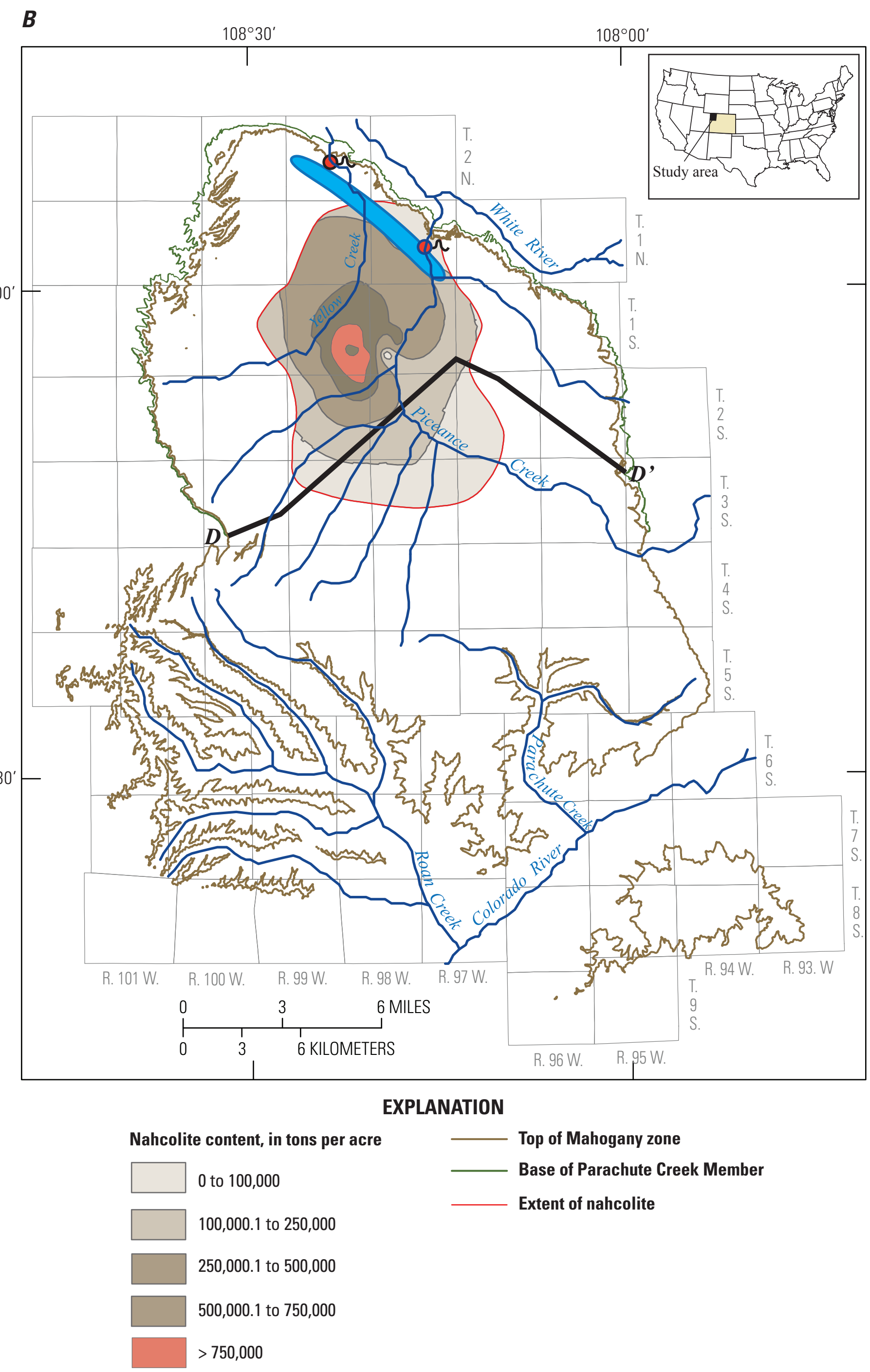


Figure 2—Continued. Maps showing (*A*) total in-place oil in barrels per acre (from Johnson, 2012) and (*B*) total in-place nahcolite in tons per acre (modified from Brownfield and others, 2010a) for all oil shale zones in the Piceance Basin. Location of highly saline springs (red circles) and zone of faulting and fracturing (blue area) in the northern part of the basin are also shown (modified from Weeks and others, 1974; Robson and Saulnier, 1981). Location of cross section *D-D′* (see fig. 9) is shown in black.

predates the Long Point transgression and the formation of saline Lake Uinta; (2) Garden Gulch Member (Bradley, 1931), applied to the illite-rich oil shale interval deposited early in the history of Lake Uinta and prior to the onset of saline mineral deposition; (3) Parachute Creek Member (Bradley, 1931), applied to the dolomite-rich oil shale interval deposited during saline mineral deposition; (4) Douglas Creek Member (Bradley, 1931), applied to marginal lacustrine rocks around the west margins of Lake Uinta; and (5) Anvil Points Member (Donnell, 1953), applied to marginal lacustrine rocks around the east margin. The Douglas Creek and Anvil Points Members are the marginal equivalents of both the Garden Gulch and Parachute Creek Members. The name Uinta Formation is applied to a sequence of sandstones and siltstones containing abundant volcanic clasts that interfingers with the upper part of the Green River Formation (Dane, 1954; Cashion and Donnell, 1974). The Uinta Formation represents the infilling stage of that part of Lake Uinta that occupied the Piceance Basin (figs. 4, 5).

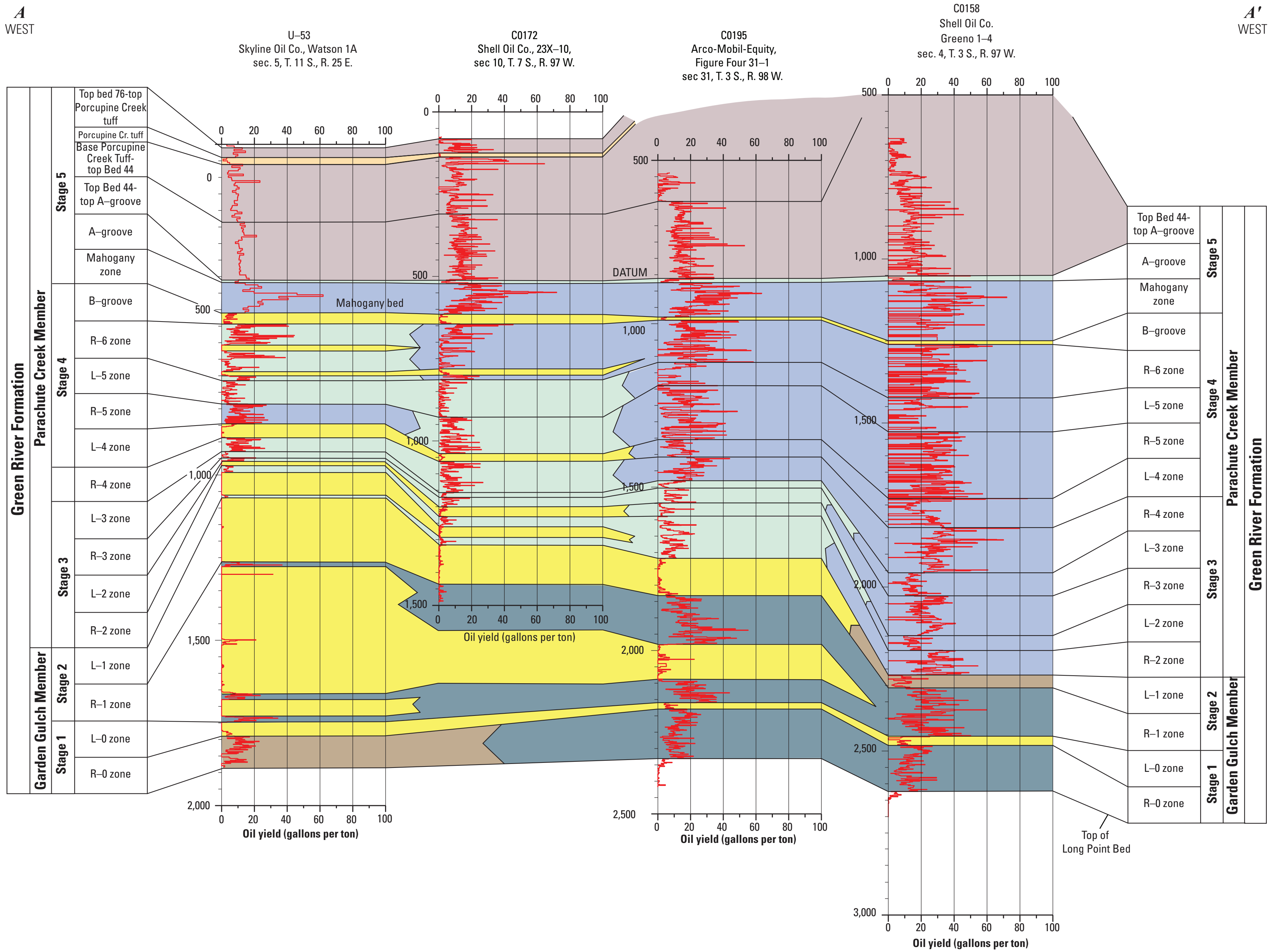
Johnson (1985) subdivided the history of Lake Uinta into five roughly time-stratigraphic periods or stages with the change from one stage to the next corresponding to significant changes in conditions in the lake (figs. 3–5). Stages 1 and 2 are equivalent to the illitic Garden Gulch Member, and stages 3–5 are generally equivalent to the dolomitic Parachute Creek Member (fig. 3, pl. 1). Johnson (1985) cited evidence of increasing salinity during the first two stages, culminating in the deposition of large quantities of nahcolite and halite during stages 3 and 4. Stage 5 of Johnson (1985) begins with a major transgression, probably caused by an increase in outflow from Lake Gosiute to the north followed fairly closely by an influx of large quantities of volcaniclastic sediments from volcanic centers in northwest Wyoming and possibly Idaho (Carroll and others, 2008).

Recently, Tanavsuu-Milkeviciene and Sarg (2012) used somewhat different criteria to subdivide the Green River Formation in the Piceance Basin into six stages: (1) Stage 1 (R-0 through R-1 zones), which they considered to be freshwater; (2) Stage 2 (L-1 through L-3 zones) or transitional lake, when the lake became highly saline; (3) Stage 3 (R-4 through L-5 zones), a period when lake levels were highly fluctuating; (4) Stage 4 (R-6 and B-groove) or rising lake stage; (5) Stage 5 (Mahogany zone) or high lake stage; and (6) Stage 6 (above Mahogany zone) or closing lake stage.

The oil shale interval in the Piceance Basin has been additionally subdivided into eight oil-rich zones in ascending order, R-0 through R-6 and the Mahogany zone (Mahogany ledge in outcrop), and seven oil-lean zones in ascending order, L-0 through L-5, B-groove, and A-groove (fig. 3). These zones represent alternating periods of high and low organic productivity and (or) preservation in Lake Uinta, representing roughly time-stratigraphic intervals. The rich and lean zone architecture formed the basis for recent resource assessments of both the Piceance and Uinta Basins, with each rich and lean zone being assessed separately (Johnson and others, 2010 a, b). These zones also form the basis of this study, in which the extent of saline minerals and leaching was determined for each rich and lean zone within the saline mineral interval. Cashion and Donnell (1972) originally defined the rich and lean zones in the Piceance Basin and demonstrated that zones from R-4 to the top of the oil shale interval could be traced into the eastern part of the Uinta Basin as well. Recently, Johnson and others (2010b) were able to trace all the rich and lean zones below the R-4 zone into their equivalent intervals in at least the easternmost part of the Uinta Basin. A significant interval of moderate to rich oil shale also occurs above A-groove, in the interval that intertongues with southward-prograding volcaniclastic wedges of the Uinta Formation (figs. 3–5). Donnell (2008) recently traced a large number of individual oil shale beds in this interval throughout the offshore lacustrine area in the Piceance Basin and eastern Uinta Basin. The lower part of this interval, from the top of A-groove to the top of bed 44 of Donnell (2008) (fig. 3), was assessed in the Piceance Basin by Johnson and others (2010a).

Nahcolite and Halite in the Piceance Basin

At present, nahcolite in the Piceance Basin is confined to a relatively restricted area in the north-central part of the basin (fig. 2) in the stratigraphic interval from the uppermost part of the R-2 zone through the lowermost part of the L-5 zone. Halite is confined to the R-5 and L-5 zones in an even more limited area in the north-central part of the basin (Smith and Young, 1969; Young and Smith, 1970; Dyni and others, 1971 a, b; Smith and others, 1972; Beard and others, 1974; Dyni, 1974 a, b, c; Brownfield and others, 2010a). Nahcolite occurs as (1) crystalline aggregates, (2) laterally continuous units of fine-grained disseminated crystals in oil shale, (3) brown microcrystalline beds, and (4) white coarse-grained beds (figs. 6–8). Individual nahcolite nodules range from less than 1 inch (in.) to several feet in diameter, but most nodules range in diameter from 1 to 3 in. (Beard and others, 1974; Dyni, 1974 b, c). Although nodular nahcolite is not bedded, nodules do appear to be concentrated in discrete zones parallel to bedding (Dyni, 1974c, fig. 10). Nodules formed while the encasing oil shale was still soft, as lamina in the oil shale beds bend around them. Dyni (1981, p. 123–124) suggested that the nodules began to form in the upper meter or so of sediment during the initial stages of dewatering in areas where overlying lake waters were not quite concentrated enough to precipitate nahcolite directly. Dyni (1974c) also believed that disseminated nahcolite precipitated at or near the sediment-water interface when lake waters were at or near saturation, with precipitation keeping pace with oil shale deposition. Disseminated nahcolite intervals have sharp to gradational contacts with adjacent oil shale beds and range in thickness from a few feet to 23 ft (Dyni, 1974c, p. 116). Beds of microcrystalline brown nahcolite have a texture and appearance of brown sugar, get their color from small amounts of organic



A
WEST
A′
WEST
U–53
Skyline Oil Co., Watson 1A
sec. 5, T. 11 S., R. 25 E.
C0172
Shell Oil Co., 23X–10,
sec 10, T. 7 S., R. 97 W.
C0195
Arco-Mobil-Equity,
Figure Four 31–1
sec 31, T. 3 S., R. 98 W.
C0158
Shell Oil Co.
Greeno 1–4
sec. 4, T. 3 S., R. 97 W.
Green River Formation
Parachute Creek Member
Garden Gulch Member
Stage 5
Stage 4
Stage 3
Stage 2
Stage 1
Top bed 76-top Porcupine Creek tuff
Porcupine Cr. tuff
Base Porcupine Creek Tuff-top Bed 44
Top Bed 44-top A–groove
A–groove
Mahogany zone
B–groove
R–6 zone
L–5 zone
R–5 zone
L–4 zone
R–4 zone
L–3 zone
R–3 zone
L–2 zone
R–2 zone
L–1 zone
R–1 zone
L–0 zone
R–0 zone
Mahogany bed
DATUM
Top of Long Point Bed
Oil yield (gallons per ton)
0
20
40
60
80
100
500
1,000
1,500
2,000
2,500
3,000

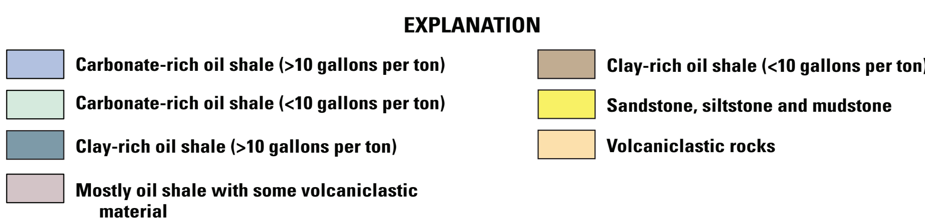
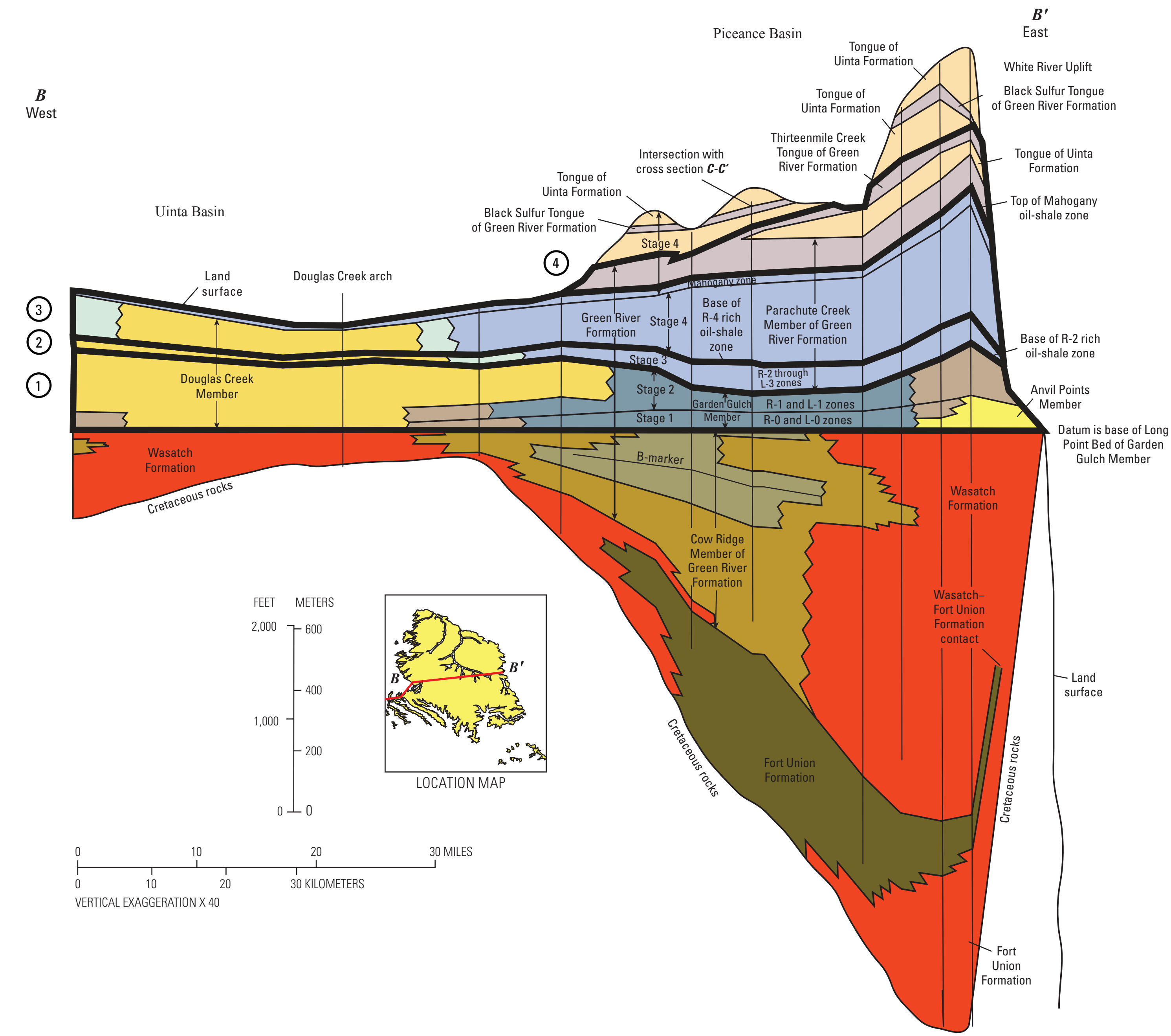


Figure 3 (previous page). Cross section *A-A′* showing (1) oil-yield histograms (red graphs), (2) members of the Eocene Green River Formation, (3) correlation of rich and lean oil shale zones of Cashion and Donnell (1972), (4) stages in the evolution of Lake Uinta, and (5) the informal phases of Lake Uinta used for convenience here. Corehole U-53 is in the northeastern part of the Uinta Basin, corehole C0172 is in the southern part of the Piceance Basin, and coreholes C0195 and C0158 are in the central part of the Piceance Basin. See figure 1 for location of cross section.



B
West
B′
East
Uinta Basin
Piceance Basin
Land surface
Douglas Creek arch
Douglas Creek Member
Wasatch Formation
Cretaceous rocks
Tongue of Uinta Formation
Black Sulfur Tongue of Green River Formation
Intersection with cross section C-C′
Thirteenmile Creek Tongue of Green River Formation
Tongue of Uinta Formation
Tongue of Uinta Formation
White River Uplift
Black Sulfur Tongue of Green River Formation
Tongue of Uinta Formation
Top of Mahogany oil-shale zone
Stage 4
Mahogany zone
Green River Formation
Stage 4
Base of R-4 rich oil-shale zone
Parachute Creek Member of Green River Formation
Stage 3
R-2 through L-3 zones
Stage 2
Garden Gulch Member
R-1 and L-1 zones
Stage 1
R-0 and L-0 zones
Base of R-2 rich oil-shale zone
Anvil Points Member
Datum is base of Long Point Bed of Garden Gulch Member
B-marker
Cow Ridge Member of Green River Formation
Fort Union Formation
Wasatch Formation
Wasatch–Fort Union Formation contact
Land surface
Cretaceous rocks
Cretaceous rocks
Fort Union Formation
1
2
3
4
FEET
METERS
2,000
1,000
0
600
400
200
0
LOCATION MAP
B
B′
0
10
20
30 MILES
0
10
20
30 KILOMETERS
VERTICAL EXAGGERATION X 40

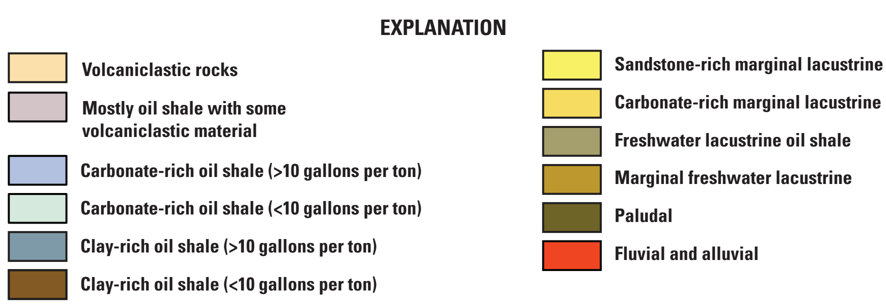
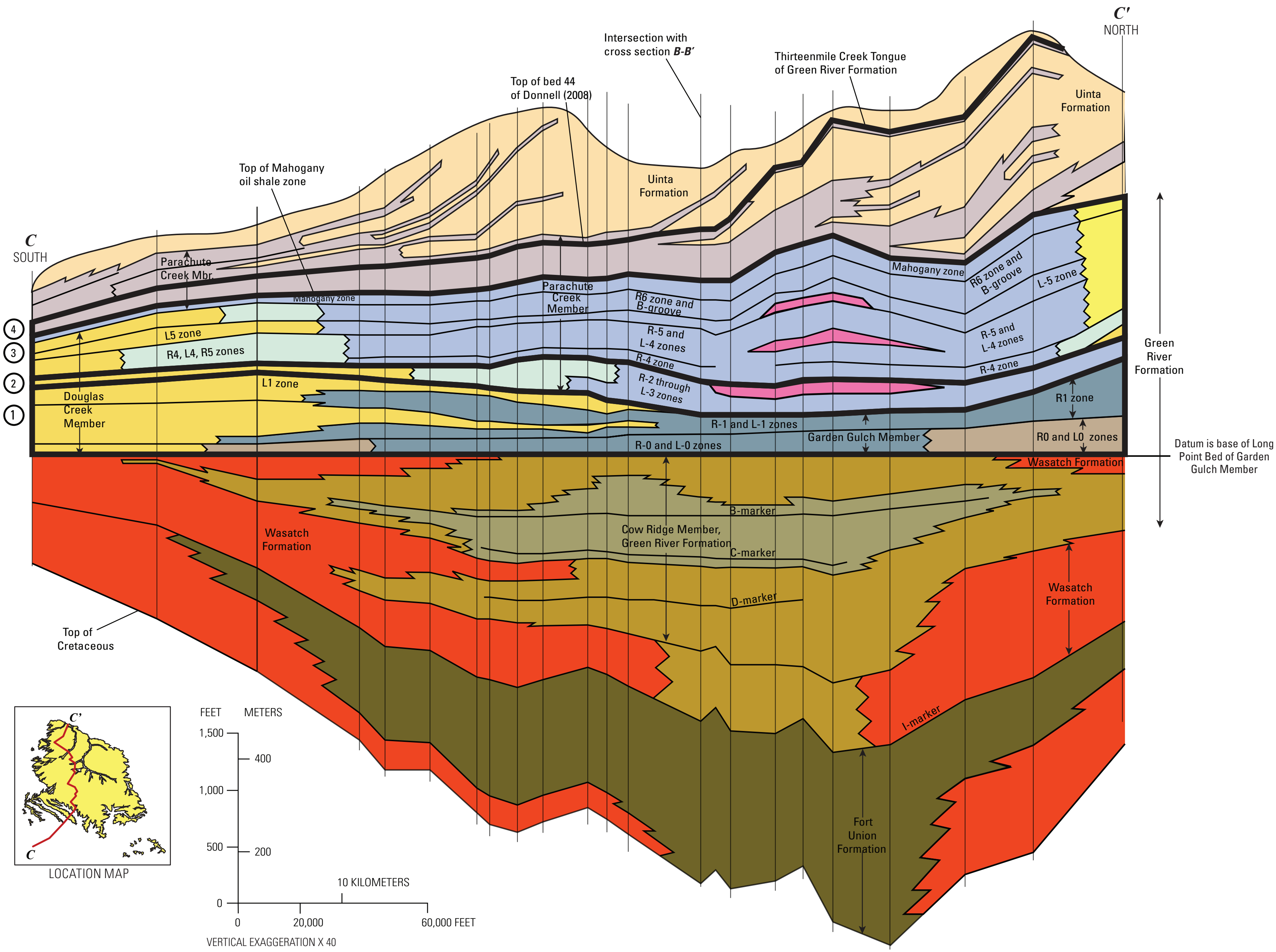


Figure 4 (previous page). East-west cross section *B-B′* through the Piceance Basin, the Douglas Creek arch, and the eastern part of the Uinta Basin showing members, stages of Lake Uinta as defined by Johnson (1985), and some of the rich and lean zones defined by Cashion and Donnell (1972). The illitic phase (labeled 1) and the early, middle, and late saline mineral phases (labeled 2–4) are outlined with heavy black lines.


C
SOUTH
C′
NORTH
Intersection with
cross section B-B′
Thirteenmile Creek Tongue
of Green River Formation
Top of bed 44
of Donnell (2008)
Top of Mahogany
oil shale zone
Uinta
Formation
Uinta
Formation
Parachute
Creek Mbr.
Mahogany zone
Parachute
Creek
Member
R6 zone and
B-groove
Mahogany zone
R6 zone and
B-groove
L-5 zone
L5 zone
R4, L4, R5 zones
R-5 and
L-4 zones
R-5 and
L-4 zones
R-4 zone
R-4 zone
L1 zone
R-2 through
L-3 zones
R1 zone
Douglas
Creek
Member
R-1 and L-1 zones
Garden Gulch Member
R0 and L0 zones
R-0 and L-0 zones
4
3
2
1
Green
River
Formation
Datum is base of Long
Point Bed of Garden
Gulch Member
Wasatch Formation
B-marker
Cow Ridge Member,
Green River Formation
C-marker
Wasatch
Formation
D-marker
Wasatch
Formation
Top of
Cretaceous
I-marker
Fort
Union
Formation
C′
C
LOCATION MAP
FEET
METERS
1,500
1,000
500
0
400
200
10 KILOMETERS
0
20,000
60,000 FEET
VERTICAL EXAGGERATION X 40

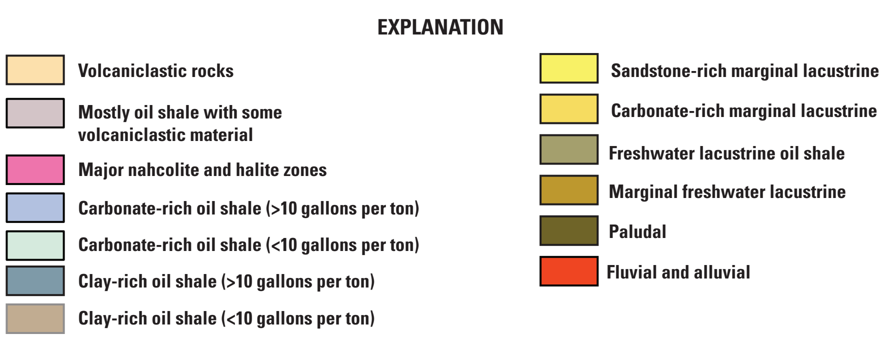


Figure 5 (previous page). North-south cross section *C-C′* through the Piceance Basin, northwest Colorado, showing members, stages of Lake Uinta as defined by Johnson (1985), and some of the rich and lean zones defined by Cashion and Donnell (1972). The illitic phase (labeled 1) and the early, middle, and late saline mineral phases (labeled 2–4) are outlined with heavy black lines.

