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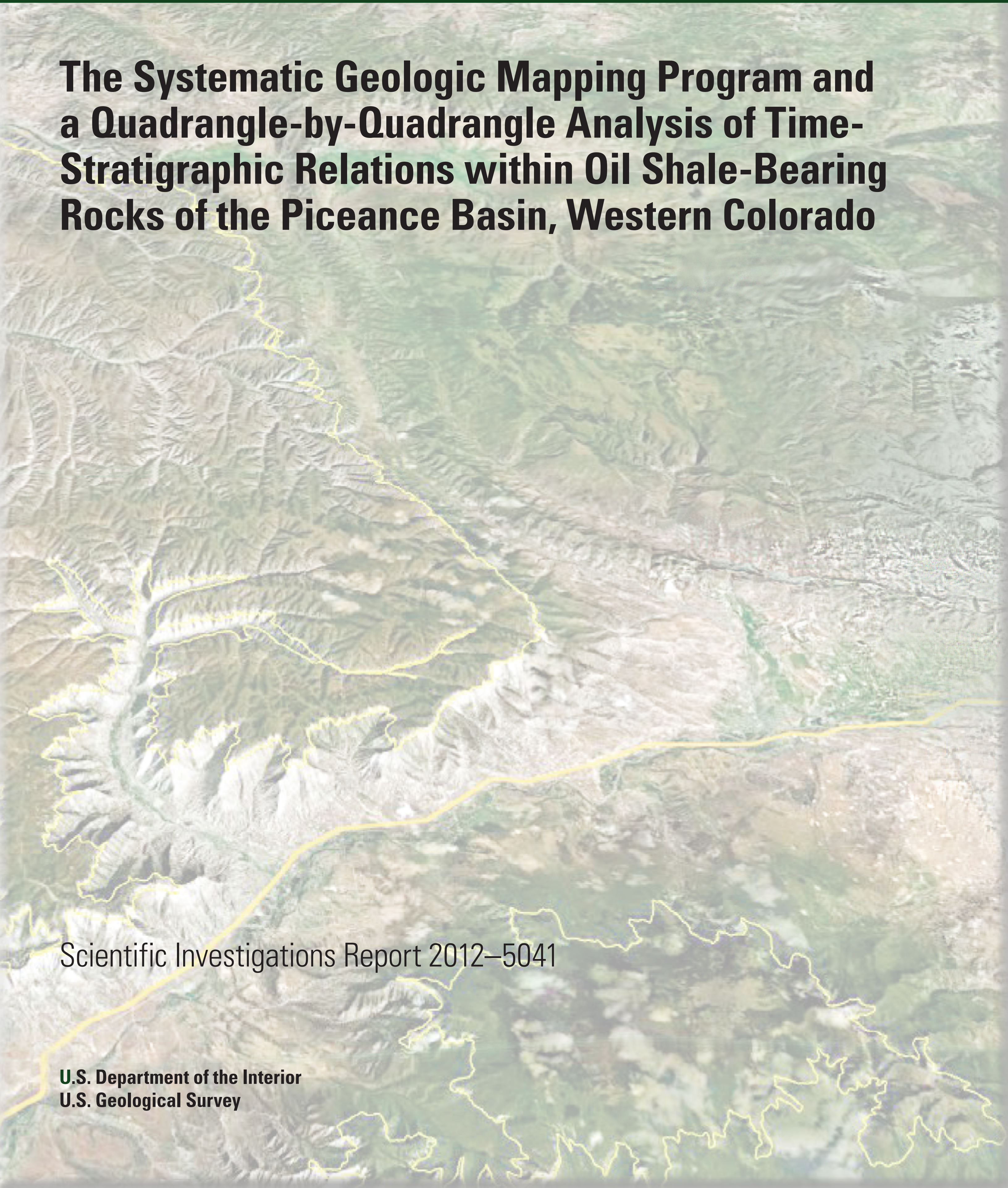

The Systematic Geologic Mapping Program and a Quadrangle-by-Quadrangle Analysis of Time-Stratigraphic Relations within Oil Shale-Bearing Rocks of the Piceance Basin, Western Colorado

Scientific Investigations Report 2012–5041

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

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U.S. Geological Survey
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Contents

Figures

Plates

The Systematic Geologic Mapping Program and a Quadrangle-by-Quadrangle Analysis of Time-Stratigraphic Relations within Oil Shale-Bearing Rocks of the Piceance Basin, Western Colorado

By Ronald C. Johnson

Abstract

During the 1960s, 1970s, and 1980s, the U.S. Geological Survey mapped the entire area underlain by oil shale of the Eocene Green River Formation in the Piceance Basin of western Colorado. The Piceance Basin contains the largest known oil shale deposit in the world, with an estimated 1.53 trillion barrels of oil in place and as much as 400,000 barrels of oil per acre. This report places the sixty-nine 7½-minute geologic quadrangle maps and one 15-minute quadrangle map published during this period into a comprehensive time-stratigraphic framework based on the alternating rich and lean oil shale zones. The quadrangles are placed in their respective regional positions on one large stratigraphic chart so that tracking the various stratigraphic unit names that have been applied can be followed between adjacent quadrangles. Members of the Green River Formation were defined prior to the detailed mapping, and many inconsistencies and correlation problems had to be addressed as mapping progressed. As a result, some of the geologic units that were defined prior to mapping were modified or discarded. The extensive body of geologic data provided by the detailed quadrangle maps contributes to a better understanding of the distribution and characteristics of the oil shale-bearing rocks across the Piceance Basin.

Introduction

The Eocene Green River Formation in the Piceance Basin in Colorado, the Uinta Basin in Utah and Colorado, and the Greater Green River Basin in Wyoming, Colorado, and Utah (fig. 1) contains one of the largest known oil shale deposits in the world. Resources are estimated at 1.53 trillion barrels of oil in place in the Piceance Basin (Johnson and others, 2010a), 1.32 trillion barrels in place in the Uinta Basin (Johnson and others, 2010b), and 1.44 trillion barrels in place in the Greater Green River Basin (Johnson and others, 2011). The oil shale was deposited in two large long-lived lakes that covered much of these basins in Eocene time, Lake Uinta in the Uinta and Piceance Basins and Lake Gosiute in the Greater Green River Basin (fig. 1; see Geology of the Green River Formation section). The oil shale deposit in the Piceance Basin (fig. 2), the focus of this report, is probably the world's most concentrated oil shale resource with an estimated 400,000 barrels of oil in place per acre in the oil shale depocenter in the north-central part of the basin (fig. 3A). Interest in developing this oil shale deposit increased during periods of high petroleum prices due to high demand including (1) just before World War I and extending into the 1920s, (2) during and after World War II, (3) from 1973 at the start of the Arab oil embargo into the mid-1980s, and (4) the first part of this century. For the first three high-demand periods, oil prices and demand declined before a viable oil shale industry could be established. Oil prices have also declined considerably since peaking in 2007. In view of these fluctuations in economic conditions, the future of an oil shale industry remains unclear.

A considerable body of work concerning the oil shale deposit of the Green River Formation was published by the U.S. Geological Survey (USGS), most notably during the 1960s, 1970s, and 1980s, and most of this work was scanned and made available on the USGS oil shale web page at the beginning of the recent interest in oil shale (*http://energy.cr.usgs.gov/other/oil_shale/*). Included in this work are sixty-nine detailed 7½-minute, 1:24,000-scale geologic quadrangle maps and the Citadel Plateau 15-minute, 1:62,500-scale quadrangle map that cover nearly the entire area underlain by oil shale in the Piceance Basin and that small part of the Uinta Basin that is in Colorado (fig. 4). These maps, which now represent the most detailed geologic mapping available for the oil shale area in Colorado, (1) largely supersede earlier, less detailed 1:63,360-scale mapping around the west, south, and east margins of the basin published in the late 1940s and early 1950s (Duncan and Denson, 1949; Duncan and Belser, 1950; Waldron and others, 1951; Donnell and others, 1953) and (2) extend the larger scale, detailed mapping into the previously unmapped central and northern parts of the basin.

The stratigraphy of the Green River Formation and related units is complex, with high variability, and may be confusing to someone unfamiliar with the area. One of the

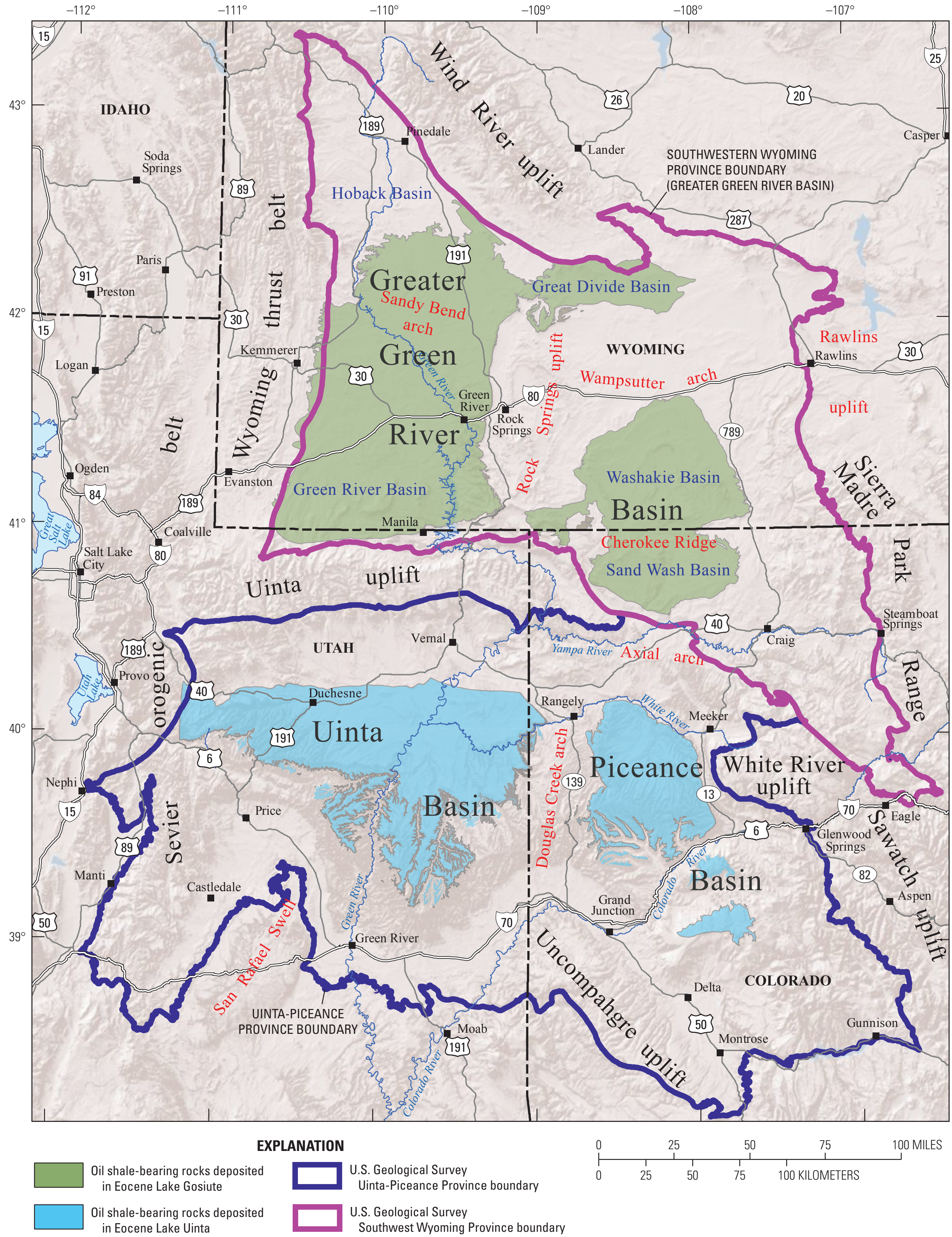

–112°
–111°
–110°
–109°
–108°
–107°
43°
42°
41°
40°
39°
IDAHO
WYOMING
UTAH
COLORADO
Wind River uplift
Wyoming thrust belt
Sevier orogenic belt
Hoback Basin
Greater Green River Basin
Sandy Bend arch
Great Divide Basin
Green River Basin
Washakie Basin
Rock Springs uplift
Wampsutter arch
Rawlins uplift
Sierra Madre
Park Range
Cherokee Ridge
Sand Wash Basin
Uinta uplift
Axial arch
Uinta Basin
Piceance Basin
Douglas Creek arch
White River uplift
Sawatch uplift
Uncompahgre uplift
San Rafael Swell
SOUTHWESTERN WYOMING
PROVINCE BOUNDARY
(GREATER GREEN RIVER BASIN)
UINTA-PICEANCE
PROVINCE BOUNDARY
Pinedale
Lander
Casper
Soda Springs
Paris
Preston
Logan
Kemmerer
Green River
Rock Springs
Rawlins
Evanston
Ogden
Manila
Coalville
Salt Lake City
Vernal
Steamboat Springs
Craig
Provo
Duchesne
Rangely
Meeker
Nephi
Price
Eagle
Glenwood Springs
Aspen
Manti
Castledale
Grand Junction
Green River
Delta
Moab
Montrose
Gunnison
Great Salt Lake
Utah Lake
Green River
Yampa River
White River
Colorado River
15
25
26
20
189
89
287
191
91
30
80
789
84
40
6
139
13
70
82
50
EXPLANATION
Oil shale-bearing rocks deposited in Eocene Lake Gosiute
Oil shale-bearing rocks deposited in Eocene Lake Uinta
U.S. Geological Survey Uinta-Piceance Province boundary
U.S. Geological Survey Southwest Wyoming Province boundary
0 25 50 75 100 MILES
0 25 50 75 100 KILOMETERS

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

main purposes of this report is to help new users better understand this large, complex body of work. For that purpose, two stratigraphic diagrams for each of the 70 quadrangle maps are presented (pl. 1 A and B). The first shows relative time represented by all the units that contain significant oil shale in each quadrangle and the second shows relative thicknesses. The stratigraphic diagrams are arranged on two large charts with each quadrangle plotted in its proper position with respect to adjacent quadrangles. This allows for the easy tracking of changes in mapped stratigraphic units from quadrangle to quadrangle. The diagrams include all mapped quadrangles to the Colorado-Utah border, as well as those in the easternmost part of the Uinta Basin (fig. 4).

A comprehensive time-stratigraphic system based on alternating rich and lean oil shale zones has been developed for the oil shale sequences in the Piceance and Uinta Basins. The system assumes that rich and lean oil shale units were deposited during alternating periods of high and low organic productivity, respectively, that occurred simultaneously across the entire area of Lake Uinta. Air fall tuffs interbedded with the oil shale, which are everywhere in the same stratigraphic positions relative to these rich and lean zones, appear to confirm this assumption. Here, all mapped stratigraphic units in the basin are placed into this time-stratigraphic system, so that the relative time represented by these units can be compared basin wide.

The focus of this study is the oil shale-bearing interval of the Green River Formation and equivalent marginal lacustrine and fluvial rocks. Older rocks exposed and mapped in many of these quadrangles are not included in the charts and are not discussed further. A discussion of the overlying volcaniclastic Uinta Formation is included, however, because it intertongues with oil shale-bearing rocks in the upper part of the Green River Formation. The oldest unit included in the charts is the Long Point Bed of the Green River Formation and its equivalent, the basal transgressive bed of Lake Uinta and the base of the stratigraphically lowest significant oil shale interval in both the Piceance and Uinta Basins (figs. 2, 5, and 6). The Long Point Bed marks the onset of a major transgression that resulted in the merger of two earlier freshwater lakes, one in the Uinta Basin and one in the Piceance Basin, to form one lake that extended between the two basins across the intervening Douglas Creek arch (figs. 2, 5, and 6) (Johnson, 1985a). These earlier freshwater-lake deposits compose the Cow Ridge Member of the Green River Formation and contain some oil shale of low grade. The Cow Ridge Member is not included in this study; however, all of the Paleocene and Eocene units that were deposited in the Piceance Basin prior to the development of Lake Uinta, including the Cow Ridge, are discussed by Johnson and Flores (2003).

The Green River Formation crops out in its entirety around much of the margins of the Piceance Basin (fig. 2) where it is typically exposed on towering cliffs with a total vertical relief of as much as 3,600 ft (figs. 7–9). Topographic relief throughout the central part of the basin, in contrast, is generally in the range of a few hundred feet, with only the uppermost part of the Green River Formation and overlying Uinta Formation typically exposed (fig. 7). At first glance, it would seem that the tremendous relief and near complete exposures around the margins of the basin would be a great advantage to mapping geologic units. However, it is nearly impossible to walk along the treacherously steep slopes to map contacts and track the rapid lateral facies changes that are in these basin-margin areas. In addition, much of the Green River Formation tends to weather white due to its high carbonate content, making it difficult to distinguish different lithologies from a distance. As a result, mapping in these areas, including the 1:62,500-scale mapping published in the late 1940s and early 1950s (Duncan and Denson, 1949; Duncan and Belser, 1950; Donnell and others, 1953) and the more recent 1:24,000-scale mapping, relied heavily on stratigraphic sections typically measured and described along the end of ridges, where access is relatively less difficult. However, measured sections, some of the more detailed of which were published along with the geologic maps, had to be as closely spaced as possible to pick up the subtle lateral facies changes. Once contacts were

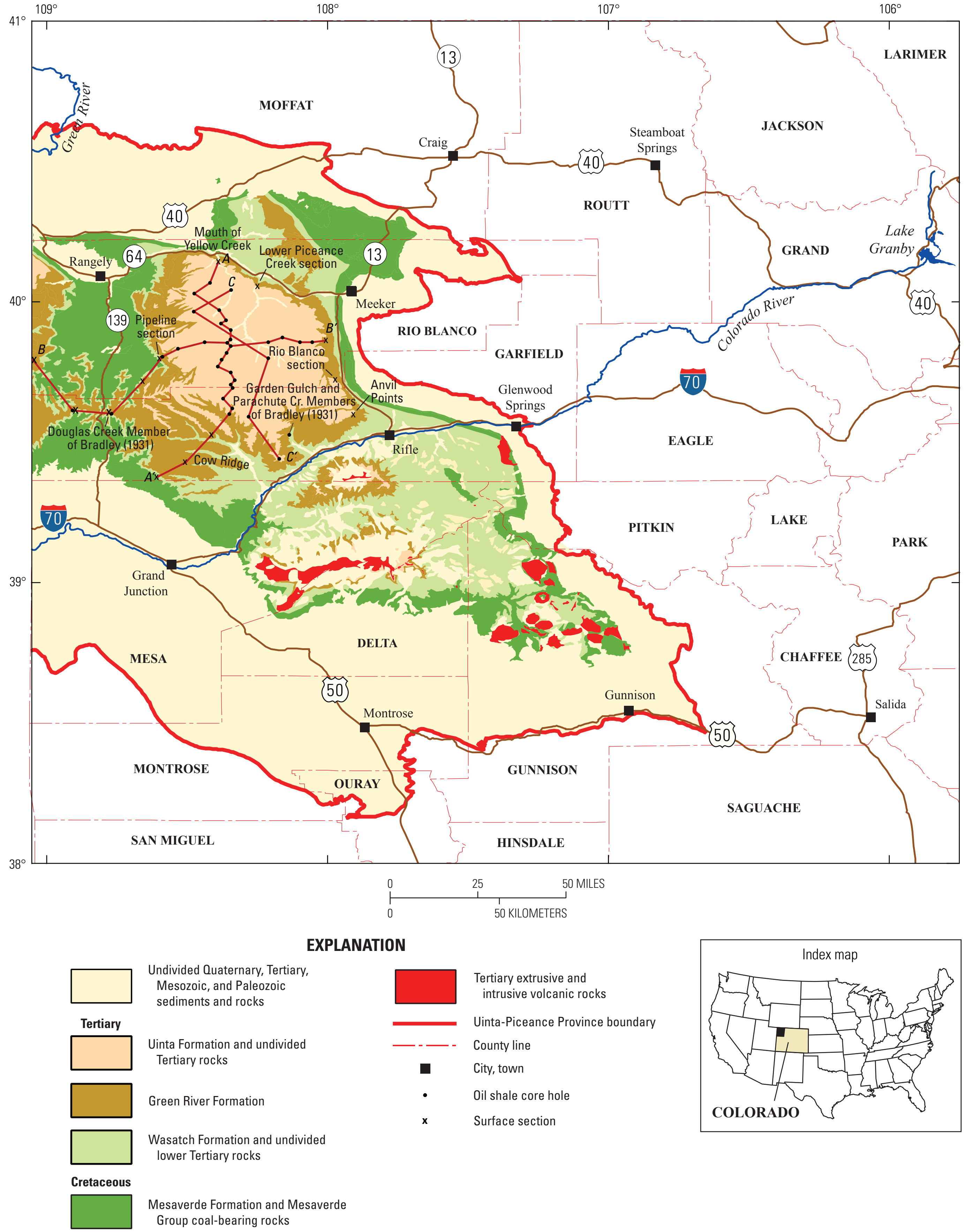

109°
108°
107°
106°
41°
40°
39°
38°
MOFFAT
LARIMER
JACKSON
ROUTT
GRAND
RIO BLANCO
GARFIELD
EAGLE
PITKIN
LAKE
PARK
MESA
DELTA
CHAFFEE
MONTROSE
OURAY
GUNNISON
SAGUACHE
SAN MIGUEL
HINSDALE
Green River
Colorado River
Lake Granby
Craig
Steamboat Springs
Rangely
Meeker
Rifle
Glenwood Springs
Grand Junction
Montrose
Gunnison
Salida
13
40
64
139
70
50
285
Mouth of Yellow Creek
Lower Piceance Creek section
Pipeline section
Rio Blanco section
Garden Gulch and Parachute Cr. Members of Bradley (1931)
Anvil Points
Douglas Creek Member of Bradley (1931)
Cow Ridge
A
A′
B
B′
C
C′
0
25
50 MILES
0
50 KILOMETERS
EXPLANATION
Undivided Quaternary, Tertiary, Mesozoic, and Paleozoic sediments and rocks
Tertiary
Uinta Formation and undivided Tertiary rocks
Green River Formation
Wasatch Formation and undivided lower Tertiary rocks
Cretaceous
Mesaverde Formation and Mesaverde Group coal-bearing rocks
Tertiary extrusive and intrusive volcanic rocks
Uinta-Piceance Province boundary
County line
City, town
Oil shale core hole
Surface section
Index map
COLORADO