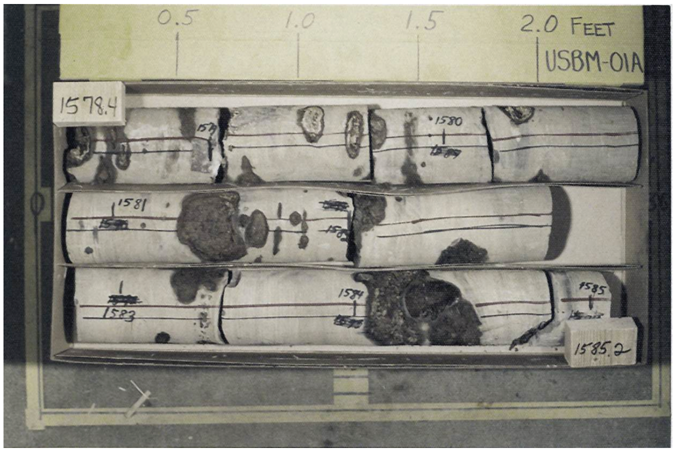


Figure 6. Drill core containing white, coarse crystals of nahcolite, small nodules of nahcolite, and dark-brown nahcolite aggregates of bladed crystals in oil shale. Some nahcolite aggregates are rimmed with pyrite. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,578.4 to 1,585.2 feet, R-5 oil shale zone). Core is stored at the U.S. Geological Survey's Core Research Center, Denver, Colorado.

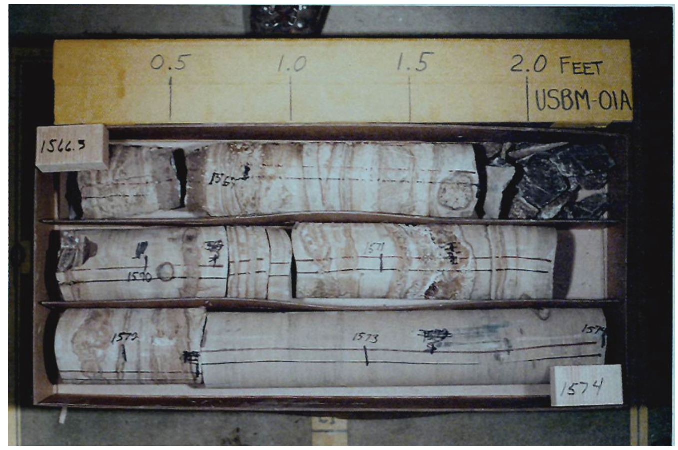


Figure 7. Drill core containing alternating beds of light-brown nahcolite and oil shale. White crystalline aggregate of nahcolite is located in right part of upper piece of core. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,566.5 to 1,574 feet, R-5 oil shale zone). Core is stored at the U.S. Geological Survey's Core Research Center, Denver, Colorado.

Figure 8. Drill core containing alternating beds of deeply dissolved halite and brown resistant wafer-like nahcolite. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,712.4 to 1,719.4 feet, R-5 oil shale zone). Core is stored at the U.S. Geological Survey's Core Research Center, Denver, Colorado.

impurities, and form laterally persistent beds from 0.5 to 12 ft thick. White, coarse-grained nahcolite beds have crystals from 1 to 6 millimeters across and are relatively free of kerogen. Bed thicknesses generally range from less than 1 ft to as great as 10 ft, but one nahcolite and halite bed is more than 60 ft thick. Six of the seven white nahcolite beds grade into mixed halite and nahcolite toward the center of the saline mineral area (Dyni, 1981, p. 42). Nahcolite aggregates formed diagenetically in soft sediments as the lamina in adjacent oil shale beds bend around the aggregates. Dyni (1981, p. 99) suggested that the saline mineral area was topographically complex, consisting of the main area in the eastern half of T. 1 S., R. 98 W. and two smaller areas, one to the north in T. 1 N., Rs. 97 and 98 W., and the other to the south in Tps. 2 and 3 S., R. 97 W. (fig. 2).

The evolution of the highly saline brines in Lake Uinta is controversial and not entirely understood, in large part because there is no modern analog (Smith, 1974, p. 71; Eugster and Hardie, 1978, p. 250). For discussions on the evolution of saline brines in Lake Uinta and Lake Gosiute see Bradley (1963), Smith (1974), Eugster and Hardie (1978), and Dyni (1974c, 1981). The importance of evaporation on lake-margin mud flats in producing concentrated brines has been stressed by many authors (Smith, 1974, p. 77; Ryder and others, 1976; Eugster and Hardie, 1978; Surdam and Stanley, 1979; Johnson, 1985, p. 272; Remy and Ferrell, 1989). Johnson (1985) demonstrated that these shallow lake-margin areas were tens of miles wide throughout much of the history of Lake Uinta. Remy and Ferrell (1989) proposed that evaporative pumping on exposed mud flats concentrated the moderately saline and alkaline lake waters, thereby producing Na-rich brines below the surface of the mud flats. According to Eugster and Hardie (1978, p. 245–246), complete evaporation on mud flats such as these produces effervescent crusts containing all the solutes previously present in the interstitial waters. Rainwater and dilute runoff would re-dissolve the most soluble salts, while the least soluble minerals, such as calcium-magnesium carbonates, would remain in the crusts. The carbonates could later be washed into the lake by flood waters. Other authors have argued that most of the carbonate found in the Parachute Creek Member precipitated directly from the lake waters (Dyni, 1974c, 1981; Smith, 1974).

Dyni (1981) suggested that the presence of nahcolite rather than trona is evidence that Lake Uinta was a deep, permanently stratified lake with a highly saline lower layer and a fresher upper layer as suggested by Bradley (1930, 1931, 1936, 1948, 1963, 1964) rather than a shallow playa-lake complex suggested by Eugster and Hardie (1978). Bradley and Eugster (1969) indicate that sodium carbonate brines in contact with the atmosphere generally have bicarbonate quotients of about 0.15 and precipitate trona, as in Lake Gosiute to the north during deposition of the Wilkins Peak Member of the Green River Formation. The precipitation of nahcolite, in contrast, would require a much higher bicarbonate quotient of about 0.45, leading Dyni (1981, p. 108–109) to suggest that the brines in the Piceance Basin were not in contact with the atmosphere, thus supporting the permanently stratified lake model.

Development of the Leached Zone in the Piceance Basin

The "leached zone" is defined as that part of the Parachute Creek Member of the Green River Formation in which nahcolite and halite have been leached out by groundwater movement, leaving behind solution cavities of varying sizes, collapse breccias, and open fractures that can greatly increase porosity, permeability, and groundwater storage capacity (Hite and Dyni, 1967; Dyni and others, 1970; Beard and others, 1974; Dyni, 1974c). Bradley (1931, pl. 5B) may have been the first to recognize the existence of the leached zone in the Piceance Basin when he noted large cavities that were once filled with radial aggregates of an unknown saline mineral in the Parachute Creek Member along lower Piceance Creek (fig. 2). Much later, after nahcolite had been discovered in the subsurface of the basin, Brobst and Tucker (1973, p. 6) speculated that the cavities along lower Piceance Creek probably once contained nahcolite. They (Brobst and Tucker, 1973) noted that the crystal cavities were in two intervals: the lower part of the Mahogany ledge and about 240 ft stratigraphically above the top of the ledge. Pipiringos and Johnson (1976) also noted solution cavities in the R-6 zone and B-groove in their measured section along lower Piceance Creek. Donnell (1961, p. 867) traced a persistent zone of solution cavities in the upper part of the Parachute Creek Member in measured sections along the Colorado River and its tributaries (fig. 1) in the southern part of the basin. Donnell (1961) noted that the solution cavities were from 280 to 345 ft above the Mahogany marker, a persistent tuff bed in the Mahogany ledge (fig. 3).

In general, the leached zone has been much less studied than the interval that still contains nahcolite and halite, largely because nahcolite is a leasable mineral. Dyni (1974c, p. 119), indicated that the extent of the leached interval had not been defined at the time of his study, but that solution breccias and cavities were present at least as high as A-groove (fig. 3). Trudell and others (1970) show vugs and collapse breccias extending stratigraphically upwards to near the top of the Parachute Creek Member in some of their plotted core descriptions from the central part of the basin. Day and others (2010, p. 6) noted that the permeability of the leached zone decreases towards the basin margins where the nahcolite facies "thins out or was not deposited."

The leached zone is a major water-bearing zone in the Piceance Basin, with reported transmissivities as high as 20,000 gallons of water per foot per day (Coffin and others, 1970). Several thick collapse breccias have been traced into thick unleached beds of halite and nahcolite (Dyni, 1974c, 1981). The base of the leached zone does not correspond to any one stratigraphic horizon (Dyni, 1974c, 1981; Brownfield and others, 2010a). In addition, small amounts of nahcolite have been noted above the lowest evidence of leaching in some areas (Beard and others, 1974, p. 102).

It is unclear when the dissolution began, but Dyni (1974c, p. 119) indicated that on the basis of the angularity of the collapse breccias and the preservation of open cavities, it must have started after the rocks were well lithified. Weeks and others (1974) and Robson and Saulnier (1981) presented considerable evidence that nahcolite and halite are still actively being dissolved by groundwater that is being recharged from exposures of the Green River and Uinta Formations around the margins of the basin. Saline groundwater is ultimately discharged from saline springs along lower Piceance Creek and lower Yellow Creek (fig. 2).

Weeks and others (1974) defined three aquifers in the basin: (1) alluvial aquifers, which are generally less than 140 ft thick and confined to alluvial valleys; (2) the upper aquifer, which includes the Uinta Formation and Parachute Creek Member of the Green River Formation above the top of the Mahogany zone; and (3) the lower aquifer, which includes that part of the Parachute Creek Member below the Mahogany zone (fig. 3). They (Weeks and others, 1974) believed that the Mahogany zone acted as a leaky confining layer and constructed a hydrologic model for the basin reproduced on figure 9. The high resistivity zone of Weeks and others (1974) is the interval that still contains intact saline minerals. Robson and Saulnier (1981, p. 7) further subdivided the upper aquifer into layer 1, Uinta Formation, and layer 2, Parachute Creek Member of the Green River Formation above the Mahogany zone. They apparently considered the contact between the two units to be a fairly persistent stratigraphic horizon. The complex intertonguing between the upper part of the Parachute Creek Member and the Uinta Formation (figs. 3, 4) had not yet been worked out at the time of their publication. Robson and Saulnier (1981) also subdivided the lower aquifer into layer 3, or Mahogany zone; layer 4, consisting of B-groove and the R-6 zone; and layer 5, consisting of that interval below the R-6 zone. Recently, Shell Exploration and Production Co. published the results of their extensive hydrologic studies in the northwestern part of the Piceance Basin near their oil shale holdings (Day and others, 2010). They (Day and others, 2010) identified a previously unidentified major seal, the R-5 seal in the uppermost part of the R-5 oil shale zone (fig. 3).

Water in the lower aquifer of Weeks and others (1974) is sodium bicarbonate–rich because of the ongoing dissolution of nahcolite and halite. Total dissolved solid concentrations of groundwater in the lower aquifer increases as intact nahcolite and halite are encountered, and the composition switches from a mixed cation bicarbonate type to a sodium bicarbonate type (Weeks and others, 1974; Robson and Saulnier, 1981). Water then moves upward from the lower aquifer, through the Mahogany zone, and into the upper aquifer, ultimately being discharged in saline springs along Piceance Creek and Yellow Creek in the northern part of the basin (figs. 2, 9). This upward movement is aided by fracture systems connecting the lower and upper aquifers (figs. 2, 9) near where the highly saline springs occur (Robson and Saulnier, 1981, p. 26). Springs near these fractures can have concentrations of dissolved solids as high as 22,100 milligrams per liter (Weeks and others, 1974, p. 19) and be accompanied by travertine deposits, indicating that calcite is near or at saturation (Robson and Saulnier, 1981, p. 29).

The Uinta Formation is hydrologically connected to the upper part of the Parachute Creek Member but is generally less permeable except where locally fractured (Robson and Saulnier, 1981, p. 6). Day and others (2010, p. 16) cite evidence of significant vertical permeability through joints in the Uinta Formation, particularly in the upper part.

Methods Used

The U.S. Geological Survey has collected a considerable amount of information on the Green River Formation, including core and cuttings stored at the U.S. Geological Survey Core Research Center in Lakewood, Colo; oil yield analyses from Fischer assays, recently compiled into databases and published (Mercier and others, 2010 a, b, 2011); and a large number of geophysical logs and core descriptions for oil shale coreholes in the Piceance Basin that were recently made available at the USGS Oil Shale Research homepage: http://energy.usgs.gov/OilGas/UnconventionalOilGas/OilShale/OilShaleDataDownload.aspx. These core descriptions were made by geologists at (1) the USGS, (2) the former U.S. Bureau of Mines, and (3) private companies that conducted oil shale research prior to the end of the last oil shale boom in the early 1980s. The U.S. Bureau of Mines data were acquired by the USGS when that agency was disbanded in 1996; the data from private companies were donated to the USGS. These unpublished core descriptions form the basis of this investigation.

The quality of these descriptions is highly variable, and many were considered unsuitable for the purposes of this investigation. A total of 57 core descriptions were considered detailed enough (fig. 10, table 1). In general, the descriptions used noted the presence of the vugs and collapse breccias formed from the dissolution of nahcolite and halite. Many of the core descriptions, in particular those made by the U.S. Bureau of Mines, included x-ray diffraction analyses that confirmed the presence or absence of nahcolite. In some instances, nahcolite-bearing intervals were identified from Fisher assay analyses, as nahcolite releases large amounts of water and carbon dioxide gas during decomposition. Both water and gas quantities are measured with Fischer assay (for a description of the method, see Brownfield and others, 2010a). It is not possible, however, to determine how much nahcolite was once present in a leached interval. Core descriptions rarely give quantitative estimates of the void space present, and there is no way to reliably estimate the original thickness of a nahcolite bed from a collapse breccia. In general, however, there appears to be fewer vugs and collapse breccias toward the outer margins of the leached zone as Day and others (2010) have suggested.

In addition, detailed descriptions of 28 surface sections were used in our analyses (fig. 10, table 2). Unfortunately, only the most conspicuous evidence for leaching is apparent in surface exposures. Small vugs, created by the leaching of individual nahcolite crystals or small aggregates, would likely be interpreted as differential weathering and not be noted. Breccias, due to dissolution and collapse, were not found in any of the measured sections.

A separate map was generated for each of the rich and lean oil shale zones within the saline interval (fig. 3). Each map shows the approximate areas were nahcolite is present today and where evidence of leaching indicates that nahcolite was once present. Extent of present-day nahcolite for each zone is generally from Brownfield and others (2010a) but was modified when necessary to reflect occurrences of nahcolite identified in this study that are outside the previously defined nahcolite resource areas. Extent of the leached zone and modifications to the digital maps of Brownfield and others (2010a) were done by hand. Each corehole on the maps is represented by a symbol indicating one of the following: (1) nahcolite is present and unleached, (2) nahcolite was present but is entirely leached, (3) nahcolite is only partially leached from the oil shale zone, or (4) there is no evidence that nahcolite was ever present. If only very minor nahcolite remains in a zone, it is plotted in the leached area. If it was deemed that significant nahcolite was still present in the zone, it is plotted in the nahcolite area.

In order to better understand the evolution of saline mineral deposition, additional information is included on all of the maps: (1) total in-place nahcolite in tons per acre (modified from Brownfield and others, 2010a), (2) extent of the marginal lacustrine facies (modified from Johnson, 1985), and (3) approximate area where oil shale exceeds 10 gallons per ton (GPT) (modified from Johnson and others, 2010a). In addition, some maps include (1) total in-place oil in barrels per acre (modified from Johnson and others, 2010a) and (2) isopach maps or partial isopach maps (modified from Johnson and others, 2010a). In some instances, a 10-GPT resource line was not present on the resource maps of Johnson and others (2010a) and one had to be extrapolated. The broad areas of marginal lacustrine deposition—more than 20 miles (mi) wide

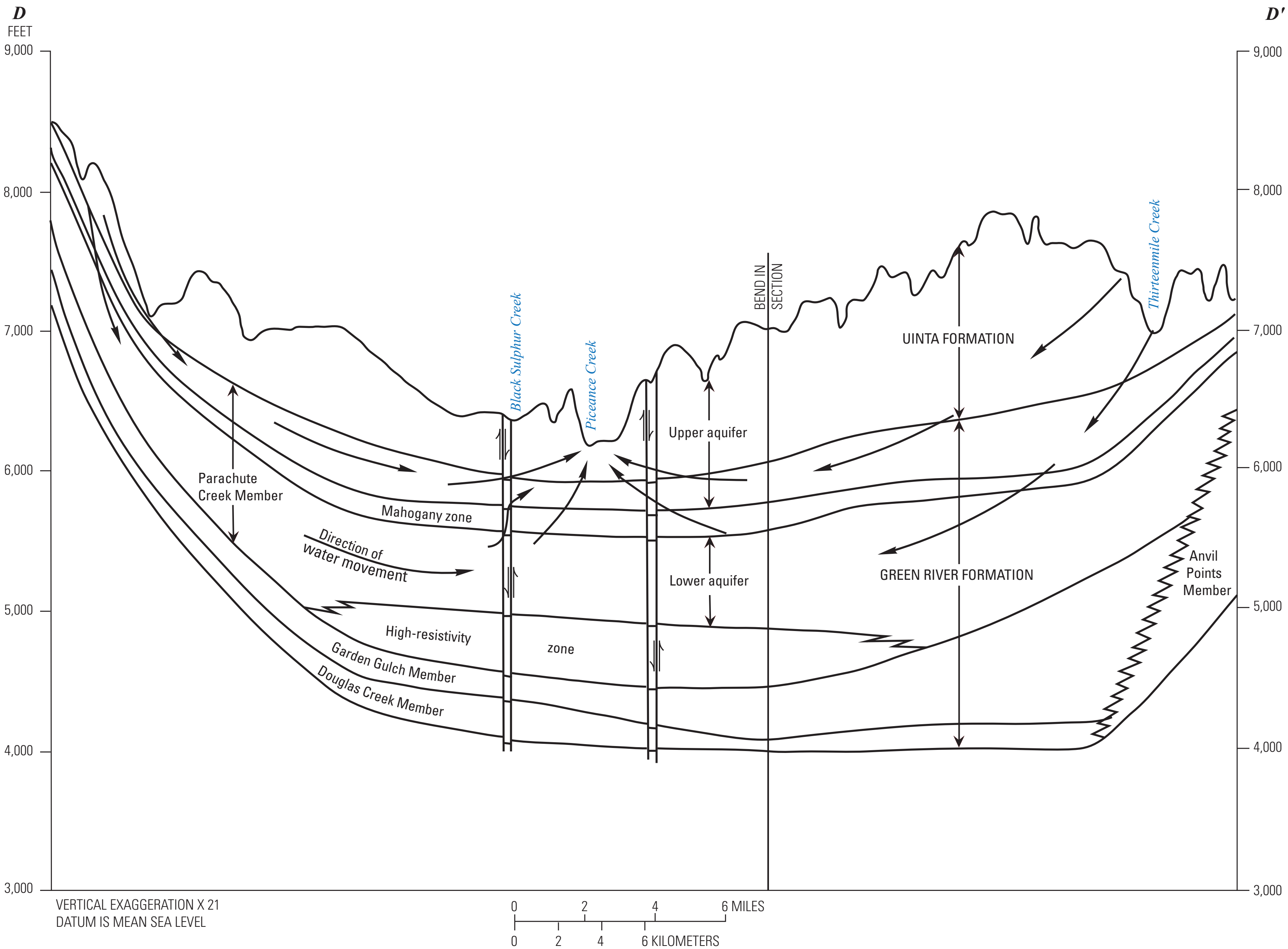


Figure 9. Geohydrologic cross section D-D′ through the Piceance Basin showing major aquifers as defined by Weeks and others (1974, fig. 18). See figure 2 for location of cross section.

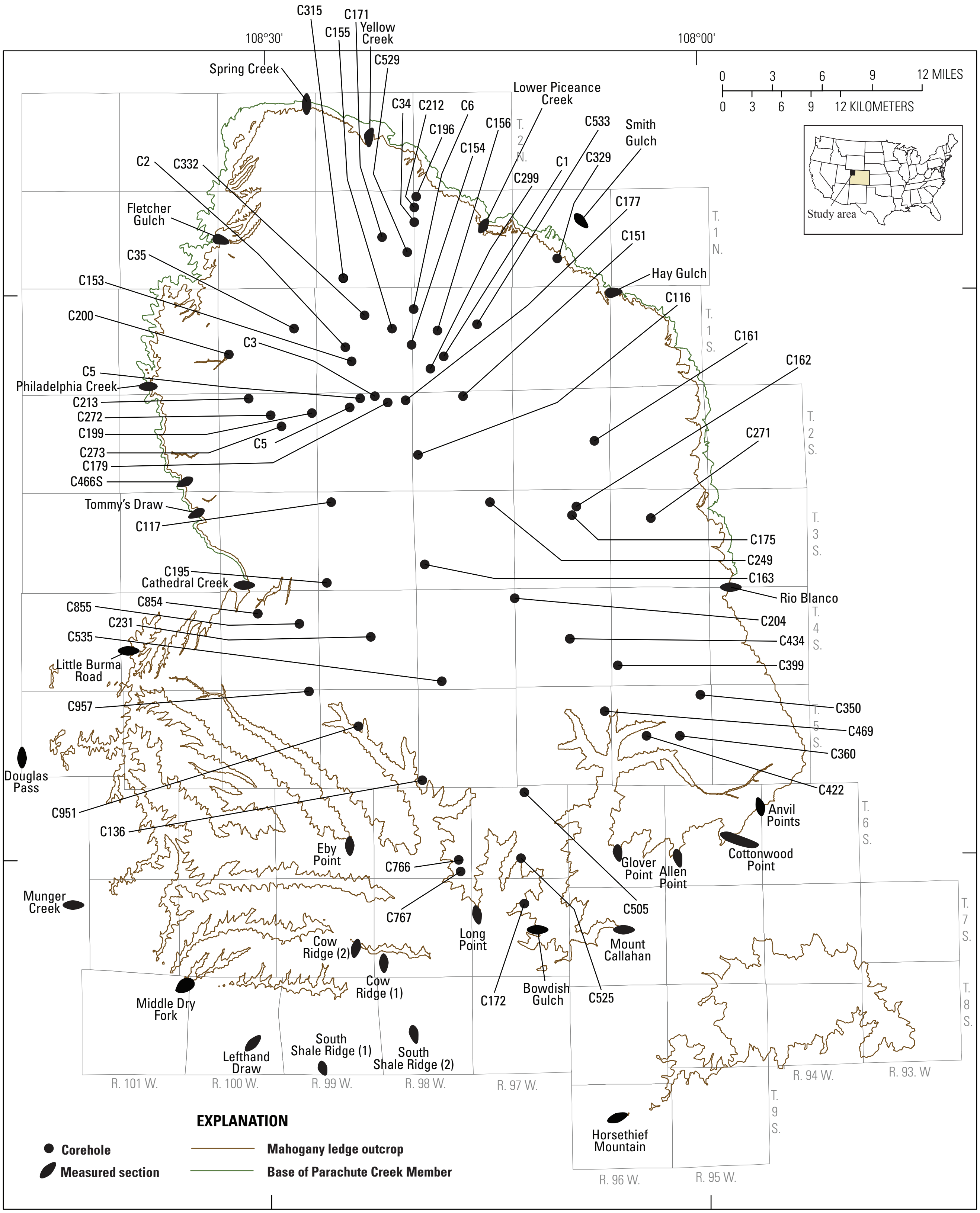


Figure 10. Map showing locations of coreholes and surface sections used in this investigation. Names of coreholes are listed in table 1, and names and sources of measured sections are listed in table 2.

Table 1. List of coreholes used in this study.

[All columns ending in "J" originated from J. Dyni's original tops file. ID, software-calculated identifier; FEL, from east line; FWL, from west line; FSL, from south line; FNL, from north line]

USGSIDJ Unique ID assigned by staff geologist	CMPNYPROJJ Name of the company or agency that drilled the borehole	NAMEJ Name of the borehole assigned by the company or agency that drilled it	EASTWESTJ Distance in feet measured east or west from section line	NORSOUJ Distance in feet measured north or south from section line	QQJ Quarter-quarter section	SECJ Secion	TWPJ Township	RANGEJ Range	LATDDJ Latitude in decimal degrees, NAD27, original record	LONGDDJ Longitude in decimal degrees, NAD27, original record
C0001	Kaiser Alum. & Chem. Co.	Nielsen 20-1	369 FEL	979 FSL	SE SE	20	01 S	097 W	39.945196	108.297279
C0002	Wolf Ridge Minerals Corp.	Dunn 20-1	1172 FEL	1197 FNL	NE NE	20	01 S	098 W		
C0003	Sinclair Oil and Gas Co.	Federal 8024	2640 FEL	2640 FSL	C	20	01 N	098 W	40.040780	108.414870
C0005	Juhan- Joe T.	Juhan 4-1	1947 FEL	1859 FNL	SW NE	4	02 S	098 W	39.907458	108.393696
C0006A	Sinclair Oil and Gas Co.	Federal strat 1 & 1-B	643 FWL	820 FSL	SW SW	6	01 S	097 W		
C0034	U.S. Bureau of Mines/AEC	Colorado 1	1284 FEL	2331 FSL	NE SE	13	01 N	098 W	40.054067	108.334852
C0035	U.S. Bureau of Mines/AEC	Colorado 2	2005 FEL	710 FNL	NW NE	14	01 S	099 W	39.969743	108.468959
C0116	Equity Oil Co.	Boies Corehole 1	1770 FWL	930 FSL	SE SW	19	02 S	097 W	39.857189	108.327264
C0117	Equity Oil Co.	BX-1	425 FEL	1870 FSL	NE SE	6	03 S	098 W	39.815737	108.426791
C0136	Getty Oil Co.	02-30	2258 FWL	767 FSL	SE SW	30	05 S	097 W		
C0151	Marathon Oil Co.	Square S No. 1	589 FWL	58 FNL	NW NW	4	02 S	097 W	39.530559	108.076026
C0153	Industrial Resources Inc.	Colorado Minerals 28-1	1360 FWL	400 FNL	NE NW	28	01 S	098 W		
C0154	Wolf Ridge Minerals Corp.	Savage 24-1	332 FEL	343 FNL	NE NE	24	01 S	098 W	39.955157	108.333725
C0155	Wolf Ridge Minerals Corp.	Colorado Minerals 14-1	1699 FEL	641 FNL	NW NE	14	01 S	098 W		
C0156	Kaiser Alum. & Chem. Co.	Nielsen 17-1	2566 FEL	905 FNL	NW NE	17	01 S	097 W	39.968728	108.304686
C0161	General Petroleum Corp.	11-24	500 FWL	500 FNL	NW NW	24	02 S	096 W	39.868147	108.124009
C0162	Equity Oil Co.	Oldland 3	450 FEL	425 FNL	NE NE	10	03 S	096 W	39.810205	108.146386
C0163	Equity-Exxon	Ebler 1/1-A	2035 FEL	2175 FNL	SW NE	30	03 S	097 W	39.761009	108.319351
C0171	U.S. Bureau of Mines/AEC	Colorado 3	210 FWL	640 FSL	SW SW	14	01 N	098 W	40.049687	108.367201
C0172	Shell Oil Co.	23X-10	1869 FWL	1781 FSL	NE SW	10	07 S	097 W	39.457747	108.208024
C0175	Atlantic Richfield Co.	Federal 2-B	1715 FEL	2261 FSL	NW SE	10	03 S	096 W	39.803203	108.150810
C0177	Shell Oil Co.	22X-1	2610 FEL	2260 FNL	SW NE	1	02 S	098 W	39.905936	108.342236
C0179A	Shell Oil Co.	23X-2	1580 FWL	2325 FSL	NE SW	2	02 S	098 W	39.905464	108.362240
C0195	Arco-Mobil-Equity	Figure Four 31-1	2060 FEL	2660 FSL	SW NE	31	03 S	098 W	39.745351	108.431843
C0196	Superior Oil Co.	Core hole 10	355 FWL	1735 FNL	SW NW	6	01 N	097 W	40.086293	108.328794
C0199	Occidental Petroleum Co.	Stake Springs Draw 1	1650 FEL	600 FNL	NW NE	12	02 S	099 W	39.896554	108.449163
C0200	Mintech Corp.	Portland 1	1775 FEL	1475 FSL	SW SE	19	01 S	099 W	39.946964	108.543352
C0204	Tosco Corp.	TG-71-4	125 FWL	2200 FSL	NW SW	6	04 S	096 W	39.730208	108.216959
C0212	Superior Oil Co.	Core hole 15	250 FWL	150 FSL	SW SW	7	01 N	097 W	40.062682	108.329305
C0213	Cameron Engineers	CE-708	975 FEL	1250 FNL	NE NE	5	02 S	099 W	39.909507	108.521838
C0231	Humble Oil & Refining Co.	Jumps Cabin 1	550 FWL	925 FSL	SW SW	15	04 S	098 W	39.696879	108.383914
C0249	Arco (C-b project)	Sorghum Gulch 01	1946 FEL	1314 FSL	SE	2	03 S	097 W	39.814632	108.243464
C0271	Carter Oil Co.	Upper Piceance Creek 2	1950 FWL	1250 FSL	SE SW	9	03 S	095 W	39.799985	108.062792

Table 1. List of coreholes used in this study.—Continued

[All columns ending in “J” originated from J. Dyni’s original tops file. ID, software-calculated identifier; FEL, from east line; FWL, from west line; FSL, from south line; FNL, from north line]

USGSIDJ Unique ID assigned by staff geologist	CMPNYPROJJ Name of the company or agency that drilled the borehole	NAMEJ Name of the borehole assigned by the company or agency that drilled it	EASTWESTJ Distance in feet measured east or west from section line	NORSOUJ Distance in feet measured north or south from section line	QQJ Quarter-quarter section	SECJ Secion	TWPJ Township	RANGEJ Range	LATDDJ Latitude in decimal degrees, NAD27, original record	LONGDDJ Longitude in decimal degrees, NAD27, original record
C0272	Rio Blanco Oil Shale Co.	C-14	810 FWL	3800 FSL	SW NW	10	02 S	099 W	39.894147	108.496591
C0273	Rio Blanco Oil Shale Co.	C-15	825 FEL	400 FSL	SE SE	10	02 S	099 W	39.884738	108.483491
C0299	U.S. Bureau of Mines	CH 02-A	1087 FWL	2387 FSL	NW SW	29	01 S	097 W	39.933973	108.310258
C0315	Exxon Co.	Pinto Gulch 1	1800 FEL	1800 FNL	SW NE	32	01 N	098 W	40.014219	108.411883
C0329	Carter Oil Co.	Opportunity 2	2150 FEL	850 FNL	NW NE	28	01 N	096 W	40.030878	108.167599
C0332	Carter Oil Co.	Yellow Creek 2	300 FEL	1450 FNL	SE NE	9	01 S	098 W	39.981678	108.387471
C0350	U.S. Navy	Core hole 15/16 (NOSR 1)	1330 FWL	3109 FNL	NW SW	1	05 S	095 W	29.642966	108.007154
C0360	U.S. Navy	Core hole 20 (NOSR 1)	610 FWL	1251 FSL	SW SW	14	05 S	095 W	39.610091	108.028503
C0399	Union Oil Co.	Fay 6-75	2275 FWL	1600 FSL	NE SW	30	04 S	095 W		
C0422A	Union Oil Co.	LR 4-75	2535 FEL	1685 FNL	SW NE	20	05 S	095 W	39.602016	108.076807
C0434	Union Oil Co.	Mary Ann 32/32B	390 FNL	2450 FEL	NW NE	22	04 S	096 W	39.693710	108.153749
C0469	Exxon Co.	CD-18	1650 FEL	2850 FNL	NW SE	12	05 S	096 W		
C0505A	Cities Service Oil Co.	Core hole 3	2320 FEL	2940 FNL	NW SE	3	06 S	097 W	39.556342	108.204450
C0525	Cities Service Oil Co.	Core hole 5	1295 FEL	615 FSL	SE SE	22	06 S	097 W	39.503078	108.200599
C0529	Exxon Co.	Yellow Creek 3	1850 FEL	1450 FSL	NW SE	24	01 N	098 W	40.037358	108.336842
C0533	Exxon Co.	Cole Gulch 1A	300 FWL	350 FSL	300	11	01 S	097 W	39.972881	108.257450
C0535	Exxon Co.	Ten Section 1			SE SW	32	04 S	097 W		
C0766	Shell Oil Co.	DH 5 (Pacific Property)	2510 FEL	2590 FSL	NW SE	25	06 S	098 W		
C0767	Shell Oil Co.	DH 6 (Pacific Property)	4560 FEL	2250 FNL	SW NW	36	06 S	098 W		
C0854	Arco-Mobil-Equity	Figure Four 09-1	2734 FWL	2165 FNL	SW NE	9	04 S	099 W		
C0855	Arco-Mobil-Equity	Figure Four 14-1	4653 FWL	2406 FSL	NE SE	14	04 S	099 W		
C0951	Chevron Oil Co.	CC-20	1997 FWL	418 FSL	SE SW	9	05 S	098 W		
C0957	Chevron Oil Co.	CC-26	1878 FEL	71 FNL	NW NE	2	05 S	099 W		

Table 2. List of surface sections used in this study.