Figure 2 (previous page). Generalized geologic map of the Piceance Basin, northwest Colorado, showing Upper Cretaceous and lower Tertiary stratigraphic units. Locations of cross sections A-A′, B-B′, and C-C′ (figures 5, 6, and 11 respectively) and surface sections mentioned in text are shown.

defined in the detailed sections, they were typically surveyed by using a plane table and alidade from high points and by tracing on aerial photographs. If aerial photographs were used, elevations of contacts were then obtained using an appropriate plotter. Most contacts were structure contoured from available data, and these structure contour maps were used to help place the contacts on topographic base maps.

Geology of the Green River Formation

The Eocene Green River Formation was deposited in two large saline lakes, Lake Uinta in the Piceance Basin of western Colorado and the Uinta Basin of eastern Utah and westernmost Colorado and Lake Gosiute in the Greater Green River Basin of southwest Wyoming, northwest Colorado, and northeastern Utah (fig. 1). These structural and sedimentary basins formed during the Laramide orogeny from Late Cretaceous through Eocene. Lake Uinta formed in Eocene time when two much smaller freshwater lakes expanded during the Long Point transgression and connected across the Douglas Creek arch to form one large lake. The Long Point Bed of the Green River Formation was deposited across large areas during this transgression (Johnson, 1984). Lake Uinta became increasingly saline through time (Johnson, 1985a). Freshwater mollusks, common in lacustrine rocks deposited during the earlier freshwater phase, are extremely rare above the Long Point Bed (Johnson, 1984), indicating a change to waters too saline for them to survive. Stromatolites appear to be completely absent from the sediments deposited in the freshwater lakes that preceded Lake Uinta, but become common in marginal lacustrine sediments deposited immediately after the Long Point transgression (Johnson and others, 1988). Stromatolites in the modern environment are known to survive only where grazers such as gastropods and algae-eating fish and burrowers are rare (Garrett, 1970)—the microbial mats that are the essence of stromatolites are consumed by the grazers and are disrupted and destroyed by the digging of burrowers.

Lake Uinta appears to have undergone a relatively steady increase in salinity throughout its early history (Johnson, 1985a), ultimately leading to the precipitation of large quantities of halite and the bicarbonate mineral nahcolite in the oil shale and saline mineral depocenter (fig. 3). The water column was probably stratified with an anoxic, highly alkaline, and highly reducing lower level that prohibited organic matter from being oxidized. For more information on the geochemical evolution of Lake Uinta see Bradley (1929, 1931), Smith (1974), Dyni (1981), and Tuttle and Goldhaber (1991). Johnson (1985a) subdivided the history of Lake Uinta into five time-stratigraphic intervals or stages (figs. 5 and 6). The first two stages are characterized by the deposition of illitic oil shales in the offshore areas, whereas carbonate-rich, mainly dolomitic, oil shales were deposited in offshore areas during the remaining three stages. The beginning of stage 1 is marked by the formation of Lake Uinta during the Long Point transgression. The illitic-rich oil shales from this stage, deposited in the offshore areas of the lake, are of low grade and generally average less than 15 gallons per ton (GPT) oil. Average oil yield increases abruptly at the beginning of the second stage, to a maximum of about 27 GPT, averaged for the entire interval in the central part of the Piceance Basin, with some thin beds averaging nearly 60 GPT. The interval deposited during stage 2 thickens markedly toward the margins of the basin (figs. 5 and 6).

A gradual shift from illitic-rich to carbonate-rich oil shales occurred at the beginning of the third stage, and for the first time the sodium bicarbonate mineral nahcolite was deposited near the center of the lake. Robb and Smith (1974), in their study of the Colorado No. 1 core hole from the oil shale depocenter, reported that the strata below this transition consist of primarily illite and quartz with minor dolomite and feldspar. After this transition, illite content drops from about 65 percent to less than 20 percent of the rock, quartz decreases, and dolomite and feldspar of probable authigenic origin (Desborough and Pitman, 1974; Smith, 1974) increase sharply. All oil shales deposited throughout the remaining history of Lake Uinta in the Piceance Basin are carbonate-rich with dolomite being the dominant carbonate (Robb and Smith, 1974). Ultimately, large quantities of nahcolite and halite were deposited in the saline depocenter of the lake in the north-central part of the Piceance Basin during stages 3 and 4 of the lake (fig. 3). Brownfield and others (2010) estimated that about 43.3 billion short tons of nahcolite remain in the saline depocenter, and much nahcolite and halite has been leached out by relatively recent invasion of groundwater into the nahcolite-bearing strata. Nahcolite in oil shale can be (1) disseminated, (2) aggregates, and (3) discrete beds (Dyni, 1974, 1981; Brownfield and others, 2010). Bedded nahcolite commonly grades laterally into halite beds toward the middle of the saline depocenter (Dyni, 1974, 1981). The interval deposited during stage 3, in contrast to the previous stage, thins considerably toward the margins of the basin (figs. 4 and 5). Lake margin areas may have been periodically exposed during this stage creating hiatuses (Bartov and others, 2007; Sarg and others, 2008).

The fourth and fifth stages in the history of Lake Uinta are marked by expansions of Lake Uinta. The fourth stage began with a relatively minor transgression (figs. 5 and 6) that may have been caused by the onset of outflow from Lake Gosiute in the Greater Green River Basin to the north (Johnson, 1985a, 2007). The transgression at the start of the fifth stage was almost certainly related to increased outflow from Lake Gosiute, as volcaniclastic sediments thought to be derived from the Absaroka volcanic field in northwestern Wyoming,

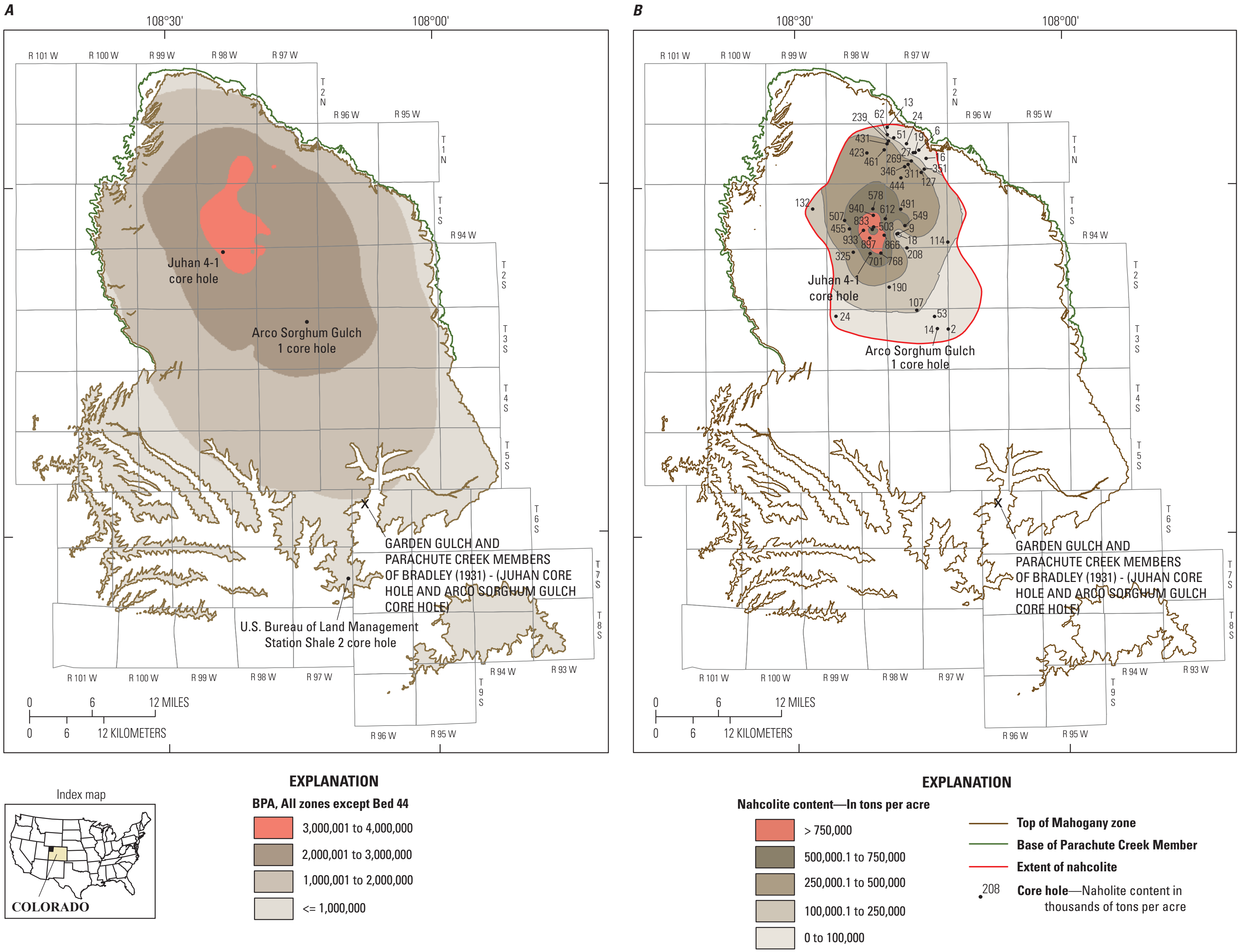

A
108°30'
108°00'
40°00'
39°30'
R 101 W
R 100 W
R 99 W
R 98 W
R 97 W
R 96 W
R 95 W
R 94 W
R 93 W
T 2 N
T 1 N
T 1 S
T 2 S
T 3 S
T 4 S
T 5 S
T 6 S
T 7 S
T 8 S
T 9 S
Juhan 4-1 core hole
Arco Sorghum Gulch 1 core hole
GARDEN GULCH AND PARACHUTE CREEK MEMBERS OF BRADLEY (1931) - (JUHAN CORE HOLE AND ARCO SORGHUM GULCH CORE HOLE)
U.S. Bureau of Land Management Station Shale 2 core hole
0 6 12 MILES
0 6 12 KILOMETERS
Index map
COLORADO
EXPLANATION
BPA, All zones except Bed 44
3,000,001 to 4,000,000
2,000,001 to 3,000,000
1,000,001 to 2,000,000
<= 1,000,000
B
108°30'
108°00'
Juhan 4-1 core hole
Arco Sorghum Gulch 1 core hole
GARDEN GULCH AND PARACHUTE CREEK MEMBERS OF BRADLEY (1931) - (JUHAN CORE HOLE AND ARCO SORGHUM GULCH CORE HOLE)
0 6 12 MILES
0 6 12 KILOMETERS
EXPLANATION
Nahcolite content—In tons per acre
> 750,000
500,000.1 to 750,000
250,000.1 to 500,000
100,000.1 to 250,000
0 to 100,000
Top of Mahogany zone
Base of Parachute Creek Member
Extent of nahcolite
208
Core hole—Naholite content in thousands of tons per acre

Figure 3 (prevous page). Maps showing (*A*) total in-place oil shale in barrels per acre (BPA), and (*B*) total in-place nahcolite in tons per acre, for all oil shale zones in the Piceance Basin. Total oil shale map is from Mercier and others (2010) and total nahcolite map is from Brownfield and others (2010).

reached the north margin of Lake Uinta shortly after maximum transgression (Surdam and Stanley, 1980). The Mahogany oil shale zone (Mahogany oil shale ledge where exposed) of the Green River Formation (figs. 5 and 6) was deposited during the early part of the fifth stage. These volcaniclastic sediments could only have reached Lake Uinta once Lake Gosiute was largely filled in, allowing the detritus to be transported farther south to gradually fill in the Piceance Basin part of Lake Uinta, thus ending oil shale deposition in that part of the lake (fig. 5) (Johnson, 1985a).

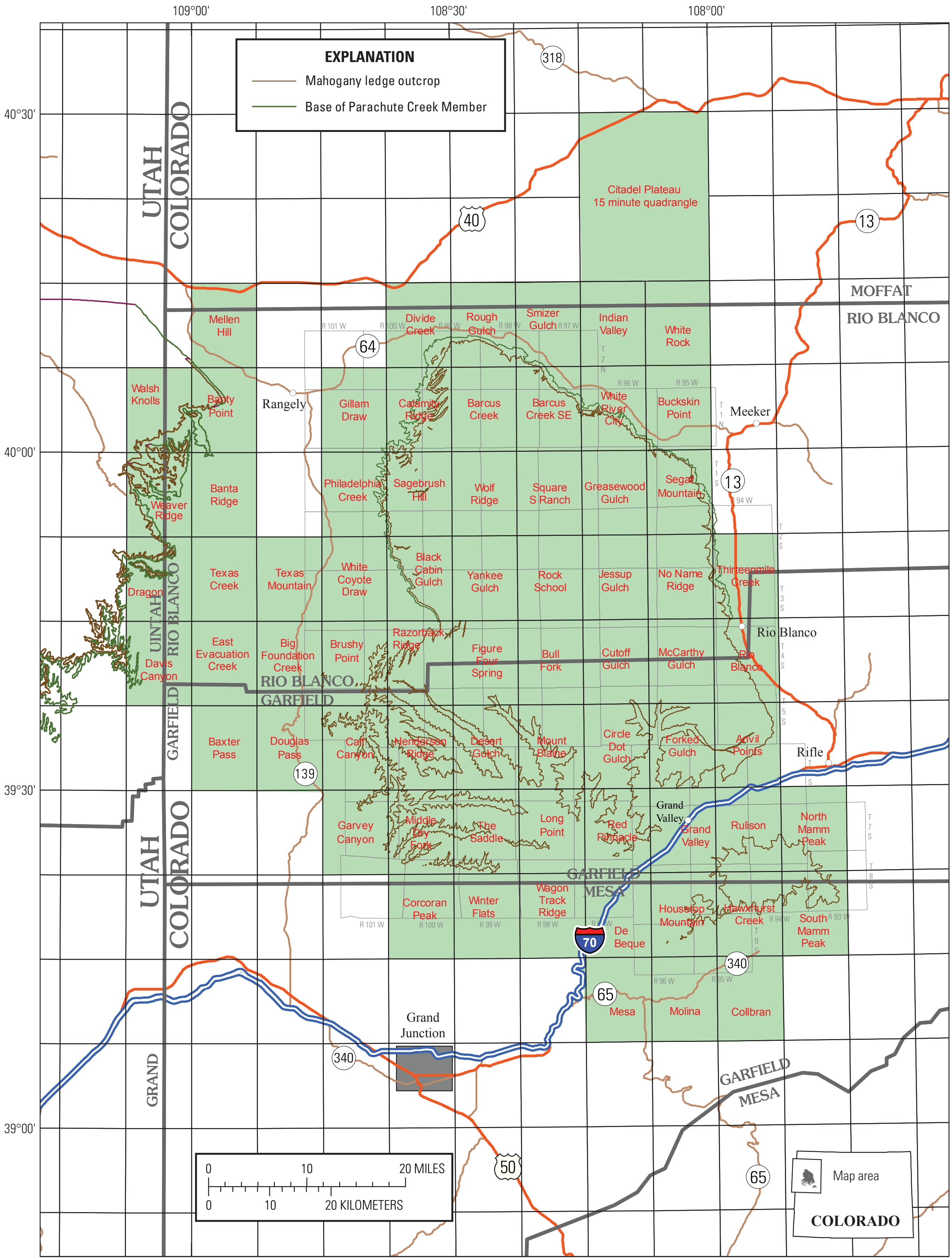
Definition of Stratigraphic Units

The four principal members of the Green River Formation are Garden Gulch, Parachute Creek, Douglas Creek, and Anvil Points Members (figs. 5 and 6). The Garden Gulch, Parachute Creek, and Douglas Creek Members were first named and defined by Bradley (1931); Donnell (1953) was the first to use the name Anvil Points Member. Locally, informal members, such as the unnamed member (Tgu) (Roehler, 1972a,b, 1973a,b) and intertonguing member (Tgi) (Scott and Pantea, 1985) were used when the authors felt that their units did not match the lithology of one of the four principal members (pls. 1 and 2). In general, Garden Gulch Member is applied to the illitic-rich oil shales deposited in offshore areas early in the history of Lake Uinta (stages 1 and 2 of Johnson, 1985a). Parachute Creek Member (figs. 5 and 6) is applied to the carbonate-rich oil shale deposited in offshore areas later in the history of Lake Uinta (Bradley, 1931) (stages 3–5 of Johnson, 1985a). There are many exceptions to this that will be discussed later. The name Douglas Creek Member is applied to marginal lacustrine rocks along the west and southwest margins of the Piceance Basin (Bradley, 1931). The name Anvil Points Member is applied to marginal lacustrine rocks along the east and southeast margins of the basin (Donnell, 1953, 1961). All of Garden Gulch Member and most of Parachute Creek Member grade into Douglas Creek and Anvil Points Members toward the basin margins. Douglas Creek and Anvil Points Members reach stratigraphically as high as the lower part of the Mahogany oil shale ledge along the west margin and the Mahogany oil shale bed along the east margin (figs. 5 and 6, pl. 1). These largely marginal lacustrine members consist of carbonate-rich and clay-rich mudstones, ostracodal, oolitic, and stromatolitic limestones, siltstones, and sandstones with some oil shale. The Anvil Points Member is generally sandier than the Douglas Creek Member, and the Douglas Creek Member contains more limestone.

Bradley (1931) originally described the Parachute Creek and Garden Gulch Members along Parachute Creek in the south-central part of the Piceance Basin (fig. 2). The sections are not ideally located, as they are considerably south of the oil shale and saline mineral depocenter (fig. 3) in an area where both members include some marginal lacustrine rocks. Problems with these sections will be addressed more fully in the discussion section. Bradley (1931, p. 10) described the Garden Gulch Member as "Paper shale with discrete laminae less than 1 millimeter in thickness, many to be measured in a few hundredths of a millimeter, is the characteristic feature of this second member of the Green River formation....Many of these paper-thin layers are low-grade oil shale….Some of the paper shale will yield more than 15 gallons of oil to the ton….Units of paper shale are intercalated with somewhat thicker units of flaky shale….The greater part of the Garden Gulch member consists of flaky shale and more thickly laminated marlstone, some of which is shaly." Clearly, flaky or papery shale is emphasized by Bradley in his description of the Garden Gulch, but the section contains other lithologies including calcareous mudstone and oolitic and algal limestone more typical of the Anvil Points and Douglas Creek Members. The Garden Gulch where Bradley originally described it along Parachute Creek is about 700 ft thick and overlies about 500 ft of Douglas Creek Member that consists of sandstone, algal and oolitic limestone, and flaky shale. The Douglas Creek there was later mapped as Anvil Points Member (Hail, 1982; O'Sullivan and Hail, 1987) as it has an eastern source.

Bradley (1931) considered the overlying Parachute Creek Member to be "...the oil-shale facies of the Green River Formation...." because it contained most of the oil shale in the formation. Bradley subdivided the Parachute Creek Member, in ascending order, into a lower oil shale group, transitional beds, and an upper oil shale group and traced these units as far to the west as the eastern part of the Uinta Basin. The lower oil shale group, where originally described by Bradley along Parachute Creek, is about 170 ft thick and includes massive oil shale and hard platy marlstone, characteristic of the Parachute Creek Member, as well as flaky oil shale more characteristic of the underlying Garden Gulch Member. The transitional beds are about 100 ft thick and consist mainly of hard platy marlstone and flaky shale largely barren of organic matter. The upper oil shale group is about 730 ft thick and contains most of the rich oil shale in the Green River Formation, including the Mahogany oil shale ledge.