Section Name	Source
Yellow Creek	Self and others (2010)
Lower Piceance Creek	Johnson (2012)
Smith Gulch	Johnson (unpub. section)
Hay Gulch	Johnson (unpub. section)
Rio Blanco	Johnson (unpub. section)
Anvil Points	Self and others (2010)
Cottonwood Point	Donnell (1961)
Allen Point	Donnell (1961)
Glover Point	Donnell (1961)
Mount Callahan	Donnell (1961)
Horsethief Mountain	Johnson and May (1978)
Bowdish Gulch	Donnell (1961)
Long Point	Johnson (1975)
South Shale Ridge (1)	Johnson and May (1978)
South Shale Ridge (2)	Johnson and May (1978)
Cow Ridge (1)	Johnson (1975)
Cow Ridge (2)	Johnson (1977)
Eby Point	Johnson (1977)
Lefthand Draw	Johnson and May (1978)
Middle Dry Fork	Johnson and others (1988)
Munger Creek	Johnson and others (1988)
Douglas Pass	Johnson and others (1988)
Little Burma Road	Johnson and others (1988)
Cathedral Creek	Roehler (1972)
Tommy's Draw	Johnson and others (1988)
Philadelphia Creek	Johnson and others (1988)
Fletcher Gulch	Johnson and others (1988)
Spring Creek	Self and others (2010)

in the southern part of the Piceance Basin and about 45 mi wide in the eastern Uinta Basin (figs. 4, 5)—will be referred to here as marginal shelves, as a distinct break in slope at the outer edge of these marginal areas can be documented using isopach maps. The limit of the marginal lacustrine facies shown was not extended beyond present day outcrop, thus the widths of marginal lacustrine facies stated here are minimum widths.

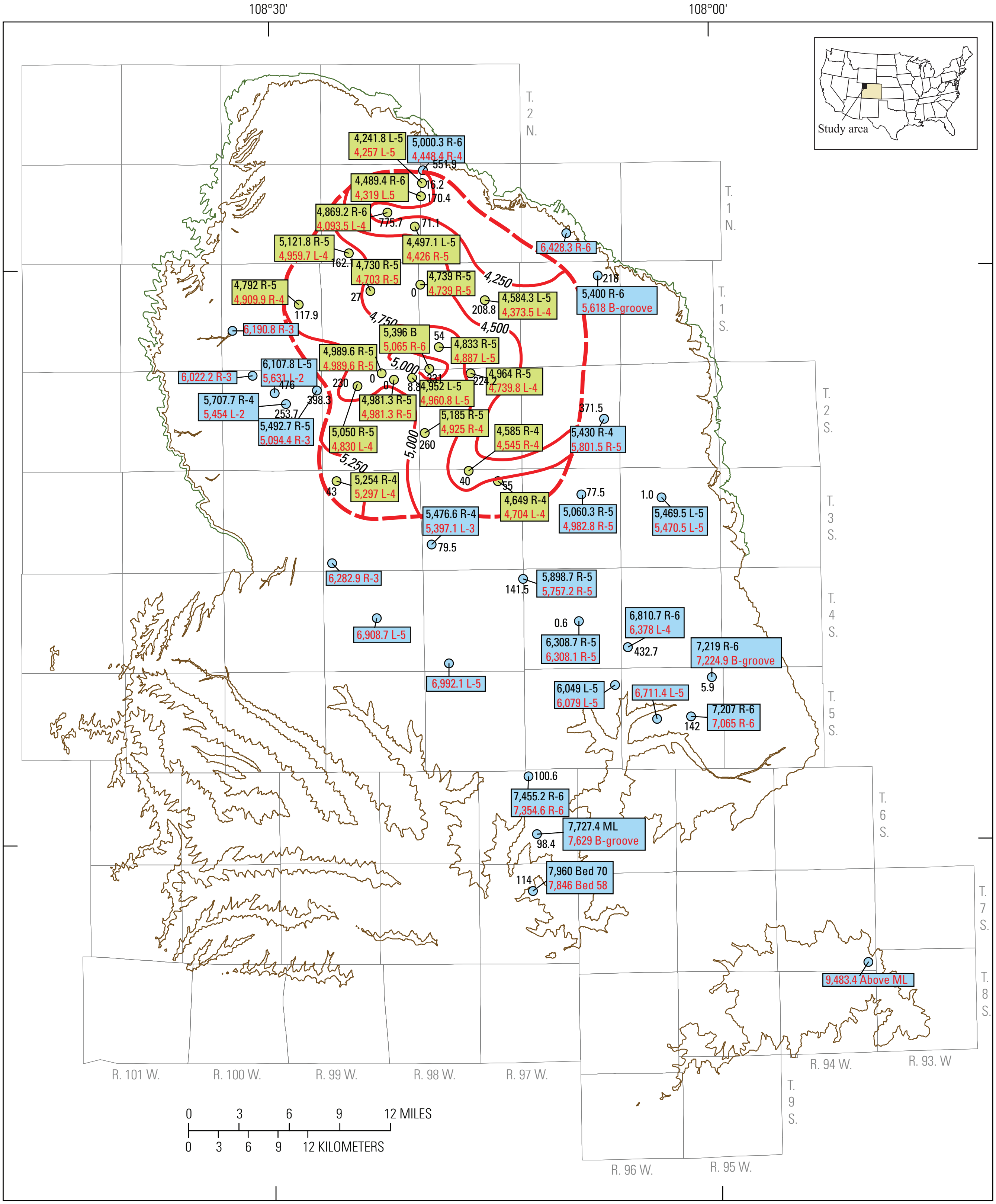
Two detailed cross sections, constructed from coreholes and measured sections, are also presented (pls. 1, 2). Datum is sea level, so the relationship between leaching of saline minerals and the structure of the basin can be studied. The cross sections were constructed by combining several cross sections recently published by Self and others (2010). In some instances, coreholes with detailed lithologic descriptions were added and some without detailed descriptions were removed. Detailed lithologic descriptions are included for the measured sections shown on the cross sections (pls. 1, 2). Oil-yield histograms are shown for each corehole, and intervals that contain nahcolite and halite and evidence of leaching are identified. Water content from Fischer assay analyses were used to determine the presence or absence of nahcolite in some of the coreholes (Brownfield and others, 2010a). Many of the coreholes were drilled in the bottom of drainages with significant thicknesses of strata exposed on nearby valley walls. This stratigraphic information (as much as 820 ft of additional strata) was added using available 7½-minute geologic quadrangle maps. For a recent summary of geologic quadrangle mapping in the Piceance Basin, see Johnson (2012).

Results of Data Analyses

Most of the information collected for this study is summarized on Figure 11, which shows for each corehole examined (1) the elevation of highest preserved nahcolite and (or) halite, in feet, and the R-zone in which it occurs; and (2) the elevation of the top of continuous nahcolite and (or) halite (lowest evidence of leaching), in feet, and the R-zone in which it occurs. In addition, different colored boxes are used to highlight whether leaching reached the base of the saline interval. Permeability of oil shale is typically very low, and fractures are needed for groundwater penetration. Occurrences of nahcolite above the lowest evidence of leaching probably represent intervals where fractures are not present. In some core descriptions it was noted that nahcolite was present but eroded. It is assumed here that this erosion occurred as a result of contact with drilling fluids. In some instances, where nahcolite is generally sparse in the corehole, there can be a significant vertical distance between the lowest vugs and the highest nahcolite. The lowest evidence of leaching represents the maximum depth of penetration of groundwater into the saline interval.

Present-Day Elevation of the Leached Zone

A structure contour map on the base of the leached zone, or the lowest evidence of leaching, is included on figures 11 and 12; additionally, figure 12 includes a structure contour map of the top of the Mahogany zone. Elevation of the base of leaching presented here is similar to the elevation on the base of the lower aquifer of Robson and Saulnier (1981, fig. 9). The base of leaching has reached the base of the saline zone beyond the dashed red line. Elevation of the base of leaching varies from more than 5,250 ft in the southwest, near recharge areas along the west margin of the basin, to less than 4,200 ft near discharge areas along lower Piceance Creek and Lower Yellow Creek in the northern part. Elevation of the base of leaching generally increases over the Piceance Creek dome (fig. 12), similar to that shown by Robson and Saulnier (1981,


108°30'
108°00'
40°00'
39°30'
Study area
4,250
4,500
4,750
5,000
5,250
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
0 3 6 9 12 MILES
0 3 6 9 12 KILOMETERS

EXPLANATION

6,308.7 R-5 — Elevation of highest preserved leaching, in feet, and oil shale zone in which it occurs.
6,308.1 R-5 — Elevation of lowest evidence of leaching, in feet, and oil shale zone in which it occurs.
If box not colored then corehole was not drilled to base of saline interval.

6,308.7 R-5 / 6,308.1 R-5 — Leaching has not reached the base of the saline interal.

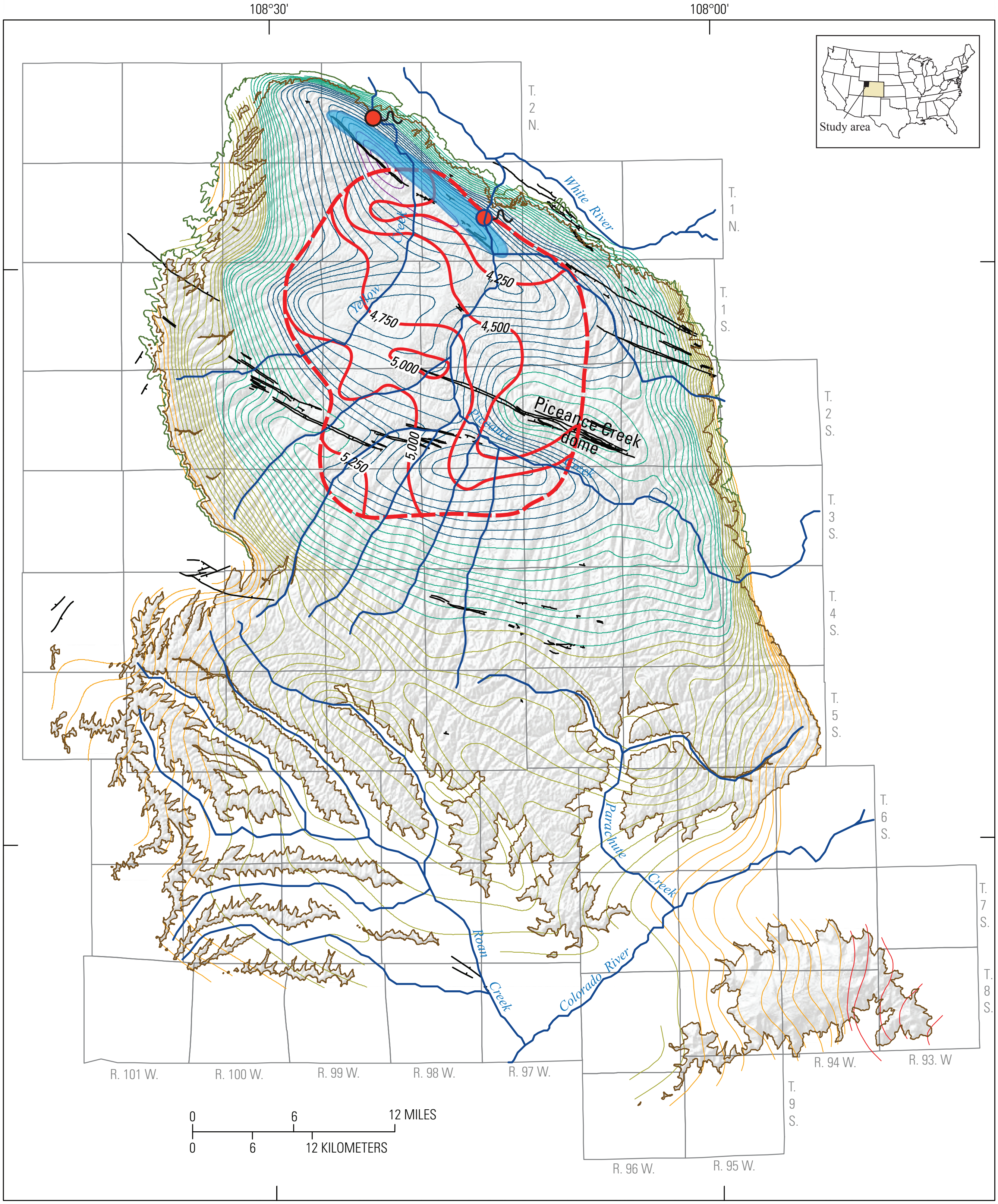
7,207 R-6 / 7,065 R-6 — Leaching has reached the base of the saline interval.

Mahogany ledge outcrop

Base of Parachute Creek Member

Elevation of base of leached zone.
Contour interval 250 feet.

Figure 11 (previous page). Map showing elevations of the highest occurrence of nahcolite and the lowest evidence of leaching of the saline interval. Structure contour map is based on elevation of the lowest evidence of leaching. Beyond the dashed contour line, the base of leaching has reached the base of the saline zone.



108°30'
108°00'
40°00'
39°30'
Study area
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
White River
Yellow Creek
Piceance Creek
Piceance Creek dome
4,250
4,500
4,750
5,000
5,250
Parachute Creek
Roan Creek
Colorado River
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

EXPLANATION

Elevation of top of Mahogany zone. Contour interval 100 feet.

- > 9,000
- 8,001–9,000
- 7,001–8,000

Elevation of base of leached zone. Contour interval 250 feet.

Mahogany ledge outcrop

Base of Parachute Creek Member

Figure 12 (previous page). Structure contour map based on the lowest evidence of leaching (heavy red lines) and structure contour map based on the top of the Mahogany oil shale zone (modified from Mercier, 2010). Locations of highly saline springs and the zone of faulting and fracturing in the north part of basin are from Weeks and others (1974) and Robson and Saulnier (1981).

fig. 9). The base of leaching clearly cuts across stratigraphic units as Dyni (1974c) indicated. This cross-cutting relationship can also be seen on the two detailed cross sections constructed for this study (pls. 1, 2).

Saline Mineral Deposition and Extent of Leaching for Each Rich and Lean Zone

For convenience in discussing the evolution of the saline mineral deposition, the “history” of the evolution of Lake Uinta is informally subdivided into four phases: (1) illitic phase that begins with the Long Point transgression and extends to the base of the R-2 zone; (2) early saline mineral phase, extending from the base of the R-2 zone to the top of the L-3 zone; (3) middle saline mineral phase, extending from the base of the R-4 zone to the top of A-groove; and (4) late saline mineral phase that includes all lacustrine strata above A-groove (figs. 3–5). Although the illitic phase predates the onset of saline mineral deposition, lake-margin shelf progradation during this period influenced many aspects of the saline mineral and oil shale deposition throughout the saline phases of Lake Uinta that followed. It is thus important to briefly discuss the illitic phase here.

Figure 13 presents schematic cross sections of the Piceance Basin for three times: (1) at the end of the freshwater lake (Lake Cow Ridge) period that predated the development of Lake Uinta; (2) at maximum transgression after the Long Point transgression formed Lake Uinta, or beginning of the illitic phase; and (3) at the end of the illitic phase. The cross sections extend from the crest of the Douglas Creek arch on the west to the White River uplift on the east. Prior to the development of Lake Uinta, the Douglas Creek arch acted as a sort of hingeline, with rates of subsidence increasing to the east toward the White River uplift. Only a thin interval of pre–Lake Uinta, early Tertiary strata is preserved on the crest of the arch (fig. 4, 13*A*). Although a fairly thick interval of Lake Uinta sediments were deposited over the crest of the arch (fig. 4), the interval from the base of Long Point Bed to the top of Mahogany oil shale zone thickens markedly to the east in the Piceance Basin (Johnson and Finn, 1986, fig. 12), indicating that overall rates of subsidence increased to the east throughout much if not all the history of Lake Uinta. The schematic cross section shown in figure 13 and subsequent schematic cross sections presented in this report assume that subsidence rates increased toward the White River uplift throughout the history of Lake Uinta.

A freshwater lake, Lake Cow Ridge, surrounded by alluvial plains, occupied the Piceance Basin immediately prior to the Long Point transgression (figs. 4, 5, 13*A*). Both the depth of Lake Cow Ridge and the slope of the alluvial plains that surrounded it are unknown, but a combination of the two controlled the topography and depth of early Lake Uinta (fig. 13*B*), and thus had some impact on the saline mineral area that developed later. About 600–700 ft of nearly continuous oil shale was deposited in the center of Lake Cow Ridge prior to the development of Lake Uinta. Only Fischer assay data from cuttings samples taken every 10 ft are available for this oil shale sequence, but on the basis of this limited dataset, the oil shale averaged about 5–10 GPT (R.C. Johnson, U.S. Geological Survey, unpub. data, 1977). The depth of Lake Cow Ridge prior to the Long Point transgression is unknown, but it may not have been shallow, as it lasted as long as 3 million years, depositing near continuous low-grade oil shale for about the last half of its existence.

Illitic Phase

The illitic phase of Lake Uinta began with the Long Point transgression, when two freshwater lakes, one in the Piceance Basin and one in the Uinta Basin, expanded and coalesced across the Douglas Creek arch to form Lake Uinta (fig. 4). During the Long Point transgression, the lake expanded across the surrounding alluvial plain about 10 to 12 mi to the east (fig. 13*B*) and nearly 40 mi to the south before maximum transgression was reached (Johnson, 1985, figs. 7, 8). Again, the slope of the alluvial plain is unknown, but the difference in the distance of transgression suggests that the slope to the south was much gentler than that of the slope to the east. The R-0 oil shale zone is directly above the Long Point Bed and represents the first and one of the most widespread oil shale zones deposited in Lake Uinta. It was deposited over large areas of both the Piceance and Uinta Basins (figs. 4, 5) (Johnson, 1985, fig. 8; Mercier and Johnson, 2012, figs. 6–8). The salinity of Lake Uinta began to increase very early on, as freshwater mollusks do not occur above the basal transgressive bed, the Long Point Bed (Johnson, 1985).

Lake-margin shelves began to prograde into Lake Uinta after maximum transgression, reaching widths in the Piceance Basin of more than 20 mi to the southeast, south, and southwest, and 2–5 mi to the east by the end of the illitic phase (figs. 4, 5, 13). This is a minimum width, as a significant part of the marginal facies has been removed by relatively recent downcutting on the perimeter of the basin by the Colorado River and White River drainage systems (fig. 1). The illitic interval is thickest on the marginal shelf areas and thinnest in the deep lake area (fig. 14). The deep lake area defined by marginal shelf progradation during the illitic phase developed almost directly over the offshore area of the preceding Lake Cow Ridge (fig. 14). Thus, the depth of the earlier freshwater lake contributed directly to the depth of Lake Uinta at the end of the illitic phase, as shown in figure 13. Marginal lacustrine rocks from the illitic phase of Lake Uinta include stromatolites, ostracodal and oolitic limestone, sandstone, and carbonate-rich mudstone (Johnson, 1985; Johnson and others, 1988), whereas offshore rocks consist almost exclusively of dark-gray to black illitic oil shale. The amount of sandstone in the marginal lacustrine facies increases in the southeastern part of the basin, where a major drainage entered Lake Uinta.

Water depth on the marginal shelves undoubtedly fluctuated because of variations in water supply and evaporation in the lake that was now internally drained, but conditions were

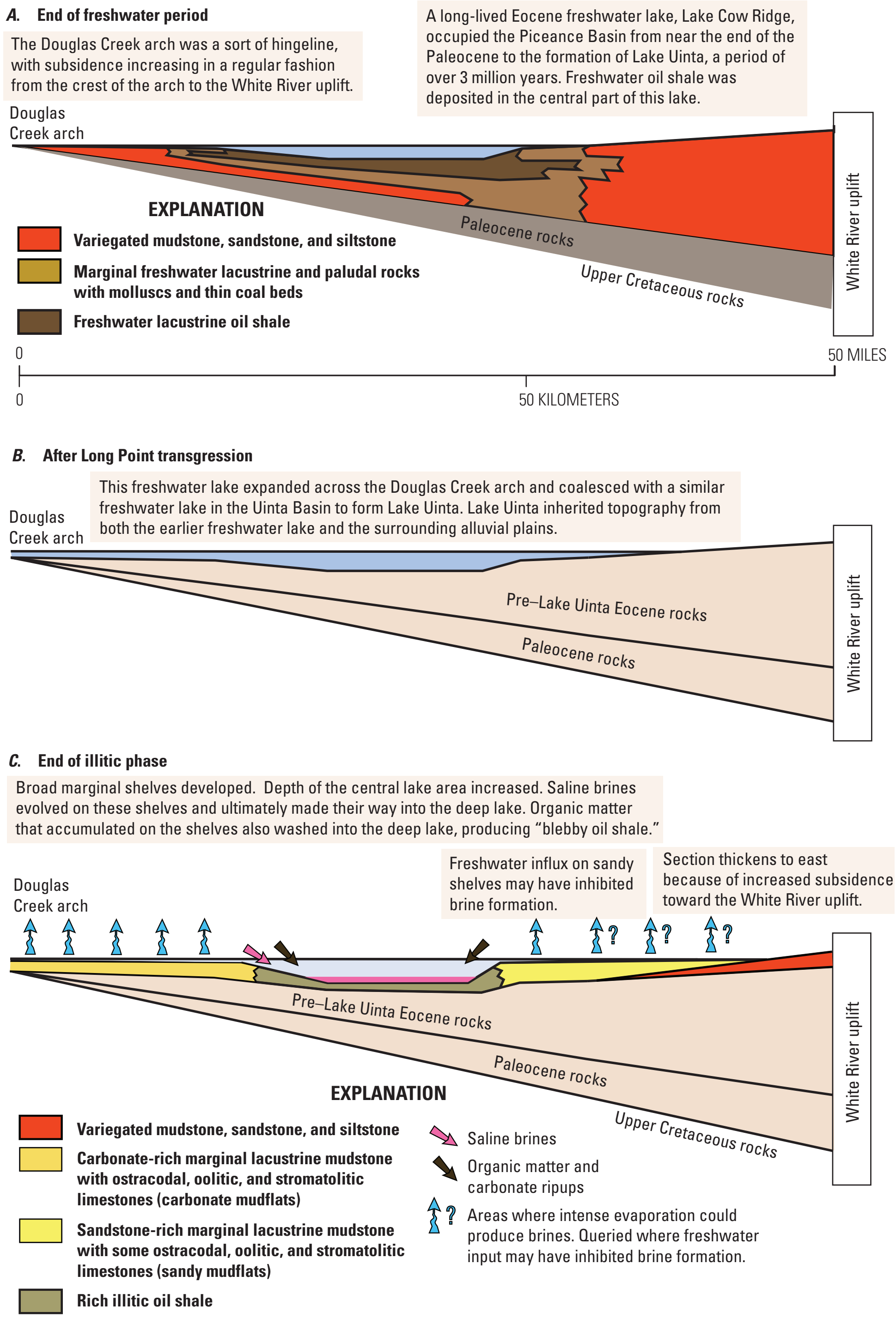
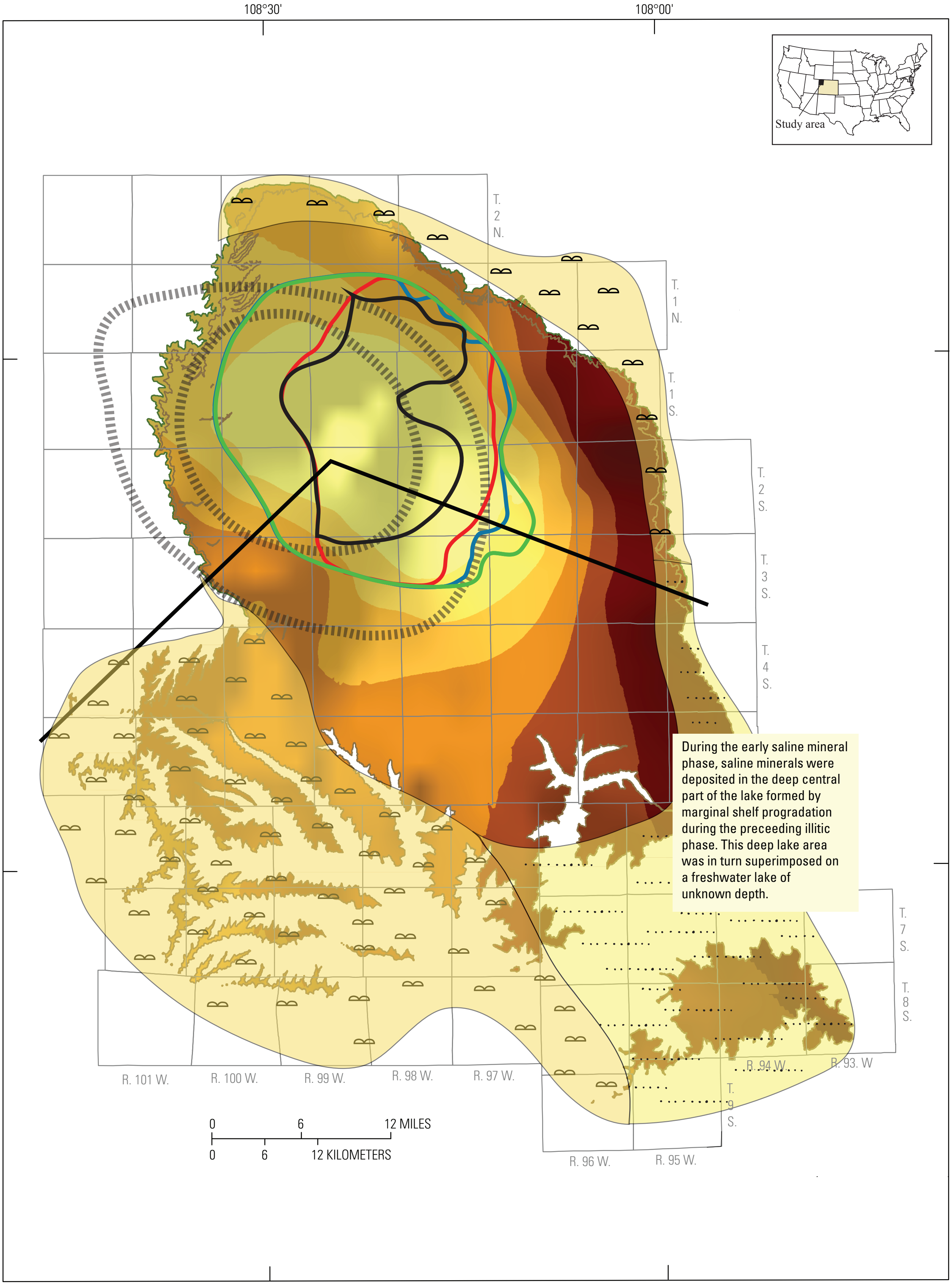


Figure 13. West-to-east schematic cross section across the Piceance Basin for three time periods. *A*, End of the freshwater period. *B*, After the Long Point transgression. *C*, End of the illitic phase. Approximate line of section shown on figure 14.