Bradley (1931) originally described the Douglas Creek Member near the head of Trail Creek along the west margin of the basin (fig. 2). Here, the Douglas Creek is about 800 ft thick and consists of sandstone, mudstone, and oolitic and algal limestone. Johnson (1984) re-described this section of the Douglas Creek Member reporting that the basal part included (1) a thin freshwater lacustrine interval deposited in the freshwater lake that predated the formation of saline Lake Uinta and (2) a thin interval of the fluvial Wasatch Formation. Johnson (1984) separated the thin freshwater lacustrine interval that had previously been mapped as part of the Douglas



EXPLANATION
Mahogany ledge outcrop
Base of Parachute Creek Member
109°00'
108°30'
108°00'
40°30'
40°00'
39°30'
39°00'
UTAH
COLORADO
MOFFAT
RIO BLANCO
GARFIELD
MESA
UINTAH
GRAND
Citadel Plateau 15 minute quadrangle
Mellen Hill
Divide Creek
Rough Gulch
Smizer Gulch
Indian Valley
White Rock
Walsh Knolls
Banty Point
Rangely
Gillam Draw
Calamity Ridge
Barcus Creek
Barcus Creek SE
White River City
Buckskin Point
Meeker
Weaver Ridge
Banta Ridge
Philadelphia Creek
Sagebrush Hill
Wolf Ridge
Square S Ranch
Greasewood Gulch
Segar Mountain
Dragon
Texas Creek
Texas Mountain
White Coyote Draw
Black Cabin Gulch
Yankee Gulch
Rock School
Jessup Gulch
No Name Ridge
Thirteenmile Creek
Davis Canyon
East Evacuation Creek
Big Foundation Creek
Brushy Point
Razorback Ridge
Figure Four Spring
Bull Fork
Cutoff Gulch
McCarthy Gulch
Rio Blanco
Baxter Pass
Douglas Pass
Caff Canyon
Henderson Ridge
Desert Gulch
Mount Blaine
Circle Dot Gulch
Forked Gulch
Anvil Points
Rifle
Garvey Canyon
Middle Dry Fork
The Saddle
Long Point
Red Pinnacle
Grand Valley
Rulison
North Mamm Peak
Corcoran Peak
Winter Flats
Wagon Track Ridge
Housetop Mountain
Hawxhurst Creek
South Mamm Peak
De Beque
Mesa
Molina
Collbran
Grand Junction
318
40
13
64
139
70
340
65
50
0 10 20 MILES
0 10 20 KILOMETERS
Map area
COLORADO

Figure 4 (previous page). Index map showing locations of sixty-nine 7½-minute quadrangles and one 15-minute quadrangle (Citadel Plateau) for which geologic maps have been published for the oil shale area, Piceance Basin and easternmost Uinta Basin.

Creek Member (Cashion, 1969; Roehler, 1972a,b, 1973a) and included it in his newly defined Cow Ridge Member of the Green River Formation that predated the formation of saline Lake Uinta (figs. 5 and 6). This member is as much as 650 ft thick where exposed along the west margin of the basin (Johnson and others, 1988); it is not included in the stratigraphic charts presented here (pl. 1).

Donnell (1953, 1961) applied the name Anvil Points Member to marginal lacustrine strata along the east margin of the basin that had previously been called the lower sandy member by Duncan and Denson (1949). The type section of the Anvil Points Member, according to Donnell (1961, p. 851), "...is an extremely heterogeneous unit. At the type locality it contains approximately 30 percent gray shale, 25 percent gray shale and interbedded thin-bedded brown and gray sandstone, 20 percent massive brown and gray sandstone beds, and slightly less than 10 percent light-brown marlstone containing little or no oil. The remainder of the member consists of siltstone, algal limestone, and oolitic limestone." The base of the Anvil Points Member drops stratigraphically approximately 600 ft about 1.5 miles southwest of the type section (see O'Sullivan, 1986) where the upper part of the underlying Wasatch Formation grades laterally into the Green River Formation. The type section for the Anvil Points (Donnell, 1961, p. 851 and his pl. 49) does not include this lower 600-ft interval, but it is included in a detailed section measured and described at Anvil Points (Self and others, 2010, their pl. 7). This Wasatch interval consists mainly of red and green mudstone, and sandstone of predominantly fluvial origin, but ostracodes and pelecypods are locally present indicating minor lacustrine influence.

The Uinta Formation is a sequence of sandstones and siltstones containing abundant volcanic debris that complexly intertongues with the upper part of the Green River Formation (figs. 5 and 6) (Cashion and Donnell, 1974). The Uinta Formation represents that stage of Lake Uinta in the Piceance Basin when the lake was gradually filled in from north to south largely by volcanic debris originating in northwestern Wyoming. The oldest volcaniclastic sandstone appears to be near the top of the Mahogany zone; the questionable stratigraphic position of this sandstone is discussed later. Tongues of lacustrine rocks that interfinger with volcaniclastic rocks of the Uinta Formation have been mapped throughout much of the basin (figs. 5 and 6, pl. 1). Although these tongues are lithologically identical to the Parachute Creek Member and merge with the Parachute Creek toward the south in the basin (fig. 3), the North American Stratigraphic Code (1983) does not recognize tongues of a member, because the units have the same stratigraphic rank. As a result these tongues have been mapped as tongues of the Green River Formation, separate from the Parachute Creek Member.

The intertonguing between the Uinta Formation and upper part of the Green River Formation is one of the most stratigraphically complex sequences in the basin because of the rapid lateral pinchouts and thickness changes. Thirteen major Green River Formation tongues have been named (figs. 10 and 11). Many minor, unnamed tongues are also present, and two or more Green River tongues commonly merge to form composite tongues such as in the Figure Four Spring quadrangle where the marlstone at Barnes Ridge and Stuart Gulch Tongue combine locally to form a new tongue (pl. 1B). Some Uinta tongues wedge out in an east-west direction, but all ultimately wedge out to the south. In the southernmost part of the basin, all the Green River tongues have joined the main body of the Green River Formation (figs. 5 and 11). Donnell (2008) determined approximately where most major Green River and Uinta tongues fall stratigraphically in the continuous oil shale section preserved in the southern part of the basin (figs. 10 and 11). Interestingly, Uinta tongues are represented by relatively thin intervals in this continuous oil shale section to the south, indicating that they were deposited much more rapidly and represent far less time than the Green River tongues.

The name Evacuation Creek Member of the Green River Formation was originally applied to this intertonguing sequence (pl. 1) in the Piceance Basin by Bradley (1931), and the name was used for this interval on some of the earliest 7½-minute quadrangles published (Cashion, 1969; Cullins, 1969; Roehler, 1972a,b, 1973a,b). Cashion and Donnell (1974) noted that the Evacuation Creek Member at its type locality in the eastern Uinta Basin is lithologically and laterally equivalent to the oil shale interval in the upper part of the Parachute Creek Member above the Mahogany zone in the Piceance Basin. Furthermore, the Evacuation Creek Member as used in the Piceance Basin is lithologically equivalent to the sandy beds of the Uinta Formation in the Uinta Basin. This miscorrelation resulted in Cashion and Donnell (1974) abandoning the name Evacuation Creek Member, and instead applied the name Uinta Formation to the sandy interval that intertongues with the upper part of the Green River Formation in the Piceance Basin. The name Uinta Formation was used for this interval on all 7½-minute quadrangles published after 1974.

Development of Rich and Lean Zone Stratigraphy

Individual rich oil shale beds and intervals in the Uinta and Piceance Basins can be traced for long distances. Bradley (1931) was one of the first to demonstrate this when he traced the Mahogany ledge (figs. 5, 6, and 9) along outcrop throughout most of the Piceance Basin and into the eastern part of the Uinta Basin. Curry (1964) and Trudell and others (1970) demonstrated that individual oil shale beds could be traced for