108°30'
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Study area
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS
During the early saline mineral phase, saline minerals were deposited in the deep central part of the lake formed by marginal shelf progradation during the preceeding illitic phase. This deep lake area was in turn superimposed on a freshwater lake of unknown depth.

EXPLANATION

Marginal lacustrine facies

Carbonate-rich marginal lacustrine

Sandstone-rich marginal lacustrine

Thickness from R-2 zone to base of Long Point Bed. Countour interval 100 feet.

300–400

400–500

500–600

600–700

700–800

800–900

L-2 saline mineral area

L-3 saline mineral area

R-2 saline mineral area

R-3 saline mineral area

Extent of marginal lacustrine facies just prior to Long Point Transgression

Extent of offshore lacustrine facies just prior to Long Point Transgression

Location of cross section in Fig. 13

Figure 14 (previous page). Map of the Piceance Basin at the end of the illitic phase showing (1) extent of offshore and marginal lacustrine facies at the end of the freshwater phase that pre-dated the illitic phase of Lake Uinta (modified from Johnson, 1985, fig. 7), (2) extent of marginal lacustrine shelves at the end of the illitic phase (modified from Johnson, 1985, fig. 10), (3) thickness of the illitic phase, from the base of the Long Point Bed to the top of the L-1 zone (new to this report), (4) limits of saline mineral deposition during each of the four oil shale zones that compose the early saline mineral phase (modified from Brownfield and others, 2010a), and (5) approximate line of section for schematic cross section shown in figure 13 (heavy black line).

probably suitable for the formation of brines and salt crusts during periods when large areas of the shelves were exposed. It is proposed here that highly saline brines evolved on these marginal shelves and that these brines ultimately made their way into the deep central lake area, helping to create a deep brine layer in a permanently stratified Lake Uinta as envisioned by Bradley (1963) (fig. 13*C*).

Organic matter and mineral matter that accumulated on the marginal shelves may also have been transported into the deep central lake area. Most of the oil shale found in outcrop around the margins of the basin consists of the classic Green River laminated oil shale interpreted as varved by Bradley (1930, 1931), who noted, however, that a few oil shale beds around the basin margins possessed a "blebby and streaked" fabric that he believed was formed from subaerial exposure and desiccation (figs. 15, 16). Dyni and Hawkins (1981), in a subsurface study of the central part of the basin, indicated that blebby oil shale can compose more than 50 percent of the strata there, with the remainder being well laminated. They (Dyni and Hawkins, 1981) noted the lack of shallow-water indicators, such as mudcracks, algal structures, and oxidized zones, and suggested instead that blebby oil shale was a deep water deposit that had been laterally transported, in part by turbidity currents down sloping surfaces on the floor of Lake Uinta. In general, blebby oil shale consists of clasts that vary in size from near-microscopic to several inches across in a very fine kerogen-rich matrix (figs. 15, 16). Clasts vary from massive to well laminated and are most commonly dolomitic marlstone (Dyni and Hawkins, 1981). Dolomitic marlstone is one of the most abundant lithologies found in the marginal lacustrine facies (see, for example, Johnson and others, 1988). Tanavsuu-Milkeviciene and Sarge (2012) recently published cross sections based on detailed core descriptions that document the increase in blebby oil shale toward the center of the deep lake area. It is proposed here that the blebby oil shale largely originated on the marginal shelves and was transported into the deep central lake area by mass-movement processes. As we are also proposing that brines were transported to the deep central lake area from the marginal shelves, it is possible that both brines and blebby oil shale were transported together. This hypothesis requires further study.

A paleogeographic map at the end of the illitic phase that includes both the Piceance and Uinta Basins is shown in figure 17. Maximum preserved width of marginal shelves in the Uinta Basin at the end of the illitic phase is about 45 mi in the southern part of the basin, where a major drainage entered the lake from the south. Offshore oil shale deposition in the Uinta Basin was confined to a narrow east-west trending trough in the northern part of the basin south of the Uinta uplift (fig. 1). As there are no known saline mineral deposits in the Uinta Basin for the early and middle saline mineral phases, it is likely that any brines that formed on the broad marginal shelves in the Uinta Basin were transported into the deep lake area in the north-central part of the Piceance Basin, as shown on figure 17. The movement of brines from the Uinta Basin into the Piceance Basin was previously proposed by Dyni (1987). Brine formation is queried in areas were major rivers entered Lake Uinta to produce sandy shelf deposits, as freshwater input may have inhibited brine formation in these areas.

Early Saline Mineral Phase

The early saline phase consists of the R-2 through L-3 oil shale zones. The saline mineral area during this phase was confined to a limited area in the north-central part of the basin, where marginal shelf progradation during the earlier illitic phase produced a deep lake area (fig. 14). Figure 18 shows where each of the four zones that compose the early saline mineral phase is thickest. The R-2, L-2, and R-3 oil shale zones are thickest along the southern margin of the deep central lake area, with the thick area for each succeeding zone slightly farther to the north than that of the preceding zone. This is consistent with sediment being transported from the shelf, down the slope, and accumulating at the break in slope along the southern margin of the deep central lake area. There appears to have been minimal change in the position of the shelf edge during deposition of the early saline mineral phase, and the shelf edge is shown at the same position for all four zones that compose this phase (figs. 19–22).

The first occurrence of nahcolite in the Piceance Basin is in the form of scattered disseminated crystals and crystalline aggregates in the upper part of the R-2 zone in a limited area in the north-central part of the basin (Dyni, 1974c; Dyni, 1981, pl. 1) (fig. 19). A shift from illitic oil shale to dolomitic oil shale also occurred in the R-2 zone. No evidence of saline leaching from the R-2 zone has been reported, and thus the present-day extent of saline minerals is the same as the maximum extent. Total in-place nahcolite in the R-2 zone is quite small, with a maximum of 13,248 tons per acre (Brownfield and others, 2010a, fig. 18).

The saline mineral area expanded significantly during L-2 time, covering an irregularly shaped area extending from the northern part of T. 2 S., R. 98 W. to the southern part of T. 1 N., R. 97 W. (fig. 20). Nahcolite is confined largely to an interval about 10 ft thick in the lowest part of the L-2 zone and consists of nahcolite beds, bands, and aggregates (Dyni, 1974c, 1981). Total nahcolite in place has increased markedly compared to the R-2 zone, to a maximum of more than 75,000 tons per acre (Brownfield and others, 2010a). Evidence of leaching, in the form of empty vugs, occurs in two coreholes in sec. 10, T. 2 S., R. 99 W. (fig. 20, pl. 1), west of the main nahcolite area in T. 2 S., R. 99 W. The area of 10-GPT-or-greater oil yield has contracted when compared with the underlying R-2 zone (figs. 19, 20).

The area of nahcolite deposition increased again during R-3 time, covering much of the deep central lake area (fig. 21). Nahcolite occurs as disseminated crystals, aggregates, and discrete beds throughout the R-3 zone, with maximum in-place values of as much as 135,000 tons per acre (Brownfield and others, 2010a). For the first time, there is abundant evidence for widespread leaching of nahcolite along the western margin of the saline mineral area and downdip from outcrops

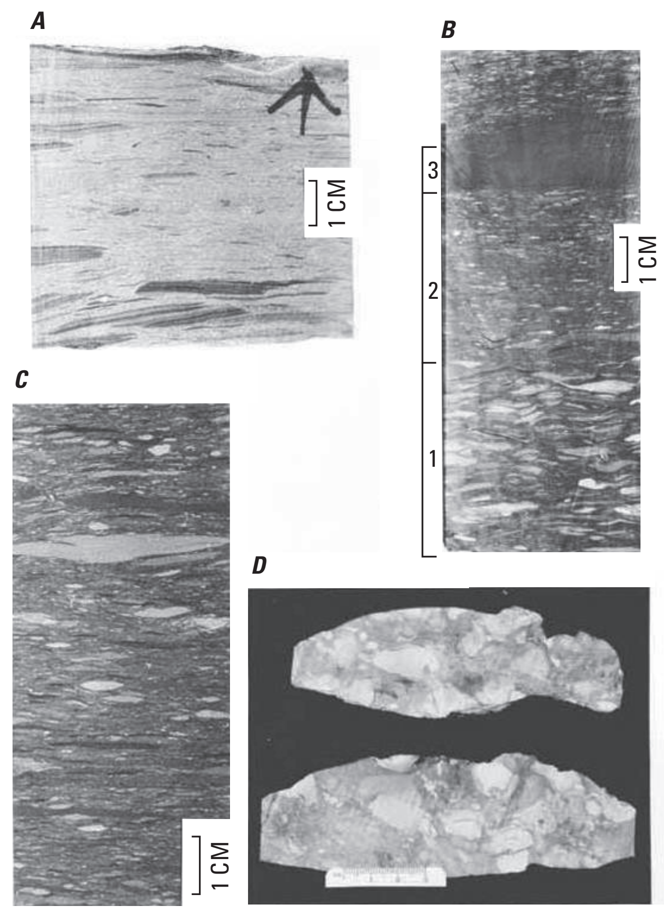


Figure 15, Photographs of slabbed core and mine rock. *A*, Streaked oil shale containing large flat clasts of laminated marlstone. *B*, Blebby oil shale displaying graded bedding. *C*, Blebby oil shale containing unsorted clasts of nonlaminated marlstone. *D*, Blebby marlstone cut parallel to bedding. From Dyni (1981, fig. 12).

along the western margin of the basin (fig. 21). Leached and unleached intervals alternate in the R-3 zone in two coreholes in T. 2 S., R. 99 W. The 10-GPT-or-greater oil shale area expanded during deposition of the R-3 zone.

During deposition of the L-3 zone, the area of nahcolite deposition remained largely unchanged from the previous R-3 zone (fig. 22). Maximum in-place nahcolite is only about 35,000 tons per acre (Brownfield and others, 2010a), largely because of thinning of the L-3 zone to about one-third to one-quarter the thickness of the underlying R-3 zone (Johnson and others, 2010a, figs. 65, 69). Nahcolite occurs mainly as thin beds and aggregates. As in the underlying R-3 zone, saline minerals have been leached out from the western part of the saline area. The area of 10-GPT-or-greater oil yield has contracted significantly from the previous zone, almost matching the area of nahcolite deposition. By the end of the early saline mineral phase, about 300–400 ft of blebby and laminated oil shale and nahcolite had been deposited in the deep central lake area, whereas a somewhat thinner interval of marginal lacustrine lithologies had been deposited on the marginal shelves (figs. 4, 5, 23*A*).

Figure 16, Photograph of oil shale with clasts of laminated marlstone. Photo was taken near the center of sec. 16, T. 5 S., R. 98 W. at an elevation of about 6,970 feet. The outcrop is in the middle of the R-6 oil shale zone about 220 feet below the top of the Mahogany ledge.

Middle Saline Mineral Phase

The middle saline mineral phase of deposition in Lake Uinta begins with the R-4 zone and ends with deposition of A-groove (figs. 3–5). During the middle saline phase, offshore oil shale deposition gradually expanded over the marginal lacustrine shelves, covering nearly all the shelf areas by the beginning of deposition of the Mahogany oil shale zone (figs. 4, 5, 23*B*, 24–31). Despite the ultimate drowning of the marginal shelf, the approximate position of the shelf edge at the end of the illitic phase seems to have exerted some control over both oil shale and saline mineral deposition throughout the middle saline phase, suggesting that a topographic break was still present near there. The position of this shelf break at the end of the illitic phase is shown on each of the middle saline phase maps presented here. Schematic cross sections are shown in figure 23 for (1) the end of the early saline phase and the beginning of the middle saline phase, and (2) the period just before deposition of the Mahogany oil shale zone. As in the previous schematic cross sections, these assume an increase in the rate of subsidence from the crest of the Douglas Creek arch eastward toward the White River uplift. Climate change may have played a role in the expansion of Lake Uinta during the middle saline mineral phase (Tanavsuu-Milkeviciene and Sarg, 2012), but increasing outflow from Lake Gosiute to the north, as it was progressively filled in by volcaniclastic debris, was probably the dominant factor (Surdam and Stanley, 1980; Johnson, 1985; Roehler, 1993). Sandy deltaic deposits, possibly from outflow from Lake Gosiute, appear for the first time in the northern part of the basin near the base of the R-4 zone (figs. 4, 25) (Tanavsuu-Milkeviciene and Sarg, 2012, fig. 10). Sandy deltaic deposits continue in this area throughout the middle saline zone. Later, at the beginning of the late saline mineral phase, volcaniclastic debris from Wyoming entered Lake Uinta near this location.

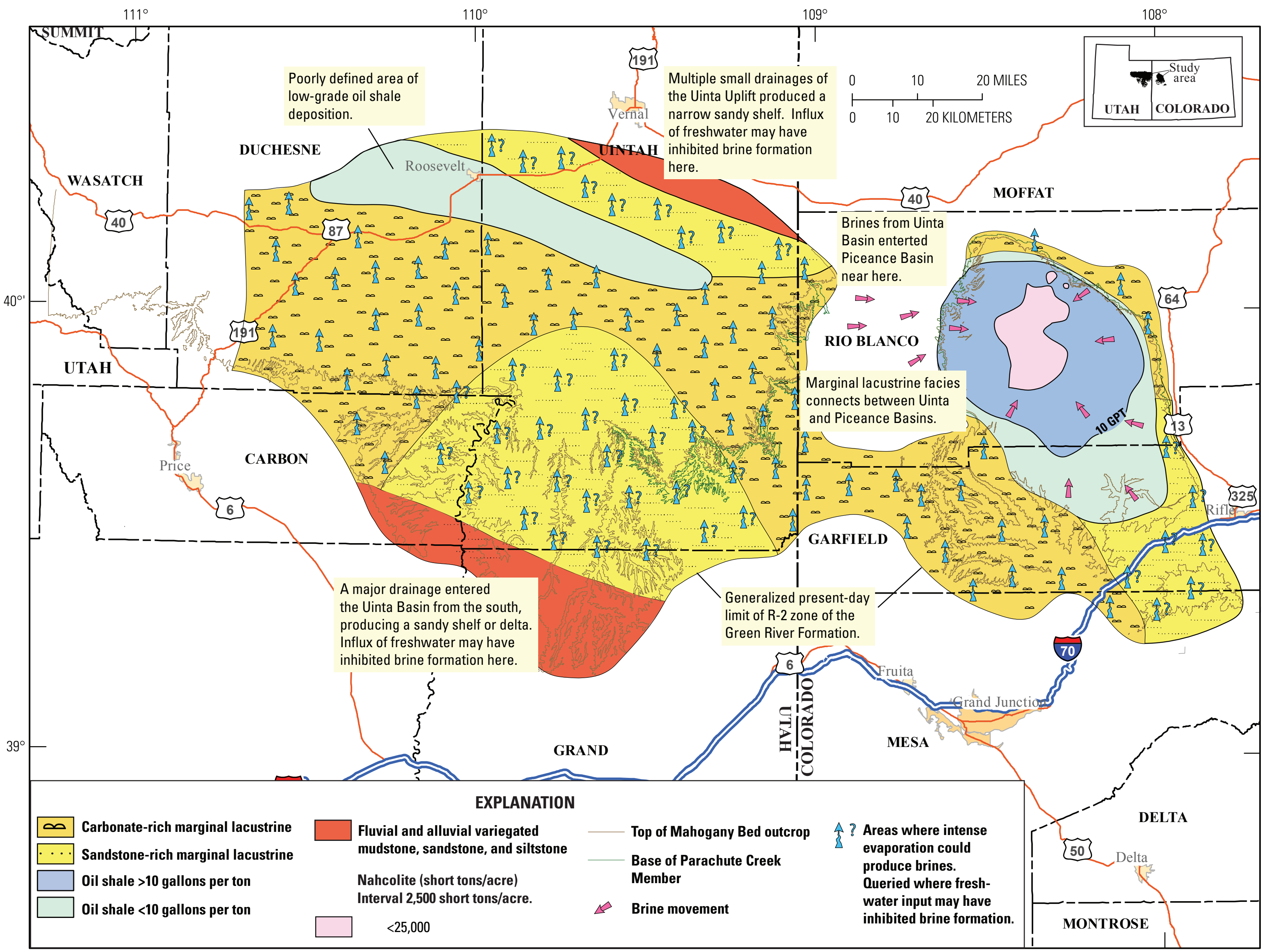


Figure 17. Paleogeographic map of the Uinta and Piceance Basins at the beginning of the saline phase showing (1) where nahcolite was deposited, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), and (3) extent of marginal lacustrine and fluvial deposition (modified from Johnson, 1985, fig. 10).

During R-4 time, low-grade (<10 GPT) oil shale deposition, expanding to cover outer areas of the marginal shelves and the area of 10 GPT or greater oil shale, expanded to near the shelf edge at the end of the illitic phase (fig. 24). Expansion of the two oil shale areas was greatest to the south, where marginal shelves and slopes, as defined during previous phases, were the widest. The area of nahcolite deposition prior to leaching has also expanded when compared to the underlying L-3 zone. Leaching has occurred along a 4- to 8-mi-wide zone on the western margin of the saline mineral area, and for the first time leaching has occurred along a 3- to 6-mi-wide area on the southern margin of the area. Saline minerals are partially leached from the R-4 zone in four coreholes (fig. 24). Nahcolite is confined largely to the upper two-thirds of the R-4 zone, with maximum in-place nahcolite of about 115,000 tons per acre (Brownfield and others, 2010a). Both nahcolite aggregates and disseminated nahcolite are present.

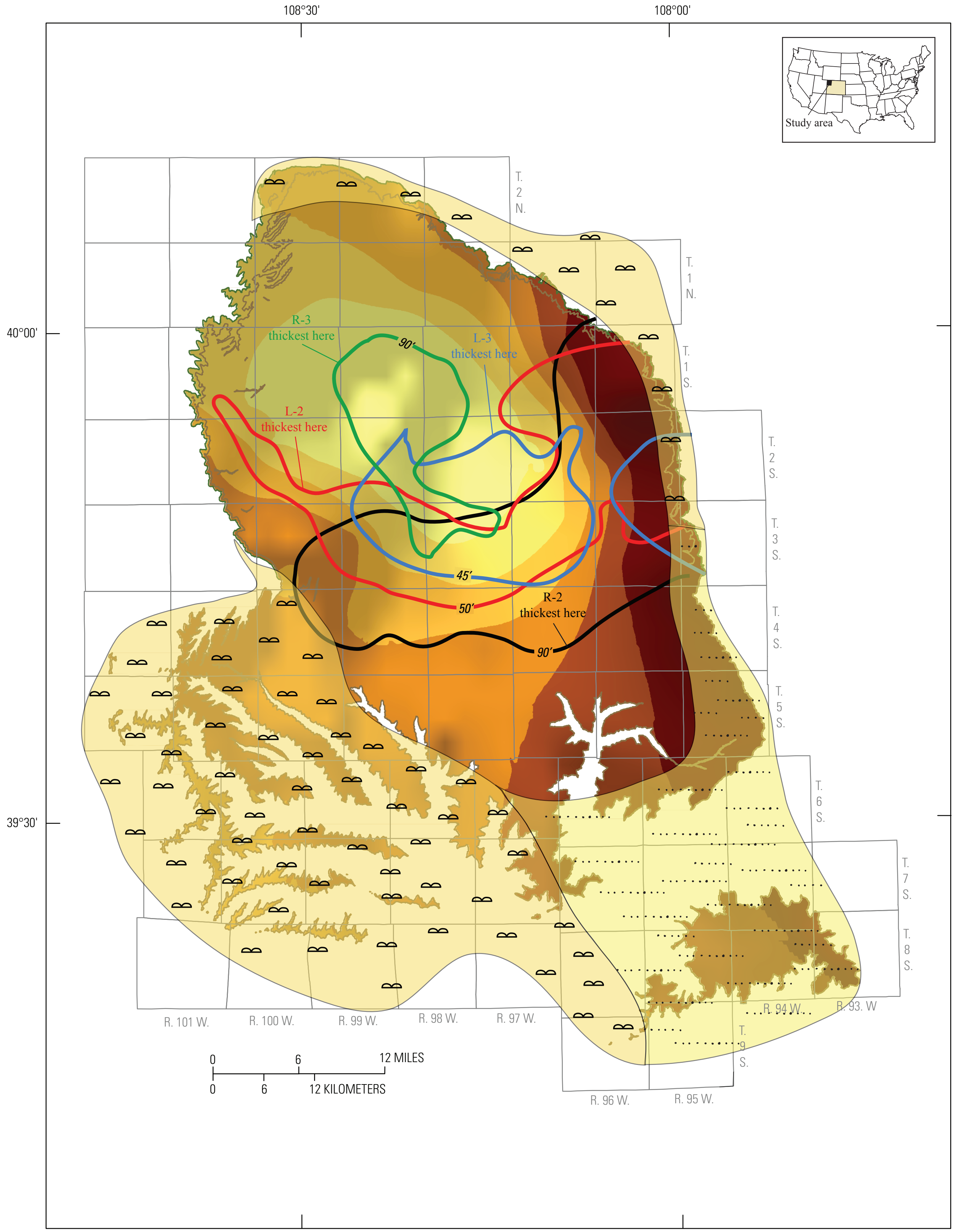
The L-4 zone marks a slight expansion of the area of original nahcolite deposition to the southeast (fig. 25). The leached zone has expanded while the area with preserved saline minerals has contracted in comparison to the underlying R-4 zone. One isolated occurrence where nahcolite is preserved in the middle part of the L-4 zone was identified in the otherwise leached area in the southeastern part of the saline area (T. 3 S., R. 96 W.) (fig. 25). The area of 10-GPT-or-greater oil yield and the area occupied by marginal lacustrine rocks are similar to that of the underlying R-4 zone. Total in-place nahcolite is significantly greater than in the underlying R-4 zone, with maximum values of more than 152,000 tons per acre. For the first time, nahcolite beds are present along with disseminated nahcolite and nahcolite aggregates. A thick sandstone unit is present in the L-4 zone near Yellow Creek in the northern part of the basin (figs. 5, 25, pl. 2), where Lake Gosiute is hypothesized to have flowed into Lake Uinta.

The original extent of saline mineral deposition expanded significantly, mainly to the south and east during deposition of the R-5 zone (fig. 26). The area where saline minerals are preserved has diminished, producing a broad area of leaching around the entire saline mineral area. Four isolated occurrences of nahcolite interspersed with leached vugs and breccia in the R-5 zone were identified in the southeast part of the leached area, with three of them possibly aligning along a linear southeast trend. Several nahcolite and halite beds, as much as 40 ft thick, are present in the upper and lower parts of the R-5 zone (Dyni, 1974c, 1981). The area where halite is present is outlined on figure 26. The halite and nahcolite beds are leached around the margins of the saline mineral area, thus the original extent of these beds is unknown. Maximum nahcolite in the R-5 zone is more than 365,000 tons per acre (fig. 26). The area of low-grade (<10 GPT) oil shale expanded slightly when compared to the underlying L-4 zone. The R-5 zone grades into a sandy interval near the mouth of Yellow Creek in the northern part of the basin (fig. 26, pl. 2).

The L-5 zone is the highest oil shale zone where saline minerals are still widely preserved (fig. 27). It includes two thick beds (up to about 60 ft thick) of nahcolite and halite in its lower part in a comparatively small area in the north-central part of the basin. The original extent of these beds is unknown as they have been extensively leached, but Dyni (1974c, 1981) traced breccias that are laterally equivalent to these two beds for a considerable distance into the leached zone. Dyni (1974c, 1981) also traced a laterally continuous breccia stratigraphically higher in the L-5 zone, indicating that another thick nahcolite-halite bed was once present. The area of saline deposition, including the leached area, is somewhat larger during L-5 time than for the previous R-5 zone. Isolated occurrences of preserved nahcolite aggregates in the leached area were identified near the northern, northeastern, southeastern and western margins of the saline area. The marginal lacustrine areas expanded slightly, and the area where oil shale is greater than 10 GPT shrank markedly during deposition of the L-5 zone when compared to the R-5 zone.

Deposition of the R-6 zone is characterized by a continued overall expansion of the area of oil shale deposition onto the former marginal lacustrine shelves. The area of 10-GPT-or-greater oil shale expanded to its maximum extent thus far (fig. 28). It is uncertain how much nahcolite and possibly halite was originally present in the R-6 zone because, as previously mentioned, core descriptions rarely note what percentage of the total volume of the core is represented by vugs and breccias. However, vugs and breccia zones have been identified throughout the R-6 zone in many coreholes, indicating it once contained large quantities of saline minerals. Today, only a few scattered occurrences of preserved nahcolite are present in the R-6 zone (fig. 28). The R-6 zone thickens near the mouth of Yellow Creek (fig. 18) because of the influx of sandstone and siltstone from the north (fig. 28, pl. 2).

B-groove represents the first of two unique, relatively thin, very lean intervals that bracket the rich Mahogany zone (fig. 3). B-groove is less than 40 ft thick throughout most of the basin, but it thickens markedly in two areas where rivers entered Lake Uinta: (1) in the southeastern corner of the basin and (2) in the vicinity of the mouth of Yellow Creek along the northern margin of the basin (fig. 29). B-groove exceeds 10 GPT oil in only two restricted areas in the central part of the basin (fig. 29). The saline mineral area for B-groove prior to leaching is only slightly smaller than that for the underlying R-6 zone. B-groove tends to be more silty and sandy than the overlying and underlying strata, but it is similar in that it is mostly even-bedded to laminated. Interestingly, there are no reported occurrences of stromatolites, a shallow-water indicator, in B-groove anywhere in the basin (fig. 29).


108°30'
108°00'
40°00'
39°30'
Study area
R-3
thickest here
L-3
thickest here
L-2
thickest here
R-2
thickest here
90'
45'
50'
90'
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0
6
12 MILES
0
6
12 KILOMETERS

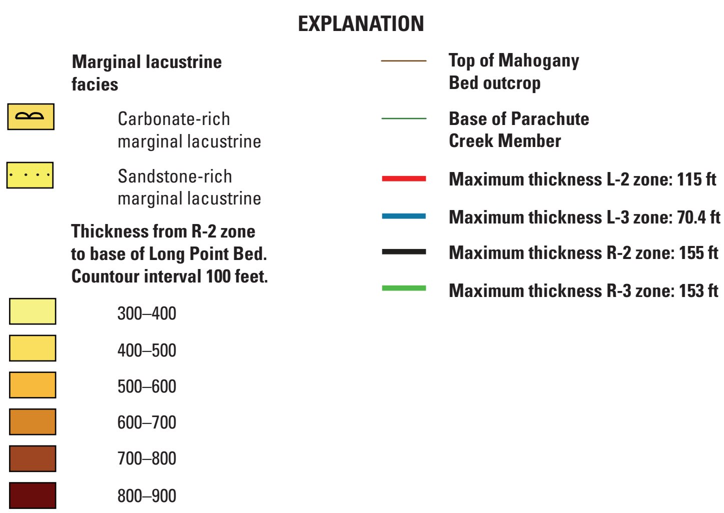
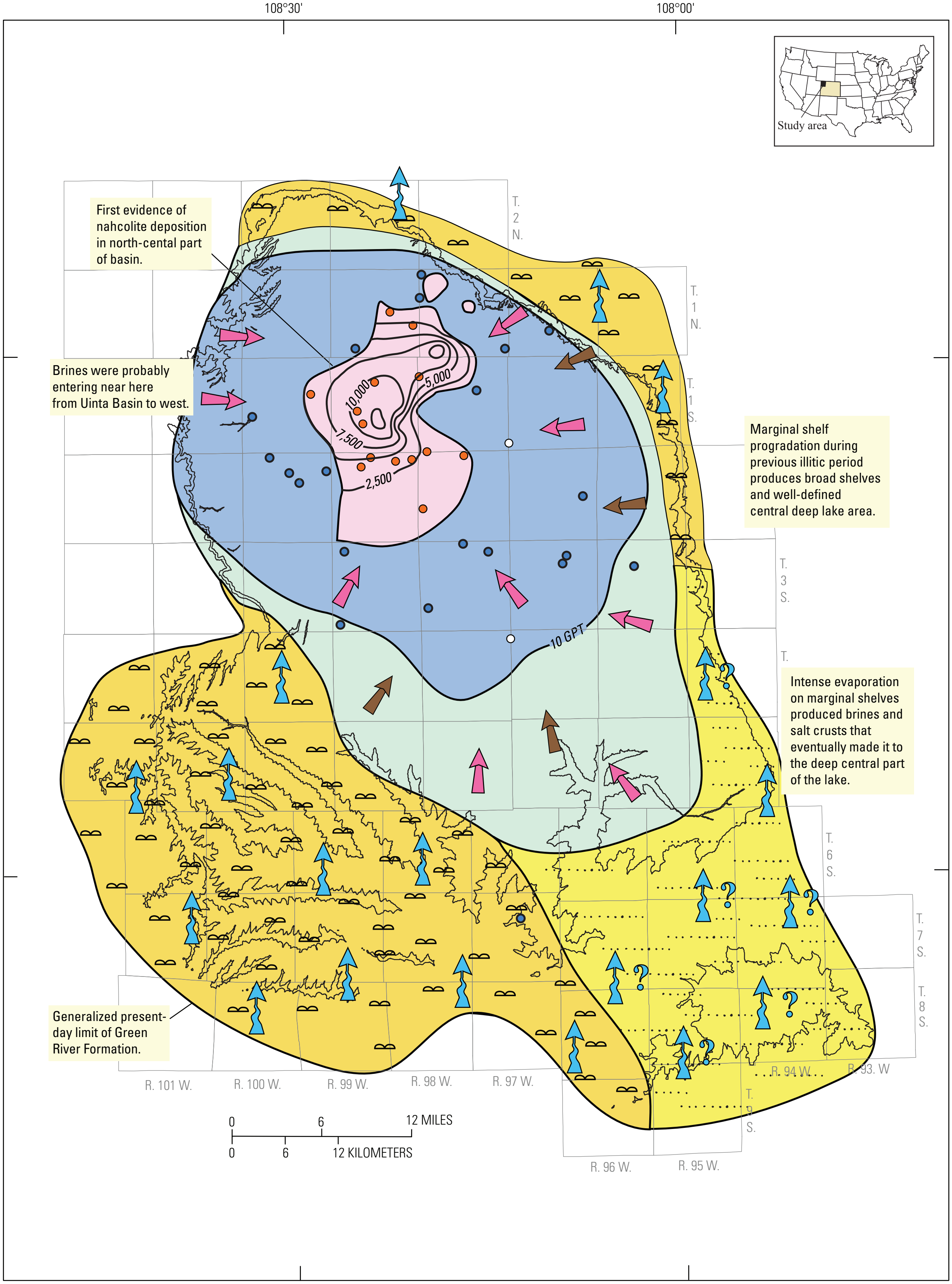


Figure 18 (previous page). Map of the Piceance Basin at the end of the illitic phase showing (1) extent of marginal lacustrine facies at the end of the freshwater phase that pre-dated the illitic phase of Lake Uinta, (2) thickness of the illitic phase, and (3) where the R-2, L-2, R-3, and L-3 oil shale zones are the thickest (modified from Johnson and others, 2010a). (ft, feet)


108°30'
108°00'
40°00'
39°30'
Study area
First evidence of nahcolite deposition in north-cental part of basin.
Brines were probably entering near here from Uinta Basin to west.
Marginal shelf progradation during previous illitic period produces broad shelves and well-defined central deep lake area.
Intense evaporation on marginal shelves produced brines and salt crusts that eventually made it to the deep central part of the lake.
Generalized present-day limit of Green River Formation.
10,000
7,500
5,000
2,500
10 GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 3 S.
T. 6 S.
T. 7 S.
T. 8 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

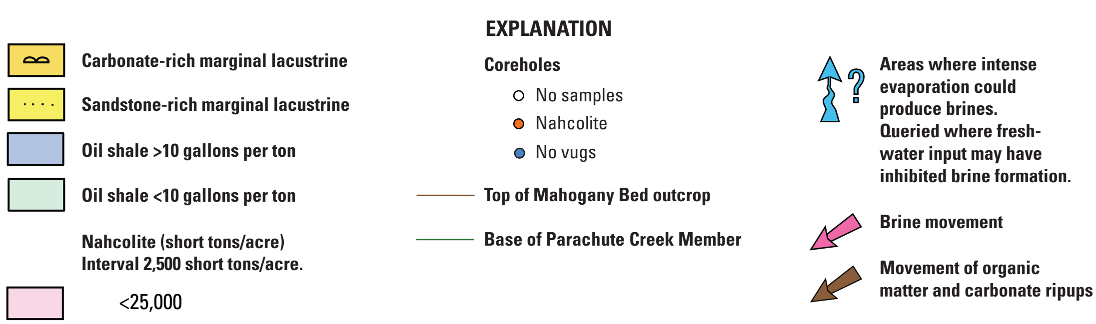
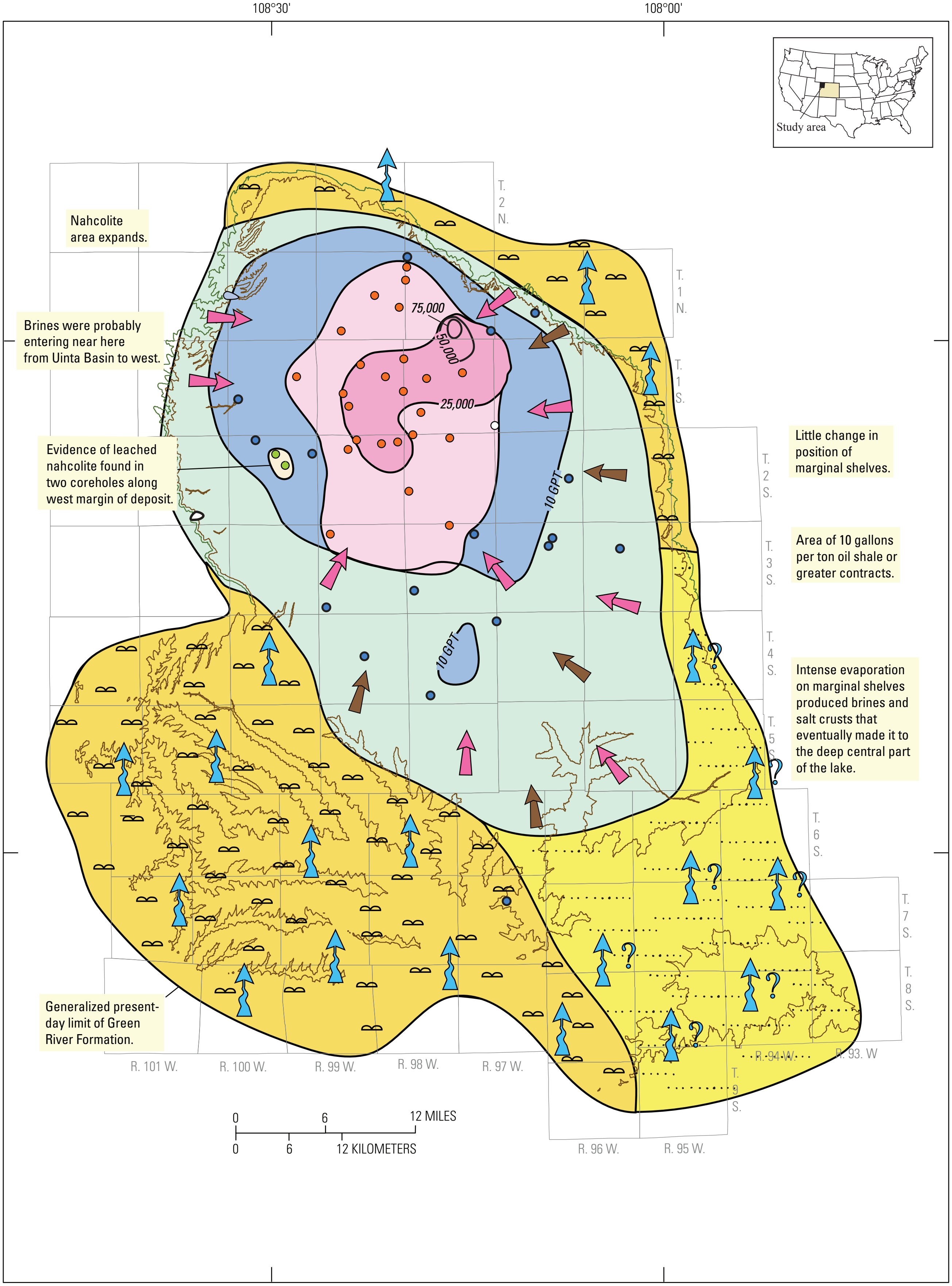


Figure 19 (previous page). Map of the R-2 oil shale zone showing (1) where nahcolite was deposited and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), and (3) extent of marginal lacustrine deposition (modified from Johnson, 1985, fig. 10). Locations of coreholes used are shown.



108°30'
108°00'
40°00'
39°30'
Study area
Nahcolite area expands.
Brines were probably entering near here from Uinta Basin to west.
Evidence of leached nahcolite found in two coreholes along west margin of deposit.
Generalized present-day limit of Green River Formation.
Little change in position of marginal shelves.
Area of 10 gallons per ton oil shale or greater contracts.
Intense evaporation on marginal shelves produced brines and salt crusts that eventually made it to the deep central part of the lake.
75,000
50,000
25,000
10 GPT
10 GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

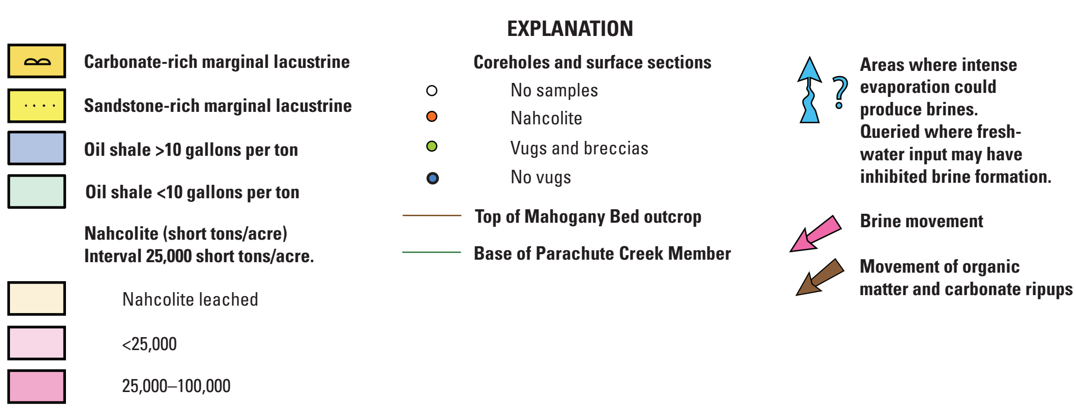
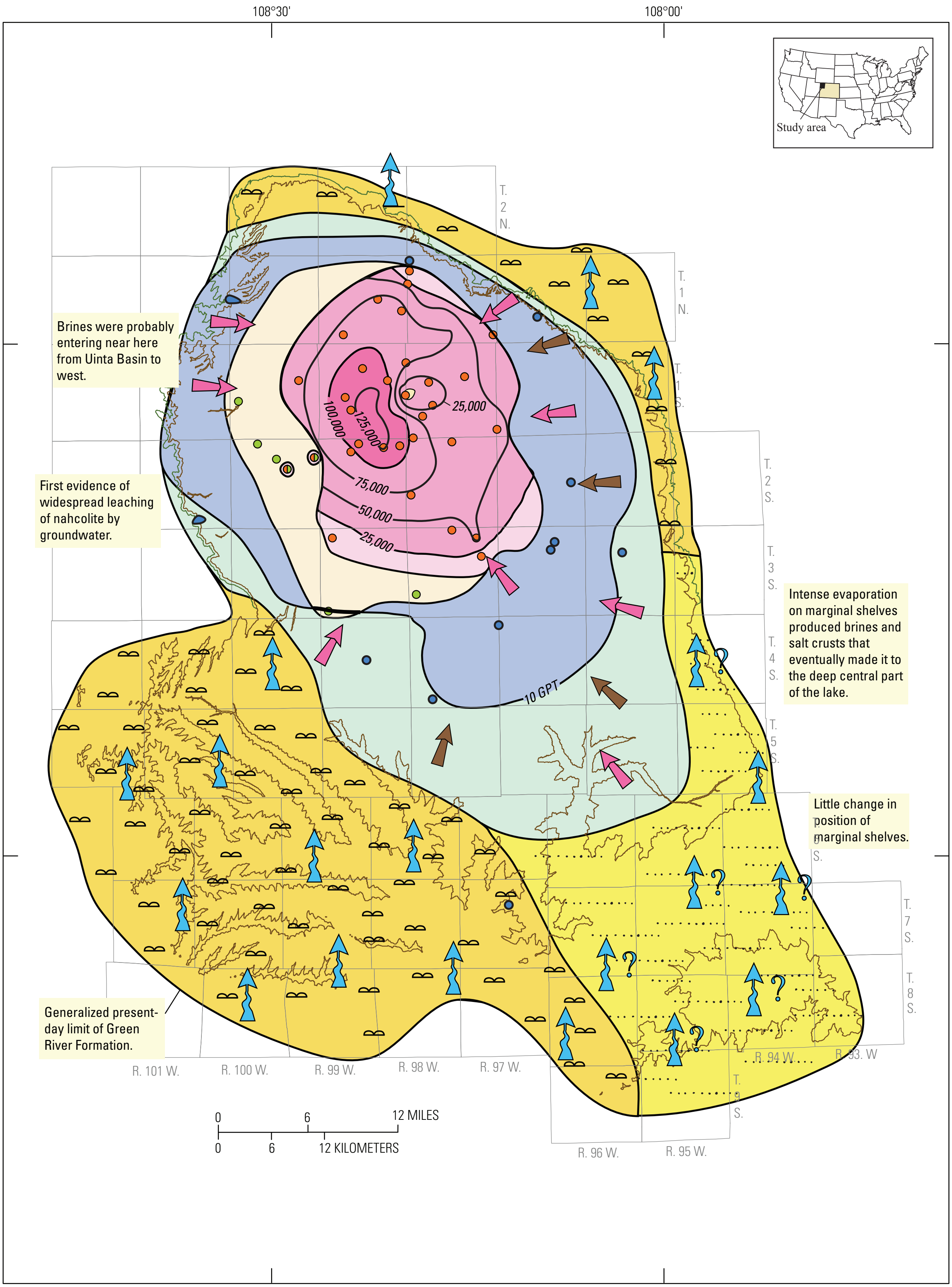


Figure 20 (previous page). Map of the L-2 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), and (4) extent of marginal lacustrine deposition (modified from Johnson, 1985). Locations of coreholes used are shown.


108°30'
108°00'
40°00'
39°30'
Study area
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
125,000
100,000
75,000
50,000
25,000
25,000
10 GPT
Brines were probably entering near here from Uinta Basin to west.
First evidence of widespread leaching of nahcolite by groundwater.
Intense evaporation on marginal shelves produced brines and salt crusts that eventually made it to the deep central part of the lake.
Little change in position of marginal shelves.
Generalized present-day limit of Green River Formation.
0 6 12 MILES
0 6 12 KILOMETERS

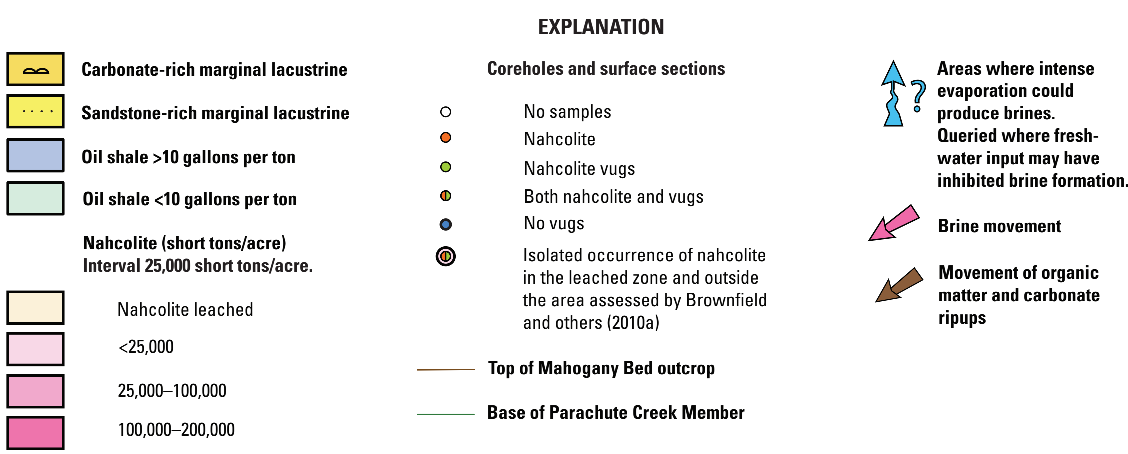
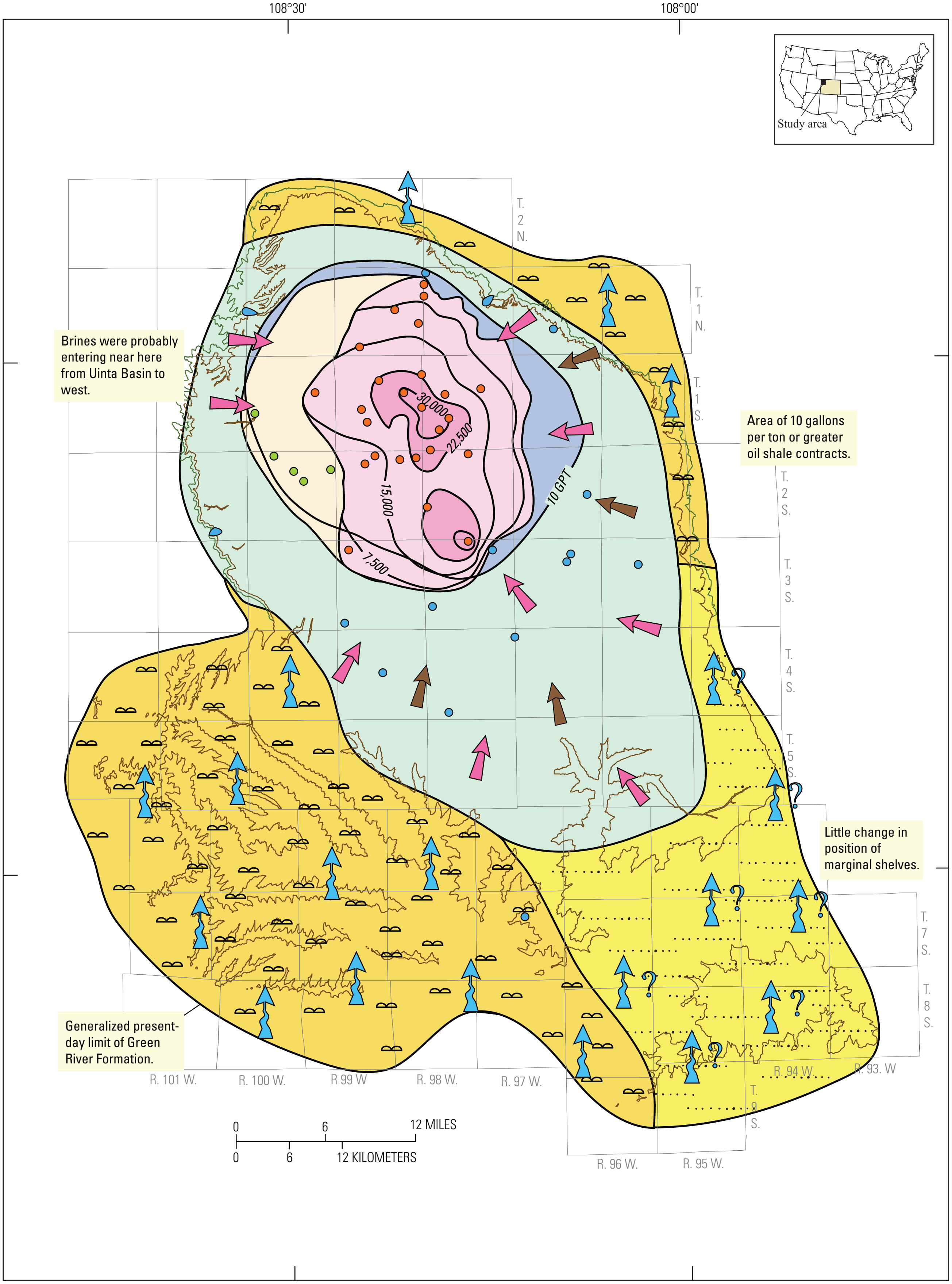


Figure 21 (previous page). Map of the R-3 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), and (4) extent of marginal lacustrine deposition (modified from Johnson, 1985). Locations of coreholes used are shown.


108°30'
108°00'
40°00'
39°30'
Study area
Brines were probably entering near here from Uinta Basin to west.
Area of 10 gallons per ton or greater oil shale contracts.
Little change in position of marginal shelves.
Generalized present-day limit of Green River Formation.
30,000
22,500
15,000
7,500
10 GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

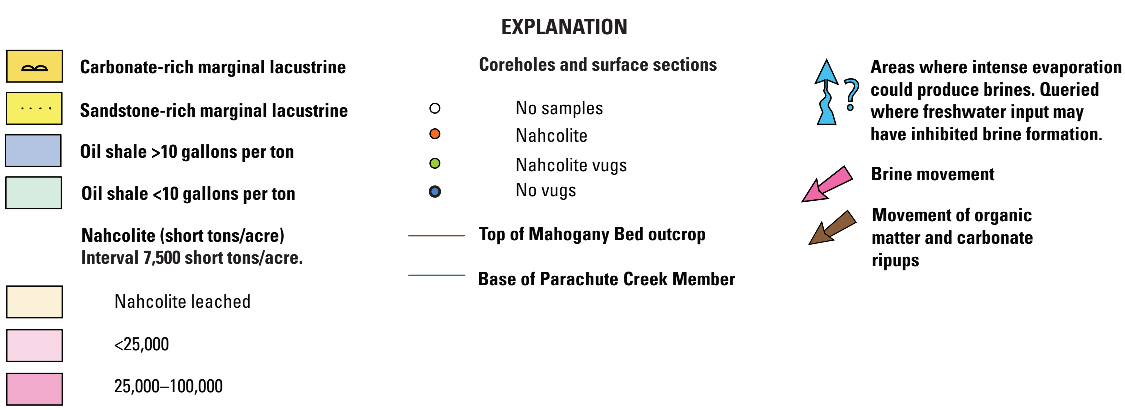
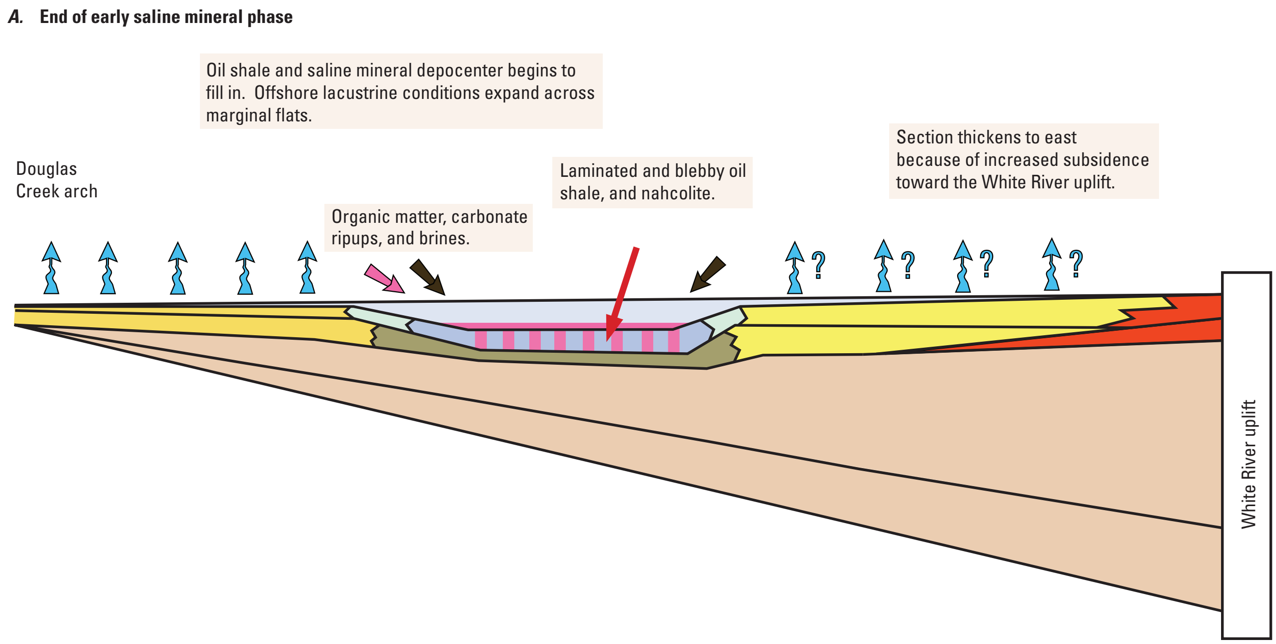
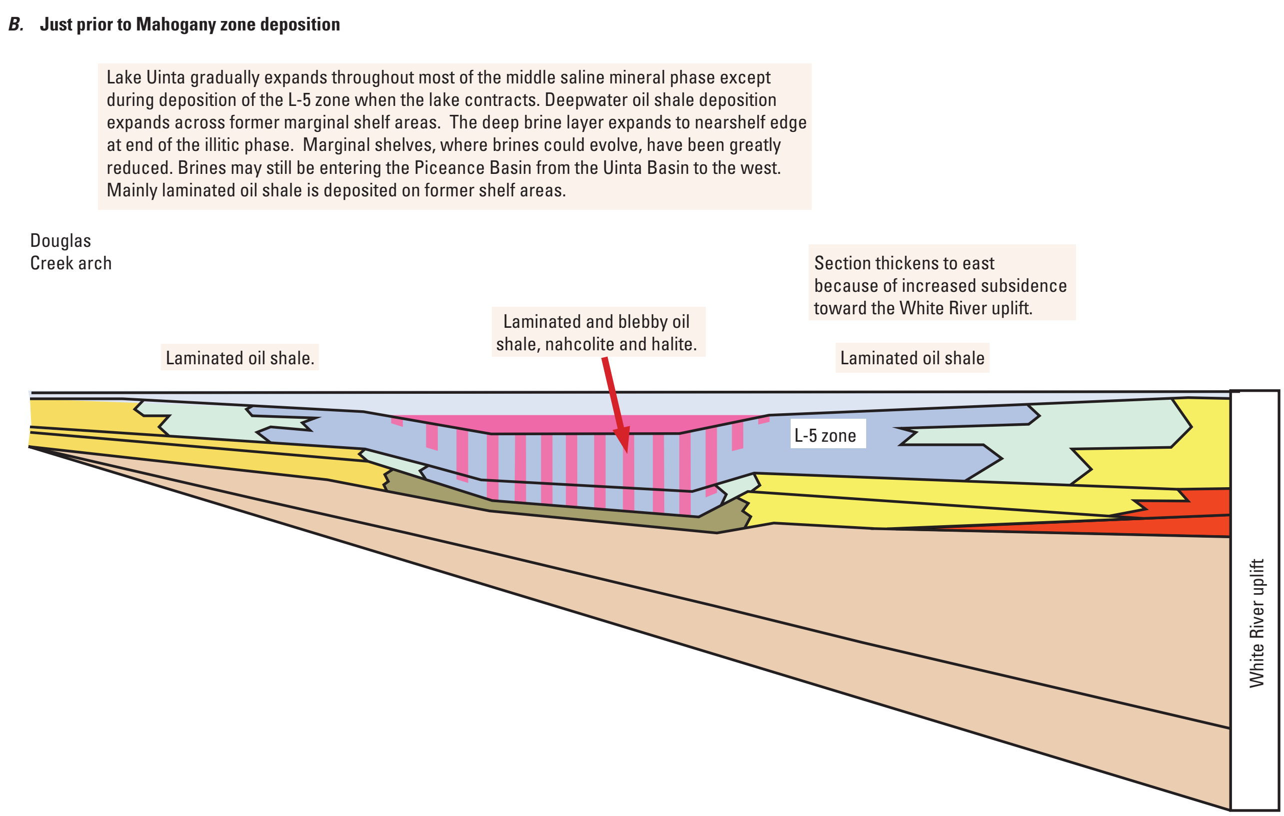


Figure 22 (previous page). Map of the L-3 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), and (4) extent of marginal lacustrine deposition (modified from Johnson, 1985). Locations of coreholes used are shown.