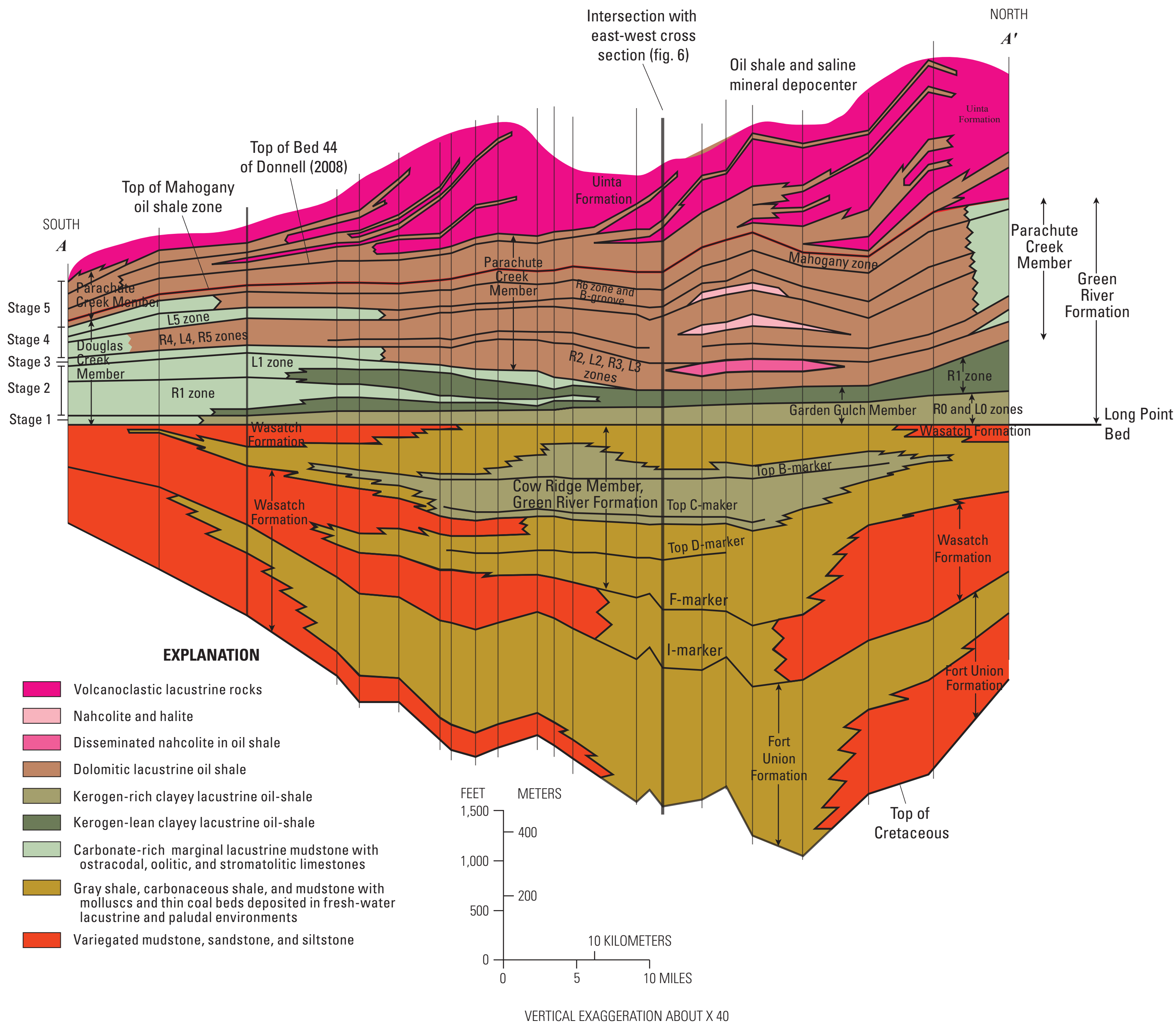

SOUTH
A
NORTH
A′
Intersection with
east-west cross
section (fig. 6)
Oil shale and saline
mineral depocenter
Top of Bed 44
of Donnell (2008)
Top of Mahogany
oil shale zone
Uinta
Formation
Uinta
Formation
Parachute
Creek Member
Parachute
Creek
Member
Parachute
Creek
Member
Green
River
Formation
Mahogany zone
R6 zone and
B-groove
L5 zone
R4, L4, R5 zones
Douglas
Creek
Member
L1 zone
R1 zone
R2, L2, R3, L3
zones
R1 zone
Garden Gulch Member
R0 and L0 zones
Long Point
Bed
Stage 5
Stage 4
Stage 3
Stage 2
Stage 1
Wasatch
Formation
Wasatch Formation
Wasatch
Formation
Wasatch
Formation
Cow Ridge Member,
Green River Formation
Top B-marker
Top C-maker
Top D-marker
F-marker
I-marker
Fort
Union
Formation
Fort Union
Formation
Top of
Cretaceous
EXPLANATION
Volcanoclastic lacustrine rocks
Nahcolite and halite
Disseminated nahcolite in oil shale
Dolomitic lacustrine oil shale
Kerogen-rich clayey lacustrine oil-shale
Kerogen-lean clayey lacustrine oil-shale
Carbonate-rich marginal lacustrine mudstone with ostracodal, oolitic, and stromatolitic limestones
Gray shale, carbonaceous shale, and mudstone with molluscs and thin coal beds deposited in fresh-water lacustrine and paludal environments
Variegated mudstone, sandstone, and siltstone
FEET
METERS
1,500
1,000
500
0
400
200
10 KILOMETERS
0
5
10 MILES
VERTICAL EXAGGERATION ABOUT X 40

Figure 5 (previous page). North-south cross section A-A′ (fig. 2) through the Piceance Basin, northwestern Colorado, showing member subdivisions, stages of Lake Uinta as defined by Johnson (1985a), and some of the rich and lean zones defined by Cashion and Donnell (1972). The B-marker through I-marker beds are from Chancellor and others (1974).

considerable distances between core holes drilled in the central part of the Piceance Basin. The persistence of some oil shale zones in the subsurface in the central part of the Piceance Basin was noted prior to 1955 when V.E. Peterson (referenced in Trudell and others, 1970, p. 4) traced distinctive electric log markers between gas wells in the central part of the basin employing a personal system that included (1) a "black marker" corresponding to B-groove, (2) a "blue marker" corresponding to the increase in resistivity at the contact between the Parachute Creek and Garden Gulch Members (base of the R-2 zone), and (3) an "orange marker" corresponding to the top of a distinctive, slight increase in resistivity near the top of the R-0 zone due to the presence of minor carbonate (Trudell and others, 1970). The blue marker, or base of the R-2 zone, corresponds to the shift from illitic-rich oil shale below to dolomitic-rich oil shale above, as discussed previously. The orange marker is equivalent to the carbonate marker in the Uinta Basin to the west (Johnson, 1985a). The term orange marker is still used today (Johnson and others, 2010a), whereas the terms black marker and blue marker are generally no longer used.

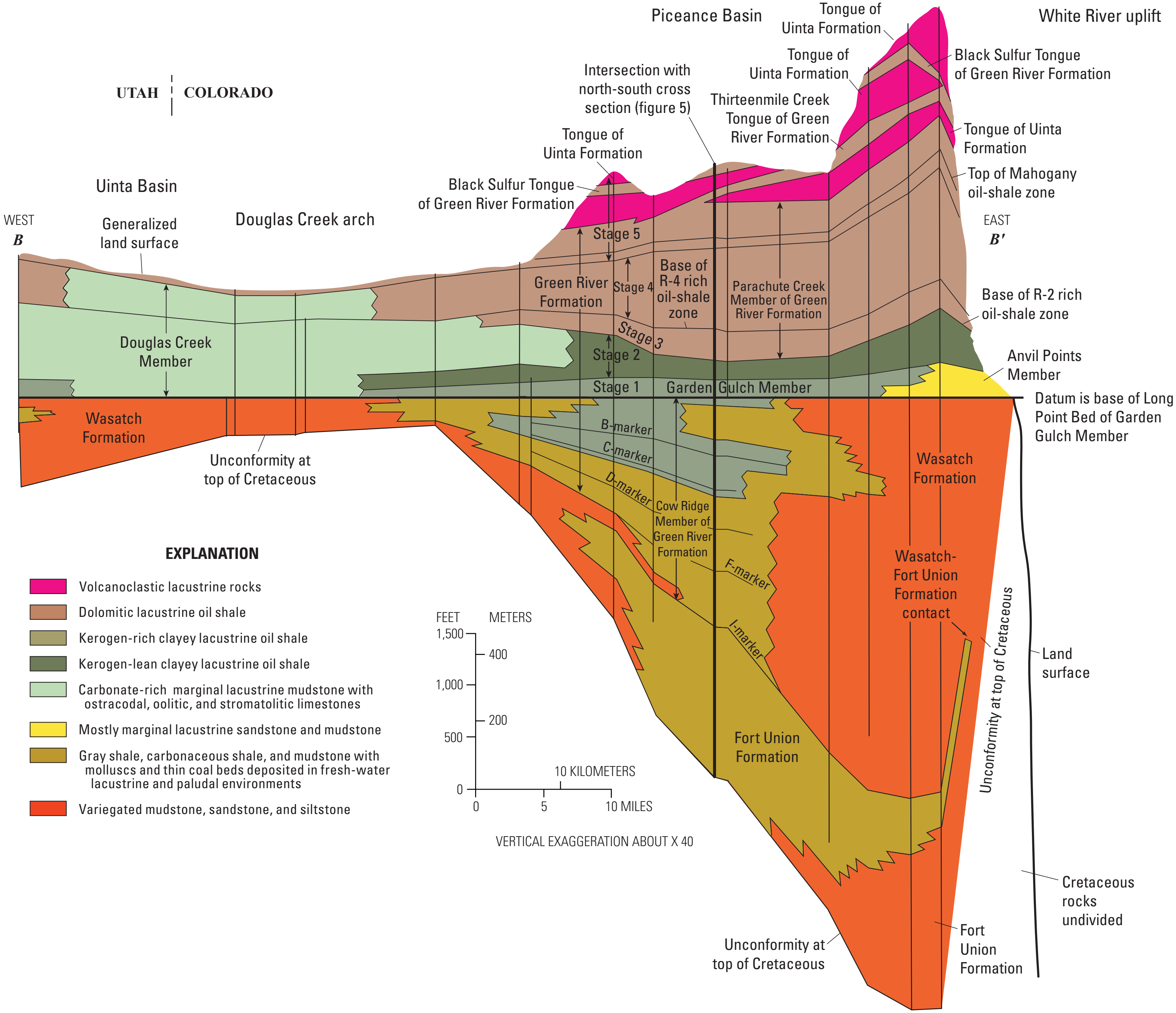
Cashion and Donnell (1972), in a publication that provided the groundwork for most subsequent assessment work in the Piceance and Uinta Basins, recognized that the entire oil shale interval in the Piceance and Uinta Basins could be subdivided into a series of oil-rich zones (R-1 through R-6 zones) and oil-lean zones (L-1 through L-5 zones) (fig. 12). Later, the terms R-0 and L-0 were applied to the lowest oil shale zones in the Green River Formation that were deposited just after the Long Point transgression (see, for example, Johnson and others, 1988). Previously named oil shale units above the R-6 zone are, (in ascending order) B-groove, Mahogany zone, and A-groove. The oil shale interval above A-groove was not named by Cashion and Donnell (1972), but they traced several oil shale marker beds through that interval. Donnell (2008) correlated 44 individual oil shale beds in the interval above A-groove across much of the Piceance Basin and the eastern part of the Uinta Basin (fig. 7). All of these oil shale beds and zones appear to closely represent time-stratigraphic units that reflect changing rates of organic matter production and preservation that occurred simultaneously throughout Lake Uinta. The differentiation of rich and lean zones is used for correlation purposes on the stratigraphic charts compiled for this report.

The lower zones, from the R-0 zone through the L-1 zone, compose the illitic-rich oil shale interval of the Garden Gulch Member of the Green River Formation (Smith and others, 1968; Trudell and others, 1970); these zones also represent stages 1 and 2 of Lake Uinta (Johnson, 1985a) (figs. 5, 6, and 12). However, the Garden Gulch Member, as mapped around the basin margins, rarely corresponds to the R-0 through L-1 zones, and possible reasons for this are presented in the Discussion section of this report. The base of the R-2 zone marks a shift from illitic-rich to dolomitic-rich oil shale discussed previously and corresponds to the base of the Parachute Creek Member (Trudell and others, 1970, 1974; Dyni, 1974) as well as to the beginning of stage 3 of Johnson (1985a) (figs. 5,6, and 12). The R-2 zone consists of interbedded illitic-rich and carbonate-rich oil shale (Dyni, 1974; Robb and Smith, 1974), whereas all oil shale deposited after the R-2 zone is predominantly carbonate-rich. As previously discussed, the transition from clay-rich to carbonate-rich oil shale is easily traced on electric logs throughout the central part of the Piceance Basin, as the carbonate-rich oil shales are much more resistive than the underlying clay-rich oil shale. The base of the R-4 zone marks the minor transgression at the beginning of stage 4 of Johnson (1985a), and the base of the Mahogany zone marks the major transgression at the beginning of stage 5 of Johnson (1985a) (figs. 5 and 6).