A. End of early saline mineral phase
Oil shale and saline mineral depocenter begins to fill in. Offshore lacustrine conditions expand across marginal flats.
Douglas Creek arch
Laminated and blebby oil shale, and nahcolite.
Section thickens to east because of increased subsidence toward the White River uplift.
Organic matter, carbonate ripups, and brines.
?
?
?
?
White River uplift


B. Just prior to Mahogany zone deposition
Lake Uinta gradually expands throughout most of the middle saline mineral phase except during deposition of the L-5 zone when the lake contracts. Deepwater oil shale deposition expands across former marginal shelf areas. The deep brine layer expands to nearshelf edge at end of the illitic phase. Marginal shelves, where brines could evolve, have been greatly reduced. Brines may still be entering the Piceance Basin from the Uinta Basin to the west. Mainly laminated oil shale is deposited on former shelf areas.
Douglas Creek arch
Section thickens to east because of increased subsidence toward the White River uplift.
Laminated and blebby oil shale, nahcolite and halite.
Laminated oil shale.
Laminated oil shale
L-5 zone
White River uplift

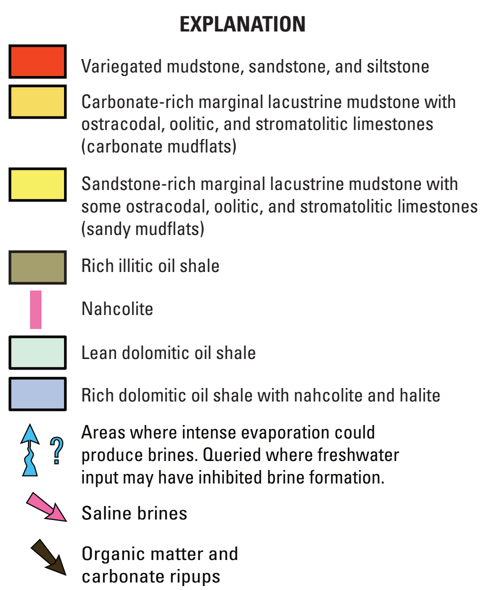
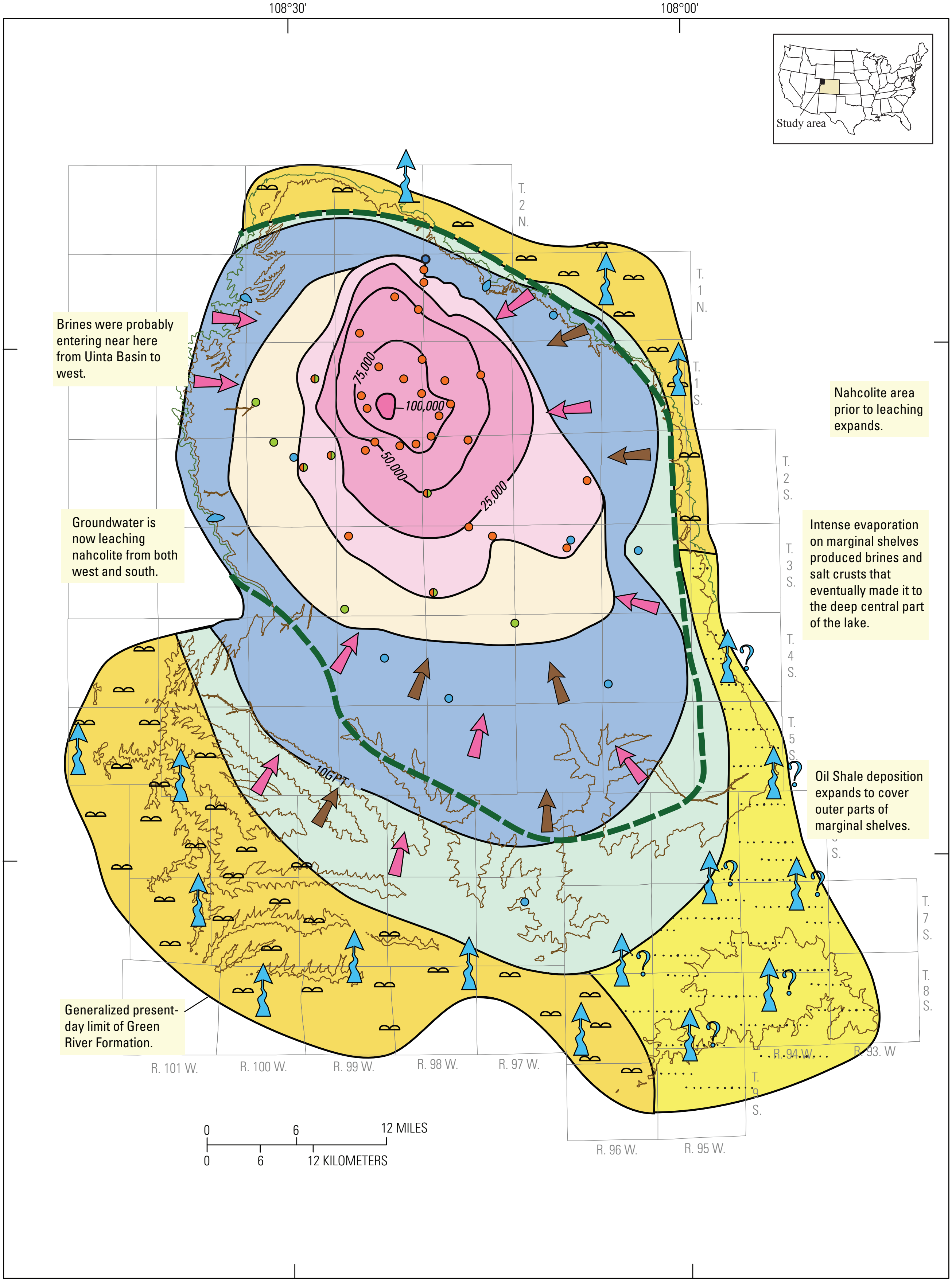


Figure 23 (previous page). West-to-east schematic cross section across the Piceance Basin for two time periods. *A*, End of early saline mineral phase. *B*, Just prior to deposition of the Mahogany oil shale zone. Figure 13 shows this cross section in three earlier time periods. Approximate line of section shown on figure 14.


108°30'
108°00'
40°00'
39°30'
Study area
Brines were probably entering near here from Uinta Basin to west.
Groundwater is now leaching nahcolite from both west and south.
Generalized present-day limit of Green River Formation.
Nahcolite area prior to leaching expands.
Intense evaporation on marginal shelves produced brines and salt crusts that eventually made it to the deep central part of the lake.
Oil Shale deposition expands to cover outer parts of marginal shelves.
100,000
75,000
50,000
25,000
10GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

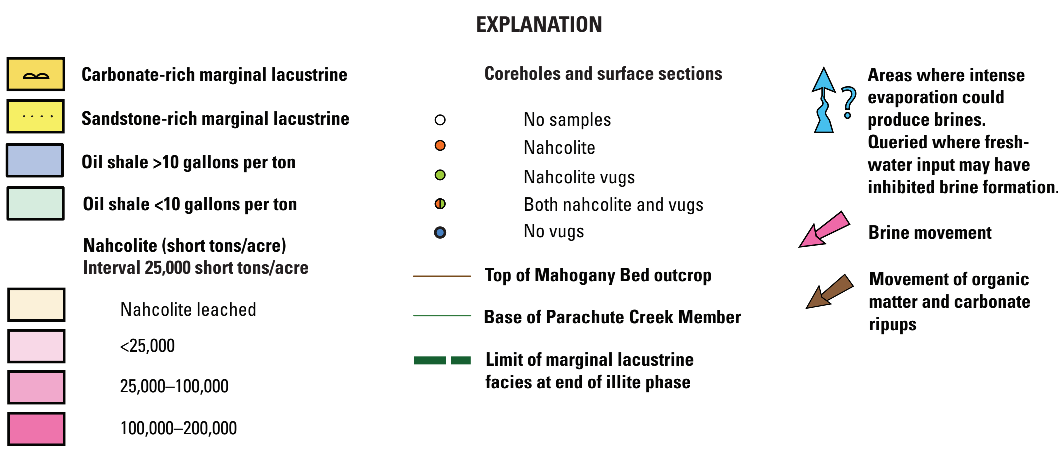
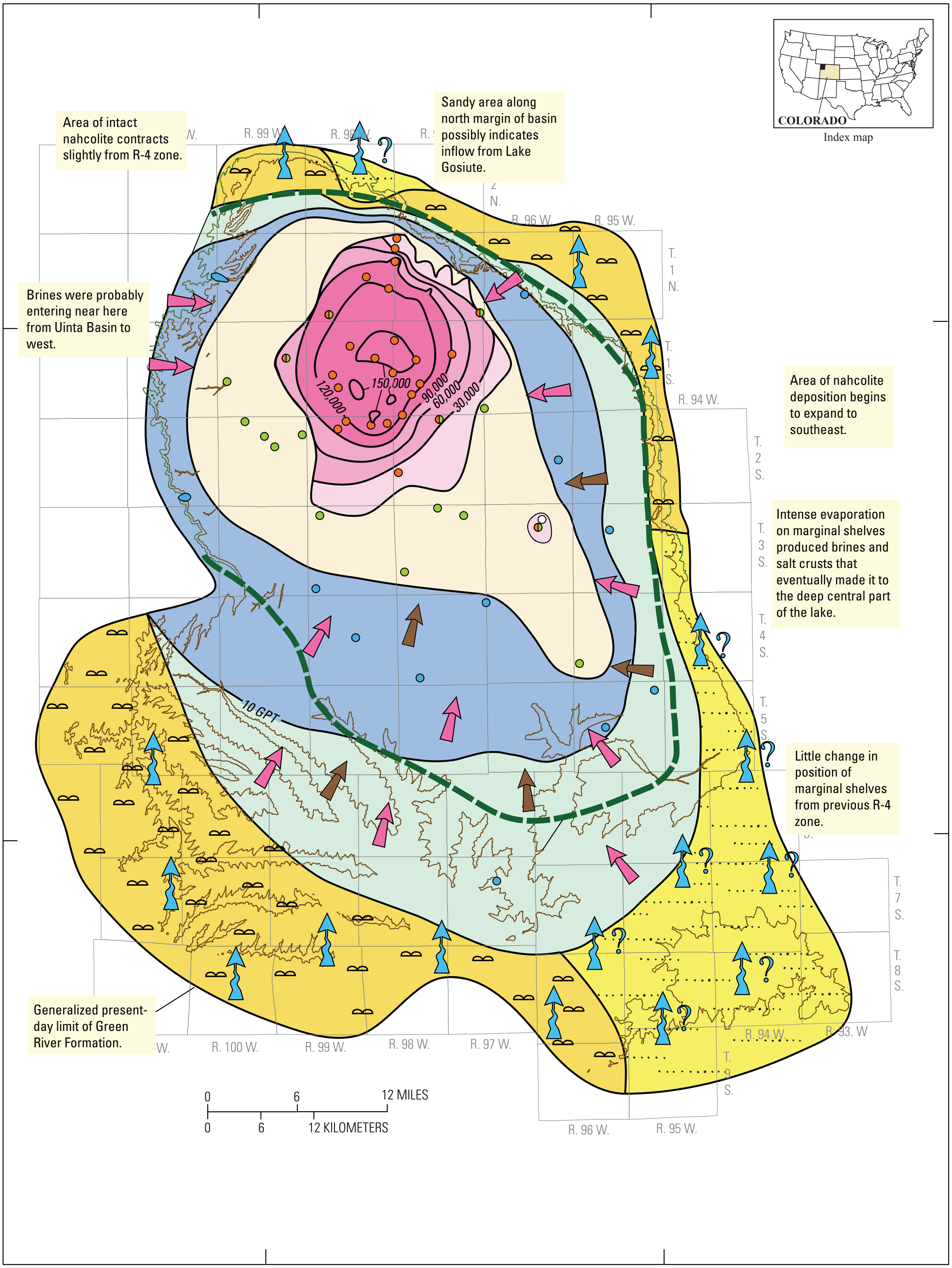


Figure 24 (previous page). Map of the R-4 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (4) extent of marginal lacustrine deposition (modified from Johnson, 1985), and (5) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown.


108°30'
108°00'
40°00'
39°30'
COLORADO
Index map
Area of intact nahcolite contracts slightly from R-4 zone.
Sandy area along north margin of basin possibly indicates inflow from Lake Gosiute.
Brines were probably entering near here from Uinta Basin to west.
Area of nahcolite deposition begins to expand to southeast.
Intense evaporation on marginal shelves produced brines and salt crusts that eventually made it to the deep central part of the lake.
Little change in position of marginal shelves from previous R-4 zone.
Generalized present-day limit of Green River Formation.
150,000
120,000
90,000
60,000
30,000
10 GPT
R. 99 W.
R. 98 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93 W.
R. 100 W.
R. 97 W.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 7 S.
T. 8 S.
0 6 12 MILES
0 6 12 KILOMETERS

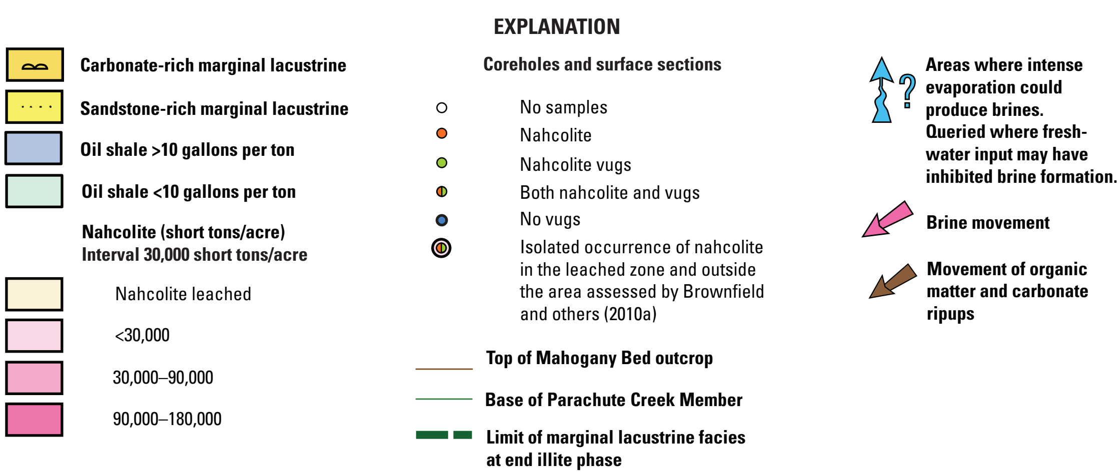
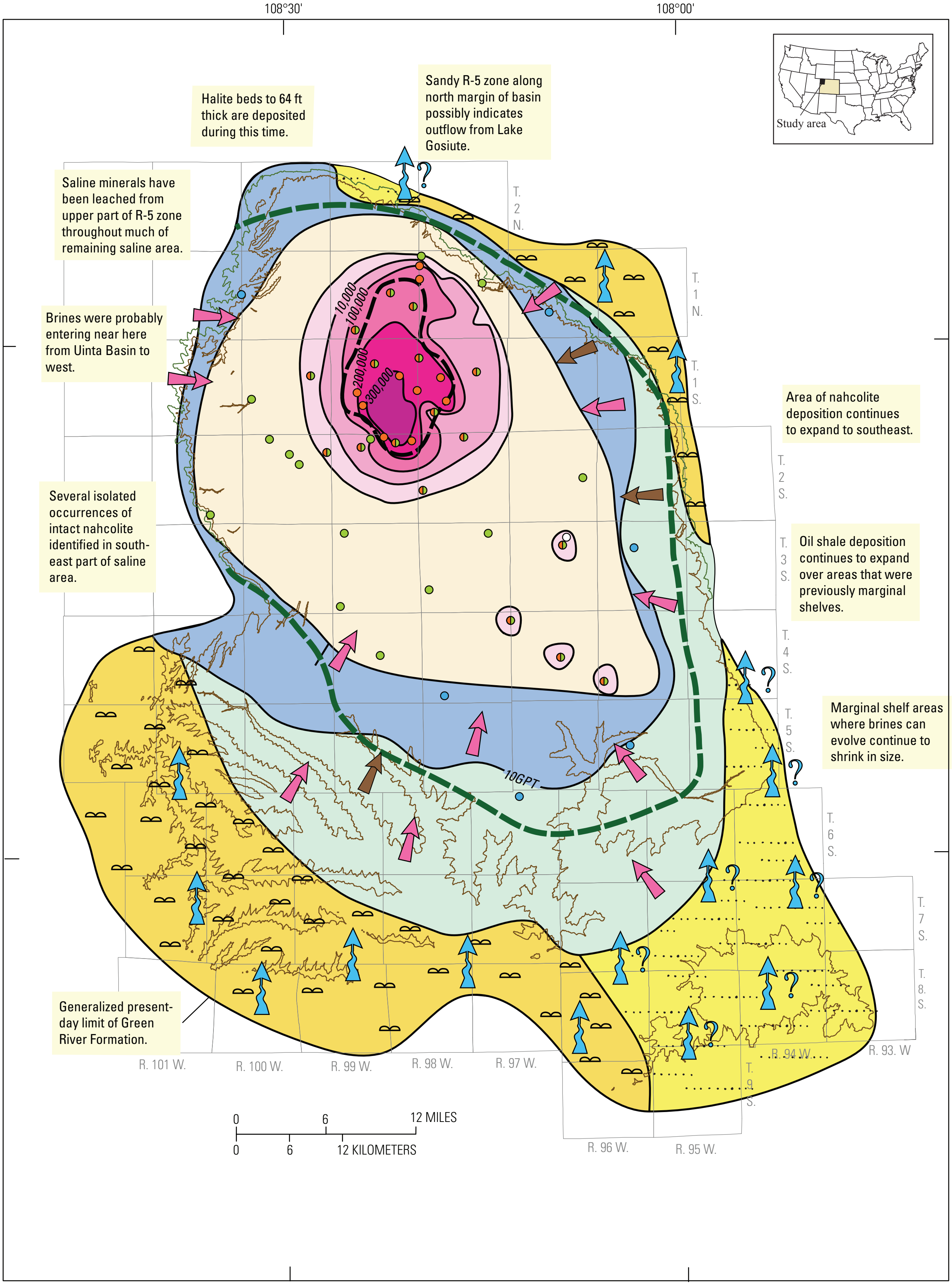


Figure 25 (previous page). Map of the L-4 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (4) extent of marginal lacustrine deposition (modified from Johnson, 1985), and (5) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. An isolated occurrence of preserved nahcolite in the southeastern part of the leached area was identified.


108°30'
108°00'
40°00'
39°30'
Study area
Halite beds to 64 ft thick are deposited during this time.
Sandy R-5 zone along north margin of basin possibly indicates outflow from Lake Gosiute.
Saline minerals have been leached from upper part of R-5 zone throughout much of remaining saline area.
Brines were probably entering near here from Uinta Basin to west.
Area of nahcolite deposition continues to expand to southeast.
Several isolated occurrences of intact nahcolite identified in south-east part of saline area.
Oil shale deposition continues to expand over areas that were previously marginal shelves.
Marginal shelf areas where brines can evolve continue to shrink in size.
Generalized present-day limit of Green River Formation.
10,000
100,000
200,000
300,000
10GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93 W.
0 6 12 MILES
0 6 12 KILOMETERS

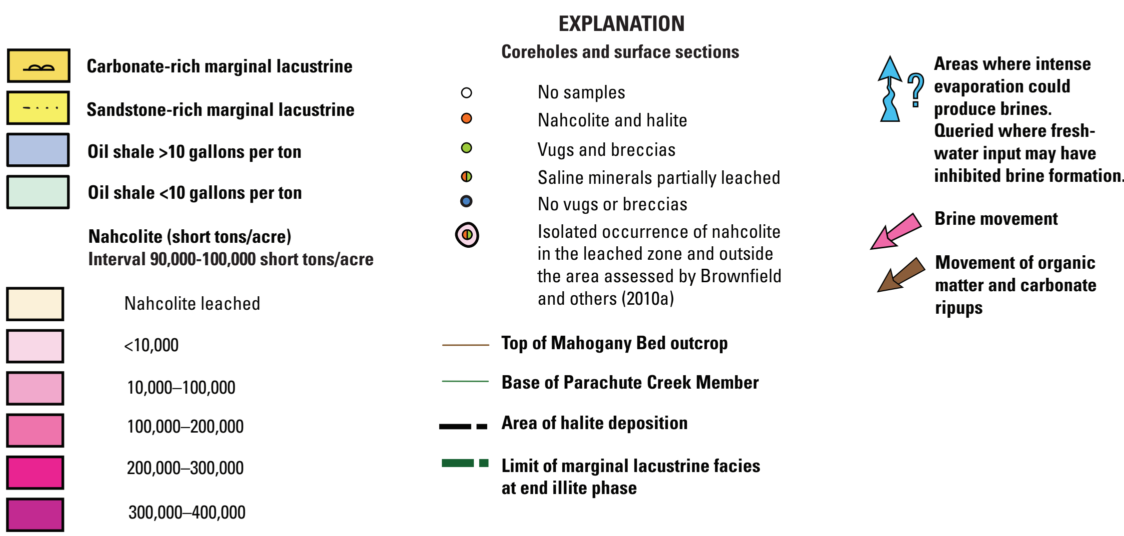


Figure 26 (previous page). Map of the R-5 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (4) extent of marginal lacustrine deposition (modified from Johnson, 1985), (5) limit of marginal lacustrine facies at the end of the illitic phase, and (6) approximate area where halite is present. Locations of coreholes used are shown. Four isolated occurrences of preserved nahcolite in the southeast part of the leached area were identified.

The Mahogany zone was deposited during the most expansive period of Lake Uinta, when the lake may have extended to near the flanks of the surrounding uplifts (Johnson, 1985). It is one of the richest oil shale zones in the basin, with nearly 192 billion barrels of oil in place, and is typically the richest oil shale zone in outcrop around the margins of the basin (Johnson and others, 2010a). As such, it has been the primary target of nearly all, if not all, of the oil shale surface mining operations in the Piceance Basin, both currently and in the past. Oil shale in the Mahogany zone everywhere exceeds 10 GPT except (1) in the extreme northeastern corner of the basin; (2) near the mouth of Yellow Creek along the northern margin, where the Mahogany zone grades into sandstone, siltstone, and marlstone and cannot be recognized (fig. 30); and (3) in the southeastern part of the basin, where it contains thin sandstones (not shown on map). Total oil in place in the Mahogany zone increases from less than 200,000 barrels per acre (BPA) to more than 300,000 BPA toward the central part of the saline mineral area (fig. 30).

The original extent of saline mineral deposition in the Mahogany zone is slightly larger than in the R-6 zone or B-groove, with minor amounts of nahcolite preserved in five isolated occurrences (fig. 30). The total amount of saline minerals in the Mahogany zone prior to leaching appears to have been relatively low when compared to the R-6 zone, as only scattered vugs and breccias have been reported in that zone. These occurrences are most abundant in the lower part of the Mahogany zone, suggesting an overall decline in saline mineral deposition during deposition of the Mahogany zone.

A-groove, the other thin lean zone that brackets the Mahogany zone, varies from about 5 to 25 ft thick throughout most of the basin, thickening to more than 30 ft along the extreme southeastern margin, where a major river entered Lake Uinta (fig. 31). A-groove cannot be distinguished from underlying and overlying strata in the vicinity of Yellow Creek along the northern margin of the basin, where another major river entered Lake Uinta (figs. 5, 31, pl. 2). It occurs, however, within an overall sandy marginal lacustrine interval and is shown as such on figure 31. Nahcolite vugs occur in A-groove throughout an area in the central part of the basin that is significantly smaller than the area with vugs and breccias in the underlying Mahogany zone (fig. 31). Intact nahcolite nodules were reported in A-groove in two coreholes in the northern part of the leached zone (fig. 31). Three coreholes within the leached area had no reported vugs. Oil shale in A-groove averages less than 10 GPT throughout most of the basin except for a few isolated areas in the central part of the basin. A-groove is generally less silty and sandy than B-groove. Similar to the underlying Mahogany zone and B-groove, there are no stromatolites reported from A-groove anywhere in the basin.

Late Saline Mineral Phase

The interval above A-groove in the Piceance Basin, considered here to be the late saline mineral phase, was deposited during the infilling of the Piceance Basin part of Lake Uinta with volcaniclastic sediments from the north. The interval is a generally southward-prograding deltaic complex consisting of volcaniclastic wedges of the Uinta Formation interfingering with oil shale and marlstone of the upper part of the Green River Formation (fig. 5, pl. 2). This study focuses on the interval from the top of A-groove to bed 44 of Donnell (2008) (figs. 3, 5, pl. 2), as it is preserved over most of the basin. The interval above bed 44 is preserved only in limited areas in the southern part of the basin. Bed 44 is within the upper part of the Parachute Creek Member of the Green River Formation in the southern part of the basin and within the Thirteenmile Creek Tongue of the Green River Formation in the northern part, where it is overlain and underlain by tongues of the Uinta Formation (fig. 5). The Thirteenmile Creek Tongue consists mainly of marlstone and oil shale but contains stromatolite and charophyte remains in the northernmost part of the basin (Johnson, 1981), where deepwater conditions had been replaced by a shallow lake-margin shelf by that time.

The late saline mineral phase is represented by four figures (figs. 32–35). Figures 32 and 33 are paleogeographic reconstructions for the earliest and latest part of the A-groove to bed 44 interval, respectively. Figure 32 includes an isopach map of the entire A-groove to bed 44 interval and the area where the entire interval exceeds 10 GPT (Johnson and others, 2010a, fig. 107). Figure 33 includes estimates of total oil in place for the entire A-groove to bed 44 interval (Johnson and others, 2010a, fig. 108). Figure 34, modified from Donnell (2008, fig. 4), shows the detailed correlation of individual oil shale beds in the interval above A-groove for two coreholes, one in the eastern Uinta Basin and the other in the southern part of the Piceance Basin. Both coreholes are in areas where the upper part of the Green River Formation does not include tongues of the Uinta Formation. Donnell (2008) was able to trace a large number of individual oil shale beds between the Uinta and Piceance Basins and to correlate most of the Green River tongues into their equivalent stratigraphic positions in the upper part of the Parachute Creek Member. The stratigraphic positions of these tongues are shown on the right side of figure 34.

Red bars to the right of the Piceance Basin corehole in figure 34 roughly show the stratigraphic intervals of saline mineral deposition for five different time periods, with the bars on the left representing the northernmost part of the basin and the bar on the right the southernmost. The approximate areal extent of each of these five time intervals is shown on figures 32 and 33. Only a limited amount of core and surface control was available to define these five areas, but they nonetheless demonstrate the southward migration of the saline mineral area as Lake Uinta was progressively filled in from the north. This southward stratigraphic rise is also apparent on the detailed north to south cross section (pl. 2). The shelf edge at the end of the illitic phase roughly defines the extent of the saline mineral deposition during time periods 1 and 2, as it does for underlying oil shale zones. As Lake Uinta was progressively filled in, the saline mineral area was pushed onto the former marginal shelf area and ultimately into the southernmost part of that area (figs. 32–34, time periods 3–5).

As the Piceance Basin part of Lake Uinta was gradually filled in, nahcolite vugs appeared for the first time in the eastern part of the Uinta Basin, indicating that the deep brine layer was shifting from the Piceance Basin into the Uinta Basin. First appearance of nahcolite vugs in the eastern part of the Uinta Basin occur at about the stratigraphic level of bed 58 of Donnell (2008), or about 65–90 ft stratigraphically above bed 44 (fig. 34) (Vanden Berg, 2010). Figure 35 shows the area in the eastern Uinta Basin where nahcolite was deposited for the first time. The interval that contains nahcolite vugs in the eastern part of the Uinta Basin is shown as a red bar to the left of the oil-yield histogram for the Uinta Basin on figure 34. Saline mineral deposition in both basins overlapped for a period of time.

Discussion and Conclusions

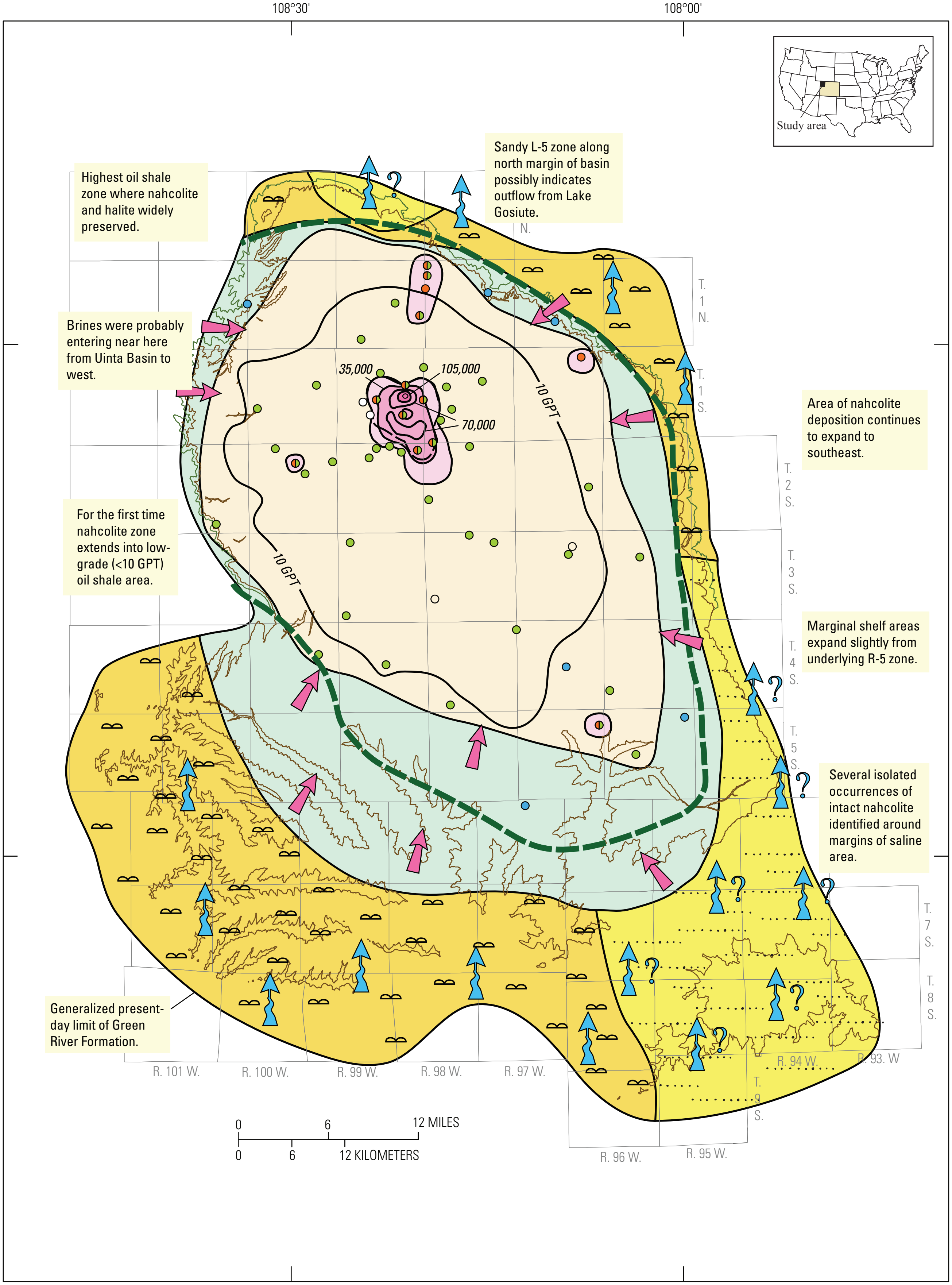
Lake Uinta formed during the Eocene when two much smaller freshwater lakes, one in the Uinta Basin and the other in the Piceance Basin, expanded and coalesced across the Douglas Creek arch during the Long Point transgression. After maximum transgression was reached, Lake Uinta gradually increased in salinity, ultimately depositing large quantities of nahcolite and halite. Early Lake Uinta inherited the preexisting topography of the transgressed alluvial plains as well as that within the preceding freshwater lake, Lake Cow Ridge. Although the depth of Lake Cow Ridge prior to the Long Point transgression is unknown, it is unlikely that the lake was shallow, as shallow freshwater lakes tend to be short lived—filling in, for instance, with even a modest increase in sediment supply. Lake Cow Ridge existed continuously in the Piceance Basin for as much as 3 million years prior to the development of Lake Uinta, depositing thick, low-grade oil shale intervals in the central part of the lake in the north-central part of the Piceance Basin. The center of subsequent saline mineral deposition in Lake Uinta occupied approximately this same area.

Lake-margin shelves began to prograde into Lake Uinta shortly after maximum transgression, and by the onset of saline mineral precipitation, these shelves had reached a width of at least 20 mi in the southern part of the Piceance Basin and more than 45 mi in the southern part of the Uinta Basin. Marginal shelf progradation was towards the deepest part of the lake in the north-central part of the basin, where oil shale deposition had occurred during the earlier freshwater lake interval. These shallow shelves were exposed to intense evaporation , with brines and salt crusts forming in areas where near complete evaporation of the water column occurred. Brines and salt crusts were likely washed into the deep central lake area once water level rose again, contributing to the deep brine layer that was accumulating there, as previously suggested by many authors (Smith, 1974, p. 77; Ryder and others, 1976; Eugster and Hardie, 1978; Surdam and Stanley, 1979; Johnson, 1985, p. 272; Remy and Ferrell, 1989). As there are no known saline mineral deposits in the Uinta Basin part of Lake Uinta until much later, after the deep central lake area of the Piceance Basin had been filled in, any brines and salt crusts that formed on the broad marginal shelves in the Uinta Basin must have been washed into the deep central lake area in the Piceance Basin as well (Dyni, 1981). Large amounts of mineral and organic matter that accumulated on the marginal shelves also appears to have washed into the deep central lake area, creating the “blebby oil shale beds” that are common there, and it is possible that the brines, mineral matter, and organic matter were transported together in density currents that sometimes resembled turbidity currents, as envisioned by Dyni and Hawkins (1981).

Saline mineral deposition throughout the early saline mineral phase (R-2 through L-2 oil shale zones) was confined to the deep central lake area. Nahcolite aggregates and disseminated nahcolite crystals in the upper part of the R-2 oil shale zone in the north-central part of the Piceance Basin mark the onset of saline mineral deposition in Lake Uinta. Nahcolite aggregates formed in the soft sediments during the initial stages of dewatering, whereas disseminated nahcolite was deposited along with kerogen-rich marl near the sediment-water interface (Dyni, 1974c, 1981). Nahcolite beds, precipitated directly from the deep brine layer, appear for the first time in the L-4 oil shale zone (Dyni, 1981).

Isopach maps of the R-2, L-2, and L-3 zones display maximum thicknesses in generally east-west trending areas along the southern margin of this topographic low with the thick area for each progressively younger zone occurring somewhat to the north of the preceding one (fig. 23). The R-3 zone thickens toward the saline mineral area. These thick areas are significantly basinward from the marginal shelf areas during the R-2 through L-3 period (figs. 7–10), suggesting that these sediments were deposited at the base of the slope between the marginal shelves and deep-basin floor.

Oil shale deposition gradually expanded over the marginal shelf areas during the middle saline mineral phase as the water level of Lake Uinta rose, probably because of increasing inflow from Lake Gosiute to the north. The saline mineral area also expanded throughout much of the middle saline mineral phase, reaching approximately to the shelf edge at the end of the illitic phase by the end of the middle saline mineral phase. This suggests that the shelf break persisted as a topographic feature throughout the middle saline mineral phase.


108°30'
108°00'
40°00'
39°30'
Study area
Highest oil shale zone where nahcolite and halite widely preserved.
Sandy L-5 zone along north margin of basin possibly indicates outflow from Lake Gosiute.
Brines were probably entering near here from Uinta Basin to west.
Area of nahcolite deposition continues to expand to southeast.
For the first time nahcolite zone extends into low-grade (<10 GPT) oil shale area.
Marginal shelf areas expand slightly from underlying R-5 zone.
Several isolated occurrences of intact nahcolite identified around margins of saline area.
Generalized present-day limit of Green River Formation.
35,000
105,000
70,000
10 GPT
10 GPT
N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

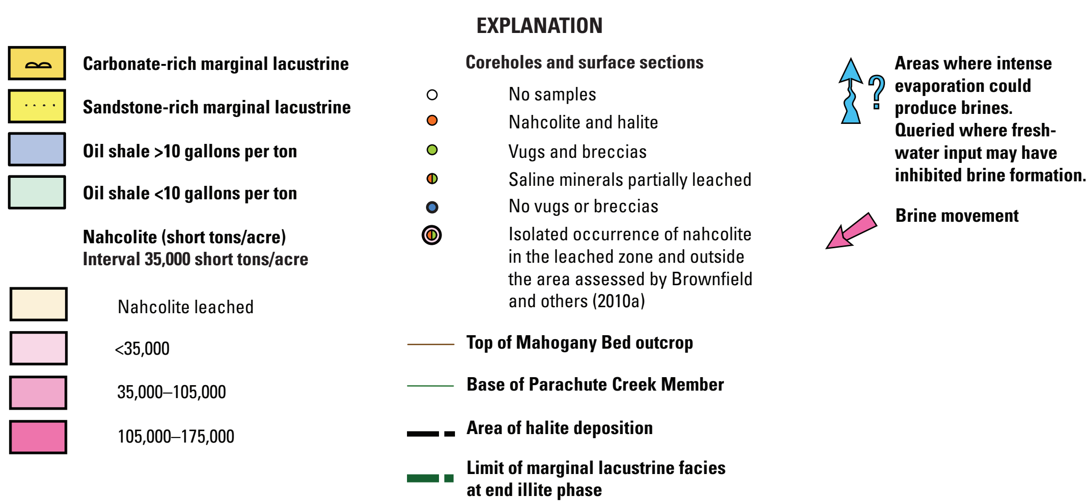
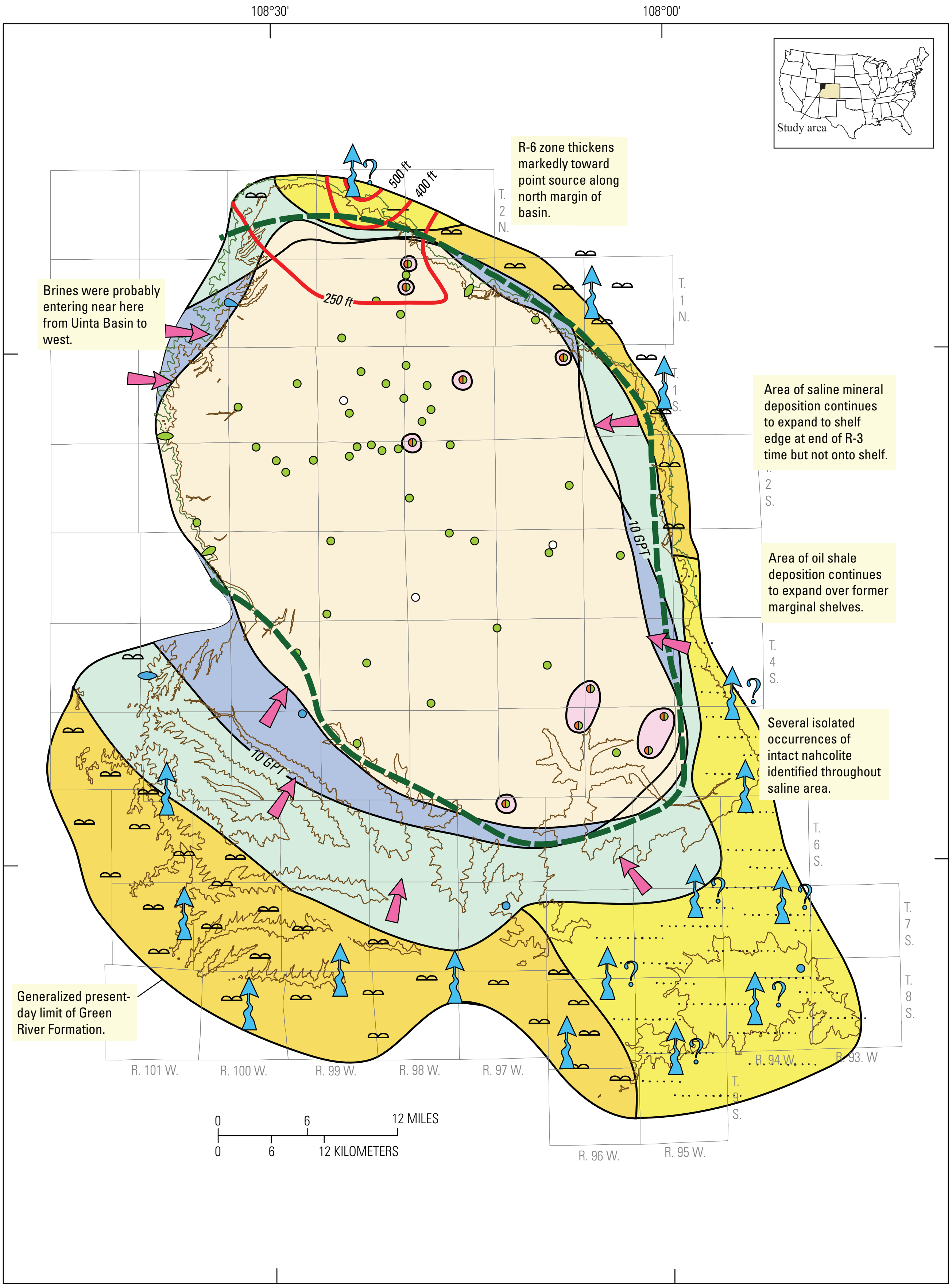


Figure 27 (previous page). Map of the L-5 oil shale zone showing (1) where nahcolite is present and total in-place nahcolite (modified from Brownfield and others, 2010a), (2) where nahcolite has been leached or partially leached out by groundwater, (3) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (4) extent of marginal lacustrine deposition (modified from Johnson, 1985), (5) limit of marginal lacustrine facies at the end of the illitic phase, and (6) approximate area where halite is present. Locations of coreholes used are shown. Several isolated occurrences of preserved nahcolite in the leached area were identified.


108°30'
108°00'
40°00'
39°30'
Study area
R-6 zone thickens markedly toward point source along north margin of basin.
500 ft
400 ft
250 ft
Brines were probably entering near here from Uinta Basin to west.
Area of saline mineral deposition continues to expand to shelf edge at end of R-3 time but not onto shelf.
Area of oil shale deposition continues to expand over former marginal shelves.
Several isolated occurrences of intact nahcolite identified throughout saline area.
10 GPT
10 GPT
Generalized present-day limit of Green River Formation.
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 4 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

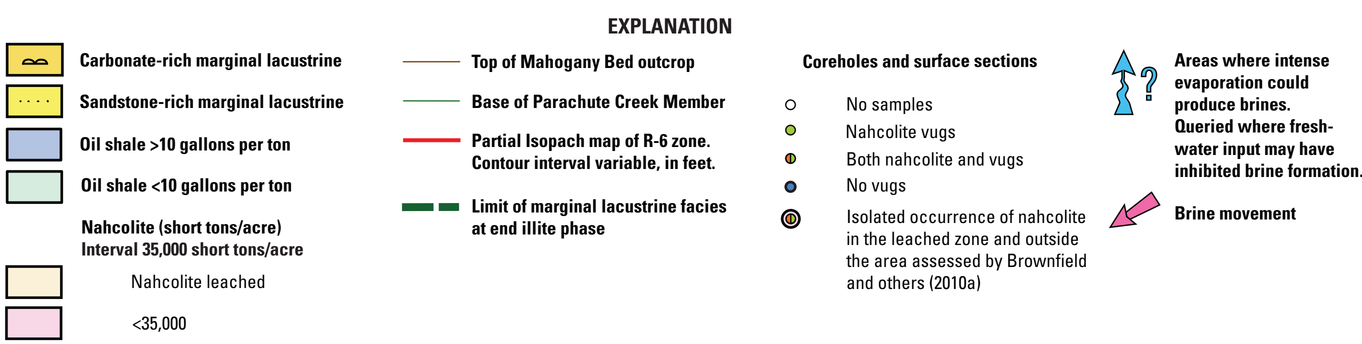
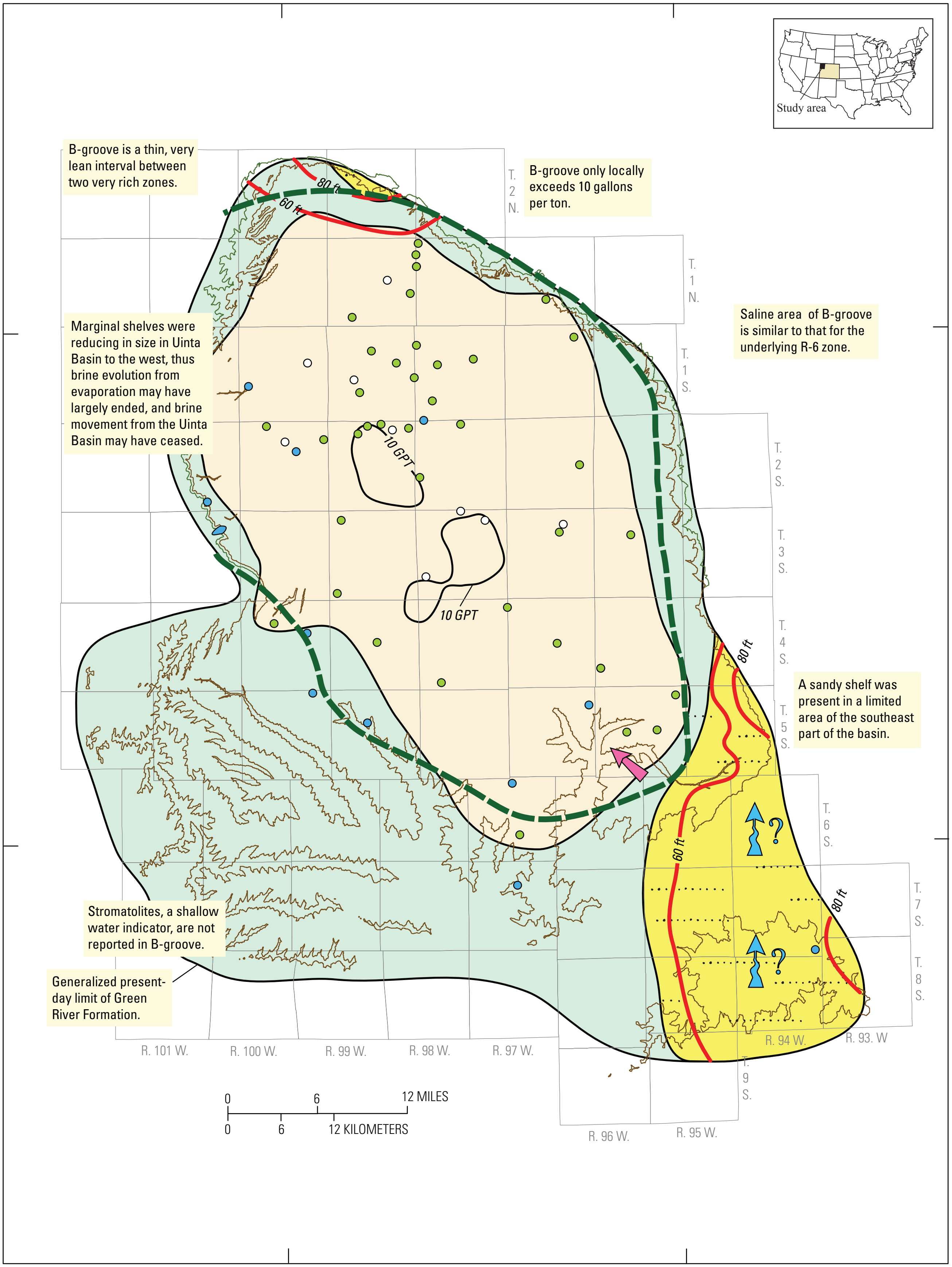


Figure 28 (previous page). Map of the R-6 oil shale zone showing (1) where nahcolite has been leached out by groundwater, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (3) extent of marginal lacustrine deposition (modified from Johnson, 1985), and (4) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. Nahcolite is mostly leached from the R-6 zone, but several isolated occurrences of preserved nahcolite were identified. Isopach lines in the northern part of the basin show thickness of the R-6 zone (modified from Johnson and others, 2010a).


108°30'
108°00'
40°00'
39°30'
Study area
B-groove is a thin, very lean interval between two very rich zones.
B-groove only locally exceeds 10 gallons per ton.
Saline area of B-groove is similar to that for the underlying R-6 zone.
Marginal shelves were reducing in size in Uinta Basin to the west, thus brine evolution from evaporation may have largely ended, and brine movement from the Uinta Basin may have ceased.
A sandy shelf was present in a limited area of the southeast part of the basin.
Stromatolites, a shallow water indicator, are not reported in B-groove.
Generalized present-day limit of Green River Formation.
80 ft
60 ft
10 GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

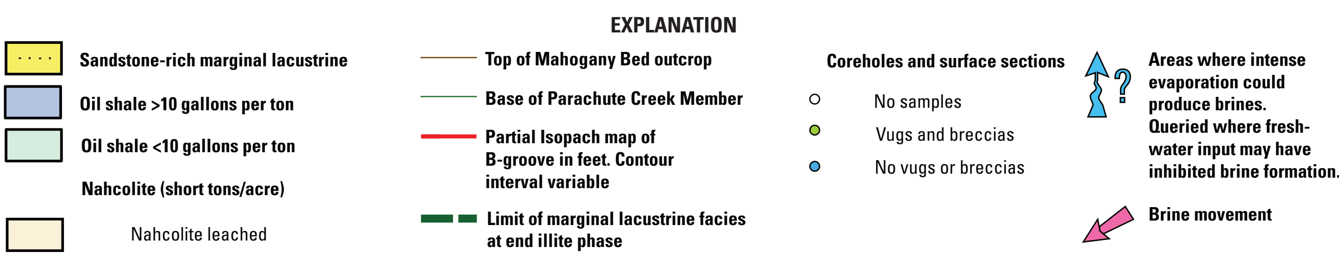
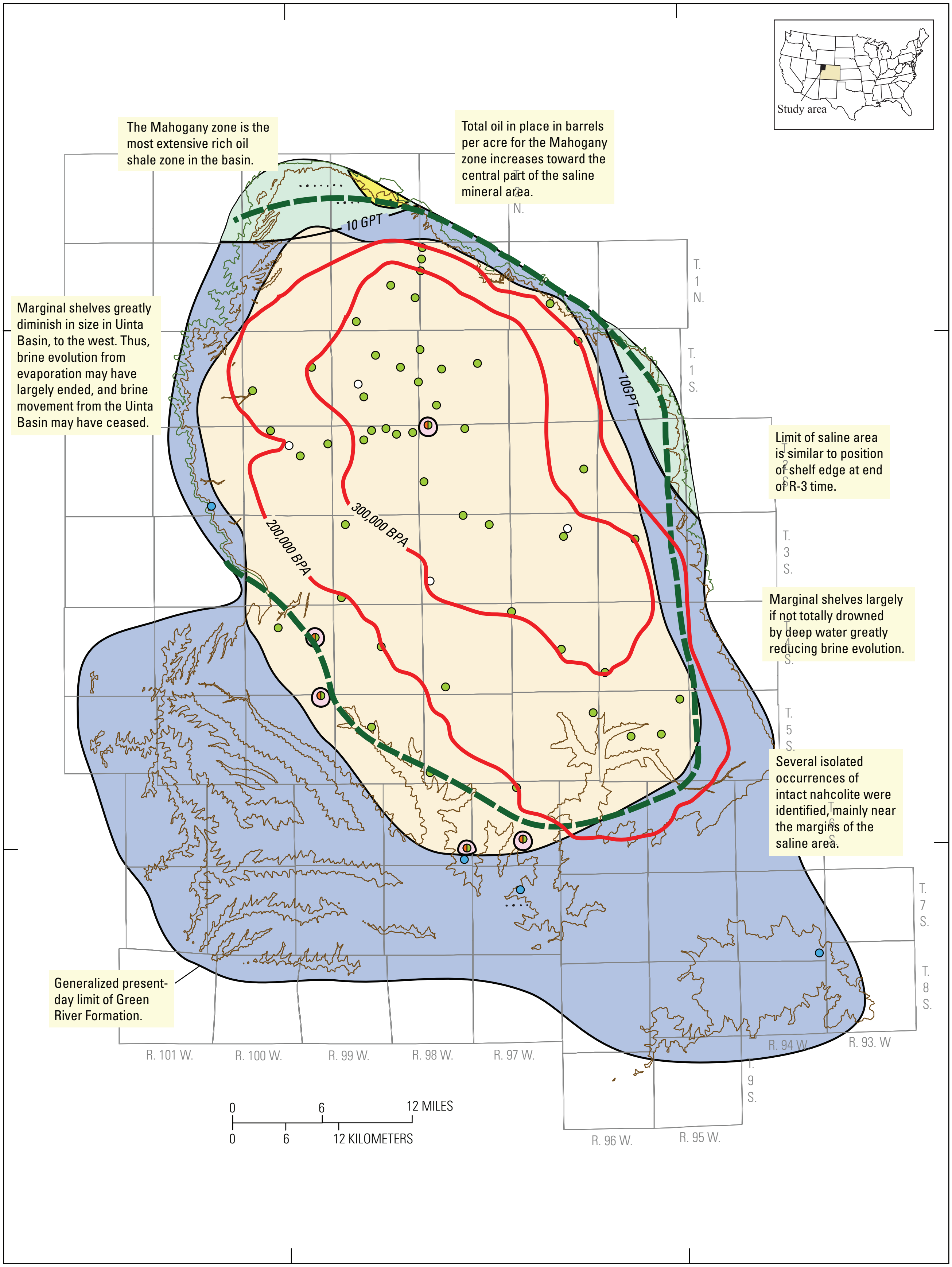


Figure 29 (previous page). Map of B-groove oil shale zone showing (1) where nahcolite has been leached out by groundwater, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), and (3) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. Sandy marginal lacustrine rocks are limited to the southeastern part of the basin and to an isolated area in the northern part of the basin. Three isolated occurrences of preserved nahcolite were identified. Isopach map in the northern part and southeast part of the basin is thickness of B-groove (modified from Johnson and others, 2010a).


108°30'
108°00'
40°00'
39°30'
Study area
The Mahogany zone is the most extensive rich oil shale zone in the basin.
Total oil in place in barrels per acre for the Mahogany zone increases toward the central part of the saline mineral area.
Marginal shelves greatly diminish in size in Uinta Basin, to the west. Thus, brine evolution from evaporation may have largely ended, and brine movement from the Uinta Basin may have ceased.
Limit of saline area is similar to position of shelf edge at end of R-3 time.
Marginal shelves largely if not totally drowned by deep water greatly reducing brine evolution.
Several isolated occurrences of intact nahcolite were identified, mainly near the margins of the saline area.
Generalized present-day limit of Green River Formation.
10 GPT
10GPT
200,000 BPA
300,000 BPA
T. 1 N.
T. 1 S.
T. 3 S.
T. 5 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

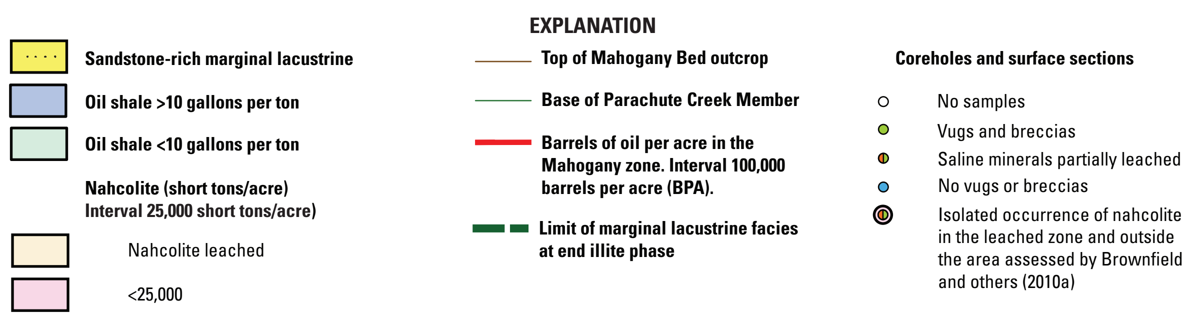
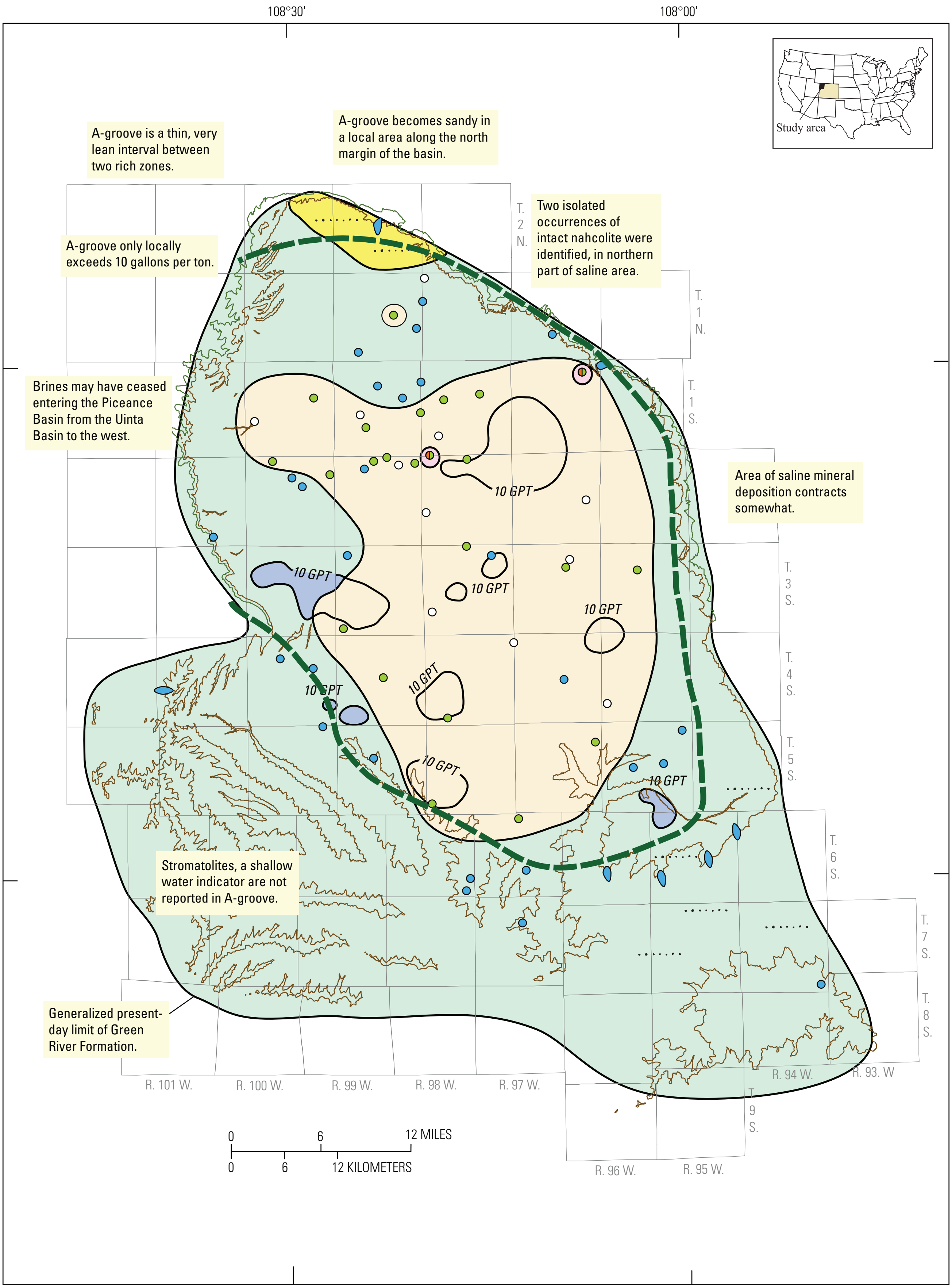


Figure 30 (previous page). Map of the Mahogany oil shale zone showing (1) where nahcolite has been leached out by groundwater, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (3) total oil yield for the Mahogany zone in barrels per acre (BPA) (modified from Johnson and others 2010a), and (4) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. Sandy marginal lacustrine rocks are present in a limited area in the northern part of the basin. Several isolated occurrences of preserved nahcolite were identified.