Tracing these rich and lean oil shale zones from the oil shale depocenter into marginal lacustrine equivalents in the Douglas Creek and Anvil Points Members that crop out around the margins of the basin is difficult and as yet incomplete. Brobst and Tucker (1973) identified all oil shale zones from the Mahogany ledge down to the base of the R-4 zone in outcrop along lower Piceance Creek and from the Mahogany ledge down to the L-3 zone at their Pipeline section along Cathedral Bluffs. Johnson and others (1988) traced some of the rich and lean zones into their marginal lacustrine equivalents in the Douglas Creek Member along the west basin margin of the Piceance Basin. This effort was expanded by Johnson and others (2010a,b), and Self and others (2010) and is expanded further here by placing all mapped contacts in all the quadrangle areas into the R-zone stratigraphic context (pl. 1). The reliability of this attempt varies considerably from quadrangle to quadrangle and between different stratigraphic units.

Constructing the Stratigraphic Charts

The stratigraphic sequence of rich and lean zones originally defined by Cashion and Donnell (1972) and later refined by other workers (see for example, Pitman and others, 1989), forms the basis of both the time-stratigraphic and thickness charts (pl. 1). To make the charts more user-friendly, the zones are grouped into three intervals shown in different colors in the background between the individual stratigraphic diagrams: (1) illitic phase or Garden Gulch Member (R-0 through L-1 zones) (gray), (2) carbonate phase or Parachute Creek Member prior to the arrival of the first volcaniclastics from Wyoming (R-2 through top of the Mahogany bed) (tan), and (3) the infilling stage in which the upper part of the Green River Formation



UTAH
COLORADO
WEST
B
EAST
B′
Uinta Basin
Douglas Creek arch
Piceance Basin
White River uplift
Generalized land surface
Douglas Creek Member
Wasatch Formation
Unconformity at top of Cretaceous
Black Sulfur Tongue of Green River Formation
Tongue of Uinta Formation
Intersection with north-south cross section (figure 5)
Thirteenmile Creek Tongue of Green River Formation
Tongue of Uinta Formation
Tongue of Uinta Formation
Black Sulfur Tongue of Green River Formation
Tongue of Uinta Formation
Top of Mahogany oil-shale zone
Base of R-2 rich oil-shale zone
Anvil Points Member
Datum is base of Long Point Bed of Garden Gulch Member
Stage 5
Stage 4
Stage 3
Stage 2
Stage 1
Green River Formation
Base of R-4 rich oil-shale zone
Parachute Creek Member of Green River Formation
Garden Gulch Member
B-marker
C-marker
D-marker
Cow Ridge Member of Green River Formation
F-marker
I-marker
Wasatch Formation
Wasatch-Fort Union Formation contact
Fort Union Formation
Unconformity at top of Cretaceous
Land surface
Cretaceous rocks undivided
Fort Union Formation
Unconformity at top of Cretaceous
EXPLANATION
Volcanoclastic lacustrine rocks
Dolomitic lacustrine oil shale
Kerogen-rich clayey lacustrine oil shale
Kerogen-lean clayey lacustrine oil shale
Carbonate-rich marginal lacustrine mudstone with ostracodal, oolitic, and stromatolitic limestones
Mostly marginal lacustrine sandstone and mudstone
Gray shale, carbonaceous shale, and mudstone with molluscs and thin coal beds deposited in fresh-water lacustrine and paludal environments
Variegated mudstone, sandstone, and siltstone
FEET
METERS
1,500
1,000
500
0
400
200
10 KILOMETERS
0
5
10 MILES
VERTICAL EXAGGERATION ABOUT X 40

Figure 6 (previous page). East-west cross section B-B′ (fig. 2) through the Piceance Basin, the Douglas Creek arch, and the eastern part of the Uinta Basin showing member subdivisions, stages 1–5 of Lake Uinta as defined by Johnson (1985a), and some of the rich and lean zones defined by Cashion and Donnell (1972). The B-marker through I-marker beds are from Chancellor and others (1974).

intertongues with the Uinta Formation (top of Mahogany bed to top of marlstone at Skinner Ridge—the highest named tongue of the Green River Formation) (pink). In a limited area along the south and west margins of the study area, significant thicknesses of Green River Formation are found above the marlstone at Skinner Ridge. About 150 ft of the Parachute Creek Member lies above the stratigraphic position of the marlstone at Skinner Ridge in the Middle Dry Fork quadrangle and more than 200 ft of Parachute Creek Member lies above the base of a tuffaceous interval (t) that is thought to be equivalent to the top of the marlstone at Skinner Ridge in the Walsh Knolls quadrangle on the Colorado-Utah border (pl. 1). Lake Uinta persisted longer in the southwestern part of the Piceance Basin and eastern part of the Uinta Basin than it did throughout the rest of the Piceance Basin.

Ideally, the vertical scale on time-stratigraphic charts should be proportional to time. At present, however, the time duration represented by each rich and lean zone is unknown, and it is unlikely that an adequate dating of these intervals will be available soon. Dateable tuffs in the Green River Formation are sparse in the Piceance Basin being confined largely to the Mahogany zone and overlying beds. These tuffs yielded $^{40}Ar/^{39}Ar$ dates between about 49 and 47 Ma (Smith and others, 2008). Only two tuffs of note are in the interval below the Mahogany zone—the yellow tuff of Pipiringos and Johnson (1975, 1976), which is in the middle part of the R-5 zone (pl. 1), and the Kimball Mountain Tuff Bed, which is in the lower part of the R-1 zone (pl. 1). An $^{40}Ar/^{39}Ar$ date of 51.39 ± 1.70 Ma was obtained from the yellow tuff (Smith and others, 2008), but the Kimball Mountain Tuff Bed has yet to be dated.

Instead of a framework based on absolute dating, the thicknesses of the rich and lean zones in a "representative" part of the basin are used here to approximate the relative time represented by each zone. An area was selected near the central part of the lake and away from marginal areas where a fluctuating water level might cause periods of non-deposition or erosion. Here, continuous or nearly continuous deposition would have occurred throughout the history of Lake Uinta. Even here, however, rates of sedimentation would have varied through time due to different rates of organic productivity and carbonate precipitation, meaning thicknesses are not directly related to time. In addition, the depocenter of the lake contains thick deposits of nahcolite and halite that may have precipitated comparatively rapidly out of the water column and within the unconsolidated lake deposits. Because of the saline problem, an area was selected that was on the margin of the saline depocenter where saline deposits are present but do not appear to have greatly altered the thicknesses of the rich and lean zones. All of the above-mentioned criteria are met in the Juhan 4-1 core hole (fig. 3) in sec. 4, T. 2. S., R. 98 W. This core hole, on the southern margin of the lake's depocenter, contains some nahcolite, but it does not appear to have greatly altered the thicknesses of the affected zones. Zones L-2 through L-4 contain disseminated nahcolite, with most of it concentrated in the L-2, R-3, and L-4 zones. These zones are only slightly thicker than the same zones in the Arco Sorghum Gulch 09 core hole in sec. 11, T. 3 S., R. 97 W., which is in the nahcolite-free area just south of the saline depocenter (Brownfield and others, 2010, their pl. 2).

The upper intertonguing interval between the Green River and Uinta Formations is only partially represented in the Juhan 4-1 core hole. The core hole is in the north-central part of the basin that was filled with volcaniclastic sediments considerably before the southernmost part of the lake was filled with sediments. A core hole in the southern part of the basin, the U.S. Bureau of Land Management Triangulation Station Shale 2 core hole in sec. 24, T. 7 S., R. 97 W. (fig. 3A), was chosen to represent thicknesses in this interval as it includes one of the most complete lacustrine sections in the basin and was used by Donnell (2008, his fig. 4) in his study of this intertonguing interval.

It is difficult to represent all the lateral stratigraphic changes taking place within a quadrangle area on two-dimensional diagrams, so compromises were made. On both the time-stratigraphic and thickness-stratigraphic diagrams (pl. 1), changes in a westerly direction are shown on the left side of the charts and changes in an easterly direction are on the right side. Changes that are more or less north-south are problematical and must be translated down to either the left or right side of the charts at the discretion of the author. A single "representative" thickness is used for each rich and lean zone for each quadrangle on the thickness stratigraphic chart (pl. 1B). It was felt that this was sufficient to characterize strata deposited prior to the infilling stage, as thicknesses in this interval change rather gradually across any given quadrangle. These thicknesses were measured from available measured sections or from drill holes near the center of each quadrangle. Regionally, however, the thicknesses of individual rich and lean zones do change markedly. For example, thicknesses overall increase toward the east due to an increase in the rate of subsidence in that direction, and this trend is easily seen on plate 1B.

Thicknesses of stratigraphic units deposited during the infilling stage, in contrast, can change greatly across individual quadrangles (pl. 1B). A Uinta Formation tongue hundreds of feet thick along the north margin of a quadrangle, for example, might pinch out before reaching the quadrangle's south border. Although it is difficult to portray diagrammatically all of the thickness relations within a given quadrangle, the ranges in thickness for each unit shown in the diagrams are intended to closely follow the ranges of those listed by the authors for their mapped quadrangles.