108°30'
108°00'
40°00'
39°30'
Study area
A-groove is a thin, very lean interval between two rich zones.
A-groove becomes sandy in a local area along the north margin of the basin.
Two isolated occurrences of intact nahcolite were identified, in northern part of saline area.
A-groove only locally exceeds 10 gallons per ton.
Brines may have ceased entering the Piceance Basin from the Uinta Basin to the west.
Area of saline mineral deposition contracts somewhat.
Stromatolites, a shallow water indicator are not reported in A-groove.
Generalized present-day limit of Green River Formation.
10 GPT
T. 2 N.
T. 1 N.
T. 1 S.
T. 3 S.
T. 4 S.
T. 5 S.
T. 6 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93. W
0 6 12 MILES
0 6 12 KILOMETERS

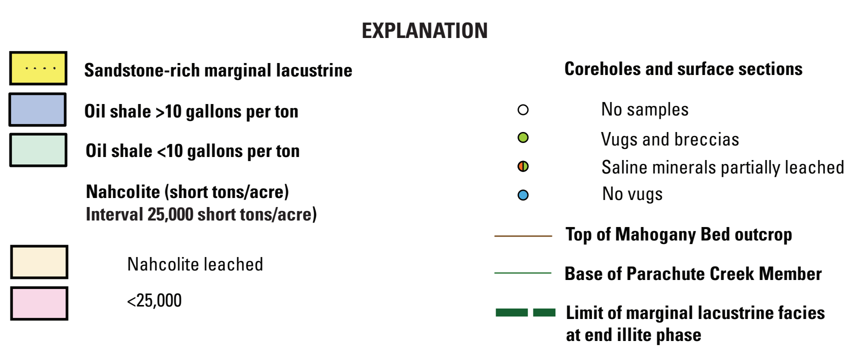
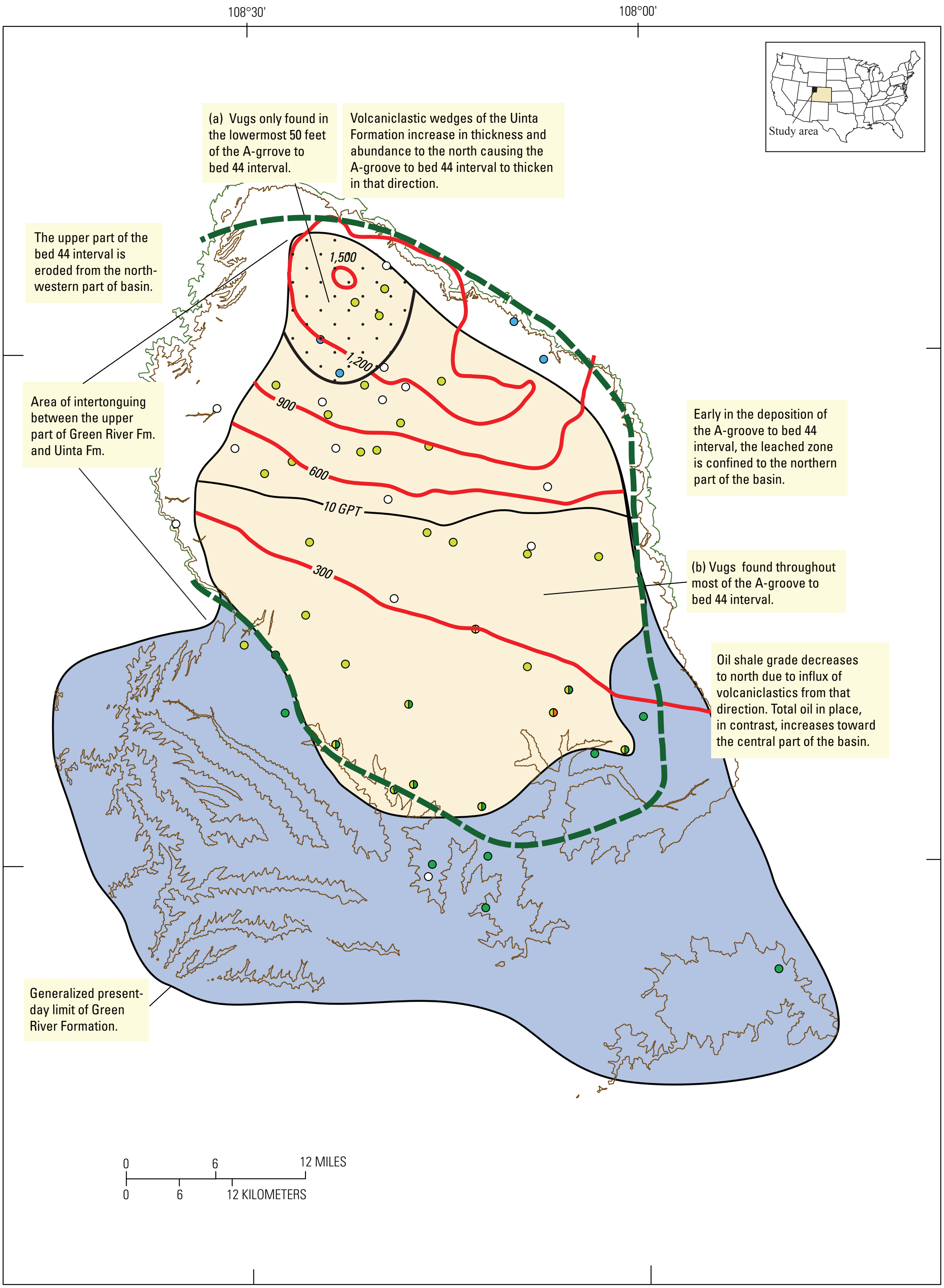


Figure 31 (previous page). Map of A-groove oil shale zone showing (1) where nahcolite has been leached out by groundwater, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (3) limited area in the northern part of the basin where marginal lacustrine rocks were identified, and (4) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. Two isolated occurrences of preserved nahcolite were identified near the northeastern margin of the leached zone.


108°30'
108°00'
40°00'
39°30'
Study area
(a) Vugs only found in the lowermost 50 feet of the A-grrove to bed 44 interval.
Volcaniclastic wedges of the Uinta Formation increase in thickness and abundance to the north causing the A-groove to bed 44 interval to thicken in that direction.
The upper part of the bed 44 interval is eroded from the north-western part of basin.
Area of intertonguing between the upper part of Green River Fm. and Uinta Fm.
Early in the deposition of the A-groove to bed 44 interval, the leached zone is confined to the northern part of the basin.
(b) Vugs found throughout most of the A-groove to bed 44 interval.
Oil shale grade decreases to north due to influx of volcaniclastics from that direction. Total oil in place, in contrast, increases toward the central part of the basin.
Generalized present-day limit of Green River Formation.
1,500
1,200
900
600
10 GPT
300
0 6 12 MILES
0 6 12 KILOMETERS

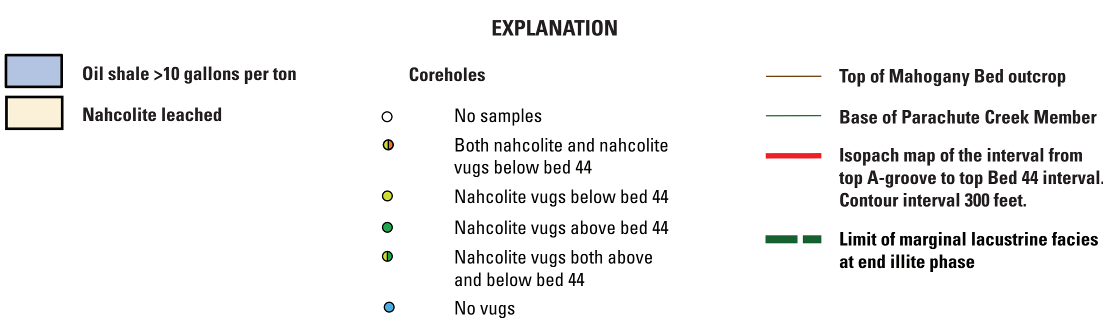
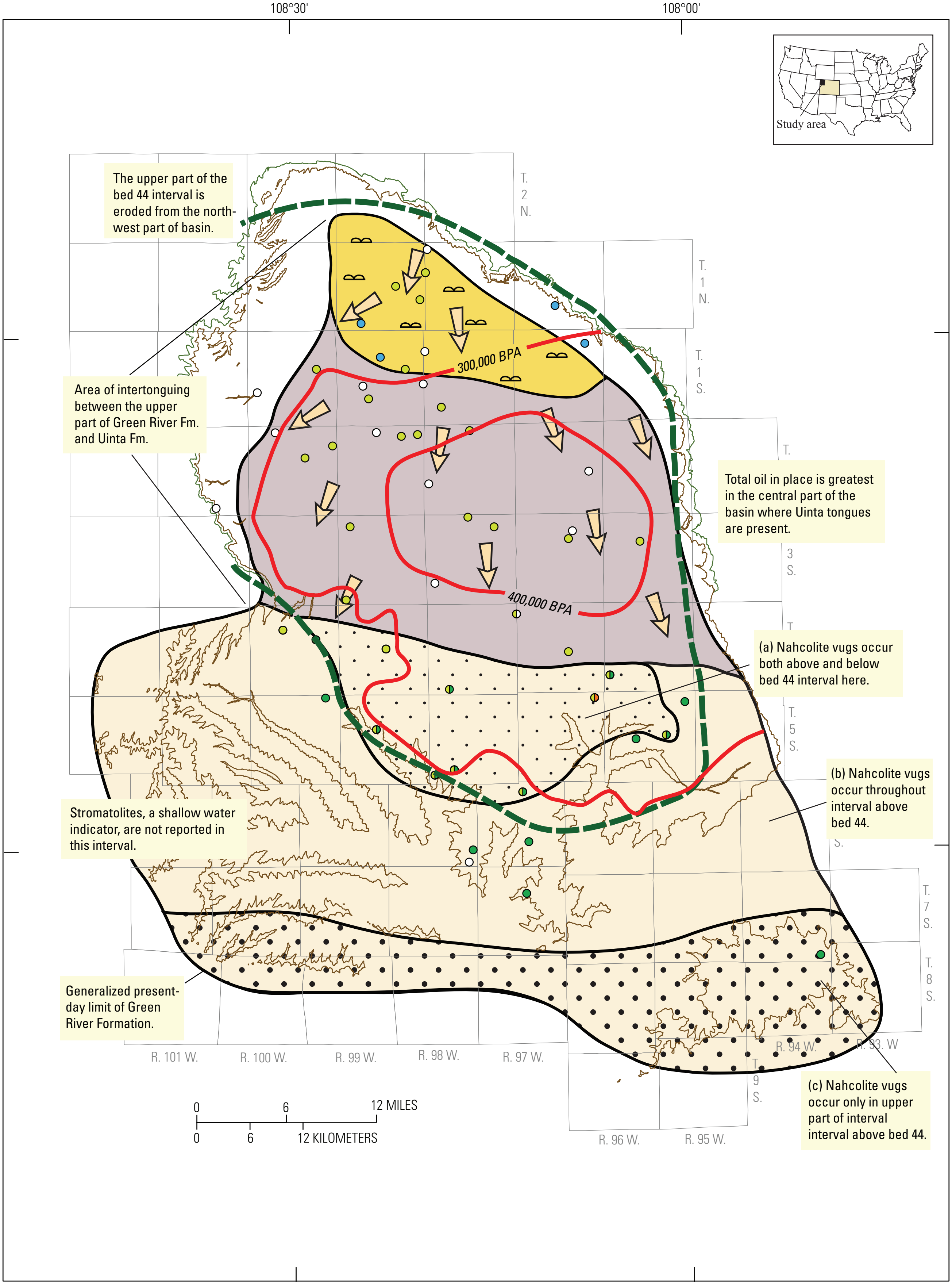


Figure 32 (previous page). Map from the beginning of deposition of the A-groove to the top of bed 44 of Donnell (2008) showing (1) where nahcolite has been leached out by groundwater, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010a), (3) thickness of the A-groove to top of bed 44 interval (modified from Johnson and others, 2010a), and (4) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. The leached area is subdivided into (a) where vugs are found only in the lowermost 50 feet of the A-groove to bed 44 interval (dotted area), and (b) where vugs are found throughout most of the A-groove to bed 44 interval.


108°30'
108°00'
40°00'
39°30'
Study area
The upper part of the bed 44 interval is eroded from the north-west part of basin.
Area of intertonguing between the upper part of Green River Fm. and Uinta Fm.
Total oil in place is greatest in the central part of the basin where Uinta tongues are present.
300,000 BPA
400,000 BPA
(a) Nahcolite vugs occur both above and below bed 44 interval here.
(b) Nahcolite vugs occur throughout interval above bed 44.
Stromatolites, a shallow water indicator, are not reported in this interval.
Generalized present-day limit of Green River Formation.
(c) Nahcolite vugs occur only in upper part of interval interval above bed 44.
T. 2 N.
T. 1 N.
T. 1 S.
T. 3 S.
T. 5 S.
T. 7 S.
T. 8 S.
T. 9 S.
R. 101 W.
R. 100 W.
R. 99 W.
R. 98 W.
R. 97 W.
R. 96 W.
R. 95 W.
R. 94 W.
R. 93 W.
0 6 12 MILES
0 6 12 KILOMETERS

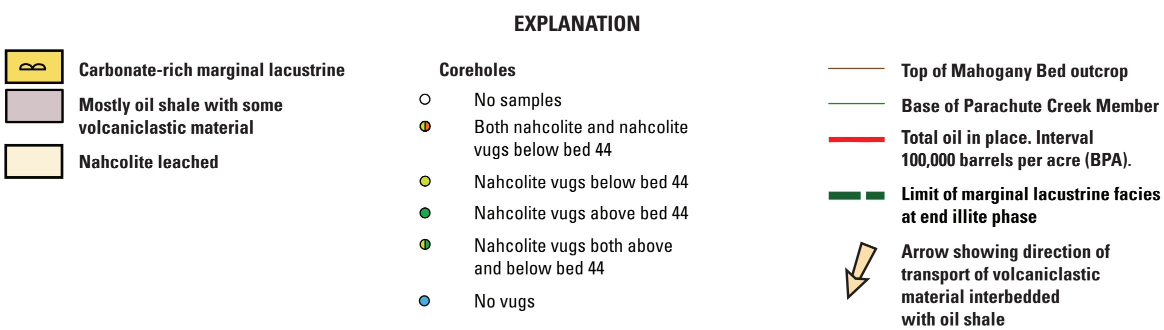


Figure 33 (previous page). Map from the top of bed 44 to the top of the oil shale interval showing (1) where nahcolite vugs occur above bed 44, (2) extent of marginal lacustrine deposition at top of bed 44, (3) total oil in place in the B-groove to bed 44 interval, and (4) limit of marginal lacustrine facies at the end of the illitic phase. Locations of coreholes used are shown. The leached area is subdivided into (a) where vugs occur both above and below bed 44 (dotted area), (b) where vugs occur throughout interval above bed 44, and (c) where nahcolite vugs occur only in uppermost part of interval above bed 44 (dotted area).

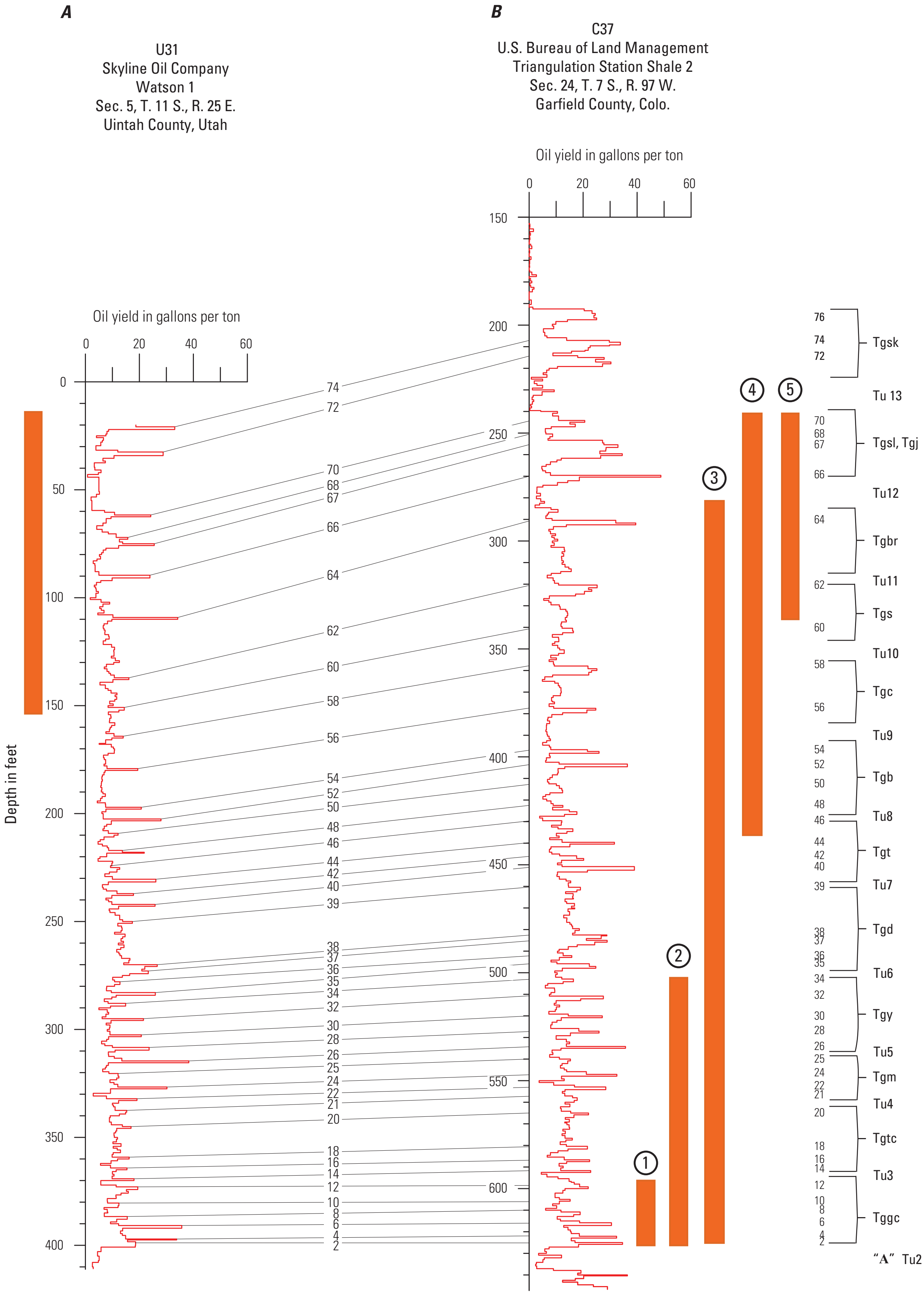

A
U31
Skyline Oil Company
Watson 1
Sec. 5, T. 11 S., R. 25 E.
Uintah County, Utah
B
C37
U.S. Bureau of Land Management
Triangulation Station Shale 2
Sec. 24, T. 7 S., R. 97 W.
Garfield County, Colo.
Oil yield in gallons per ton
Depth in feet
Tgsk
Tu 13
Tgsl, Tgj
Tu12
Tgbr
Tu11
Tgs
Tu10
Tgc
Tu9
Tgb
Tu8
Tgt
Tu7
Tgd
Tu6
Tgy
Tu5
Tgm
Tu4
Tgtc
Tu3
Tggc
"A" Tu2

Figure 34 (previous page). Cross section showing correlation of individual oil shale beds between two coreholes for the interval above A-groove (modified from Donnell, 2008, fig. 4). *A*, Eastern part of the Uinta Basin. The red bar for Uinta Basin corehole shows stratigraphic interval where nahcolite vugs are found in the eastern part of the Uinta Basin. Area where nahcolite vugs are found in the eastern part of the Uinta Basin shown on figure 35. *B*, Southern part of the Piceance Basin. Five red bars show stratigraphic interval where nahcolite vugs are found for five different areas in the Piceance Basin with area (1) the farthest north and area (5) the farthest south. Areas where vugs are found in these five intervals are shown on figures 32 and 33. Locations of coreholes are shown on figure 35. Uinta Formation units (Tu) are numbered 2 through 13. Numbers 2 through 76 are persistent oil shale beds defined by Donnell (2008). ("A", base of A-groove; Tggc, marlstone at Greasewood Creek; Tgtc, marlstone at Trail Canyon; Tgm, marlstone at Mare Canyon; Tgy, Yellow Creek Tongue; Tgd, Dry Fork Tongue; Tgt, Thirteenmile Creek Tongue; Tgb, Black Sulfur Tongue; Tgc, Coughs Creek Tongue; Tgs, Stewart Gulch Tongue; Tgbr, marlstone at Barnes Ridge; Tgsl, marlstone at Sleepy Ridge; Tgj, marlstone at Jack Rabbit Ridge; Tgsk, marlstone at Skinner Ridge.)

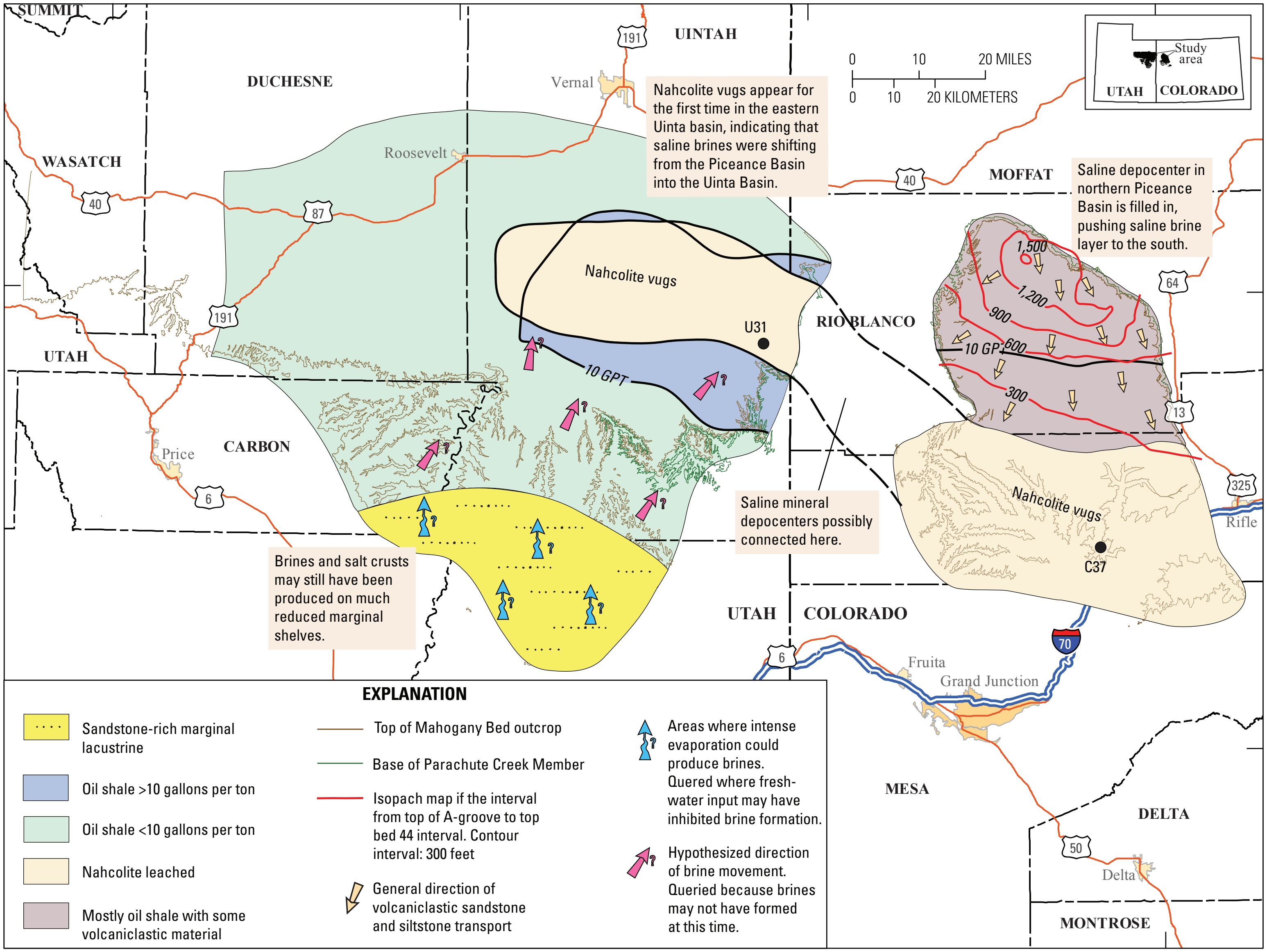


Figure 35. Paleogeographic map of the Uinta and Piceance Basins at the end of the A-groove to bed 44 interval showing (1) where nahcolite vugs occur in both basins, (2) where oil yields are greater than and less than 10 gallons per ton (GPT) (modified from Johnson and others, 2010 a, b), and (3) areas of marginal lacustrine deposition (modified from Johnson, 1985).

In the late saline mineral phase, the saline mineral area was progressively pushed southward as the Piceance Basin portion of Lake Uinta was filled in by volcaniclastic sediments, ultimately reaching the former shelf areas in the southern part of the basin. Saline minerals appear for the first time in the eastern part of the Uinta Basin during this period, indicating that the brine layer was being pushed into that basin, and for a time, saline minerals were deposited in both basins.

Leaching of the saline interval is complex, and a transition zone is commonly present in which saline minerals have been only partially removed. Permeability of oil shale is low, and a scarcity of fractures may explain the incomplete groundwater penetration in these areas. The base of the transition zone appears to be a fairly well-defined surface that generally slopes downward from recharge areas around the southern and western margins of the basin to discharge points just south of the White River in the northern part of the basin. It is not entirely clear what controls the position of this surface or even if it is a relatively smooth surface, as the limited data used here suggest. The surface appears to rise over the Piceance Creek dome, suggesting that basin structure plays some role, at least locally. The base of leaching also slopes toward the discharge area, suggesting that this may play a role. The base of the surface is about 1,600 ft lower than the saline springs in the discharge area. Robson and Saulnier (1981) presented compelling evidence that faults and fractures allow highly saline waters to reach the surface in the discharge area, but basin structure may also play a role. The basin sharply upturns, with dips to as much as 14^{o} (Pipiringos and Johnson, 1976) (fig. 21), in the discharge area, possibly allowing saline groundwater to move updip along bedding planes. In addition, groundwater movement may have been aided by the presence of permeable lithologies such as marginal lacustrine sandstones and carbonates in this area, particularly in the vicinity of the mouth of Yellow Creek (pl. 2).

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Plates

Detailed structural cross sections through the Eocene Green River Formation across the Piceance Basin, northwestern Colorado, constructed from oil-yield histograms and core descriptions from coreholes drilled to evaluate oil shale resources and from detailed surface sections. Correlation of individual oil shale zones, variations in lithologies, and intervals where saline minerals are present or where there is evidence that saline minerals were leached out are shown. Datum is sea level.

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