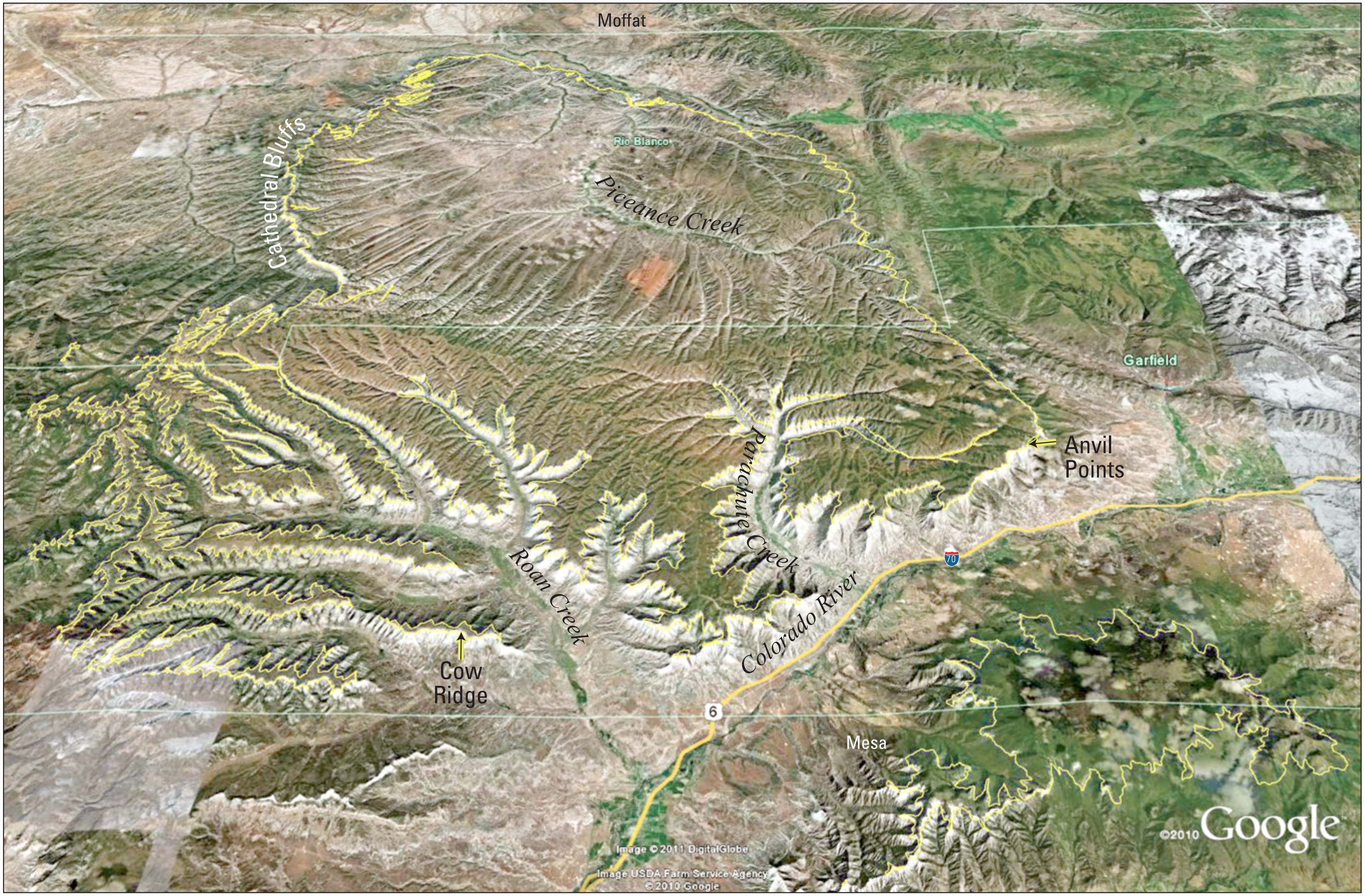


Figure 7. Oblique aerial photograph of the Piceance Basin showing prominent relief along the west, south, and east margins of the Piceance Basin. Yellow line is outcrop of top of Mahogany oil shale ledge. Location of Anvil Points (labeled on fig. 2) is shown.

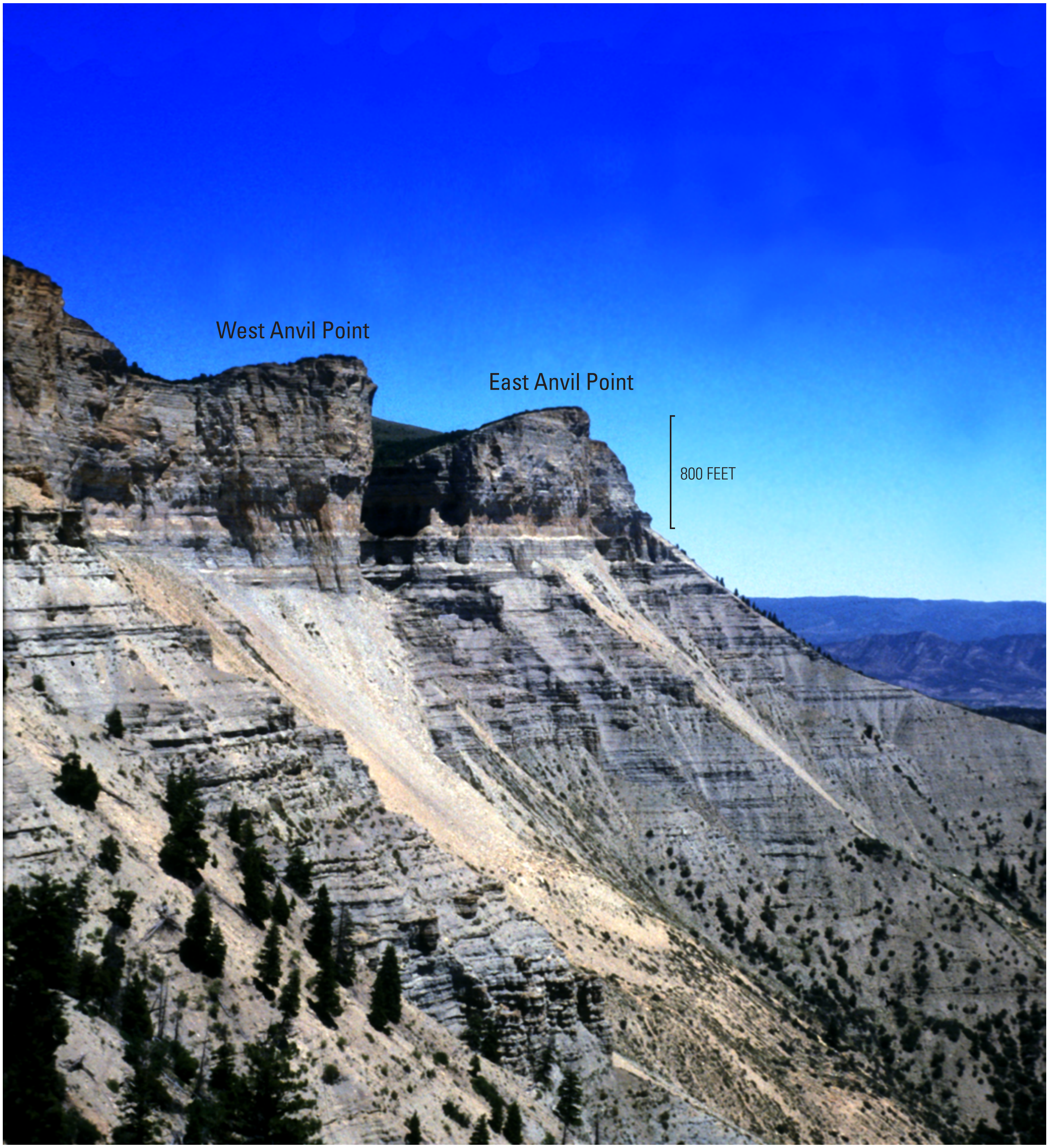


Figure 8. Photograph of the Green River Formation exposed on Anvil Points in the southeastern part of the Piceance Basin.

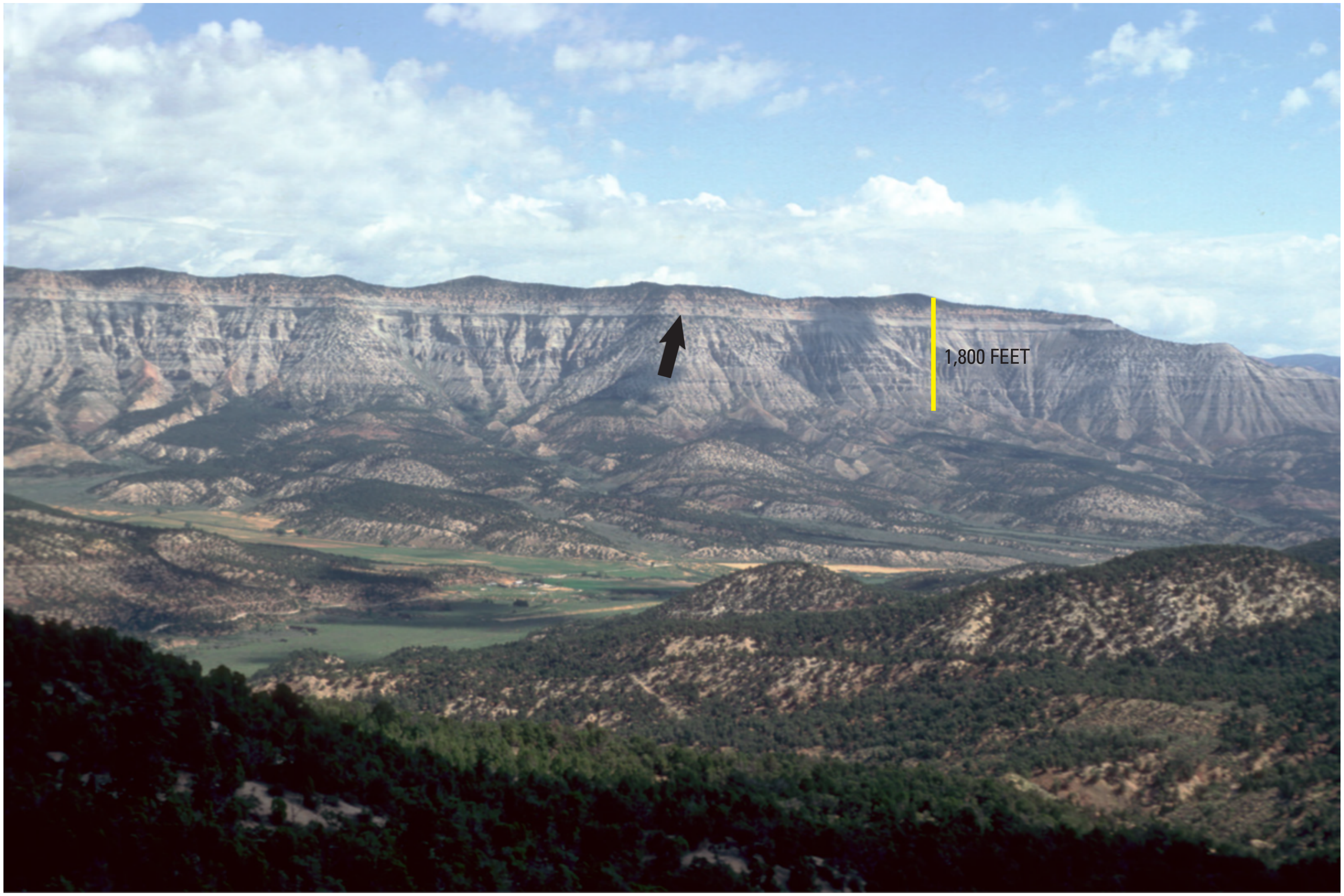


Figure 9. Photograph of the Green River Formation (shown with yellow line) and upper part of the underlying Wasatch Formation along Cow Ridge in the southwestern part of the Piceance Basin. Note that the entire Green River Formation weathers white. The Mahogany oil shale zone forms the conspicuous ledge shown with an arrow near the top of the outcrop. The base of the Green River Formation is about the base of the steep slopes. Location of Cow Ridge shown on figure 2.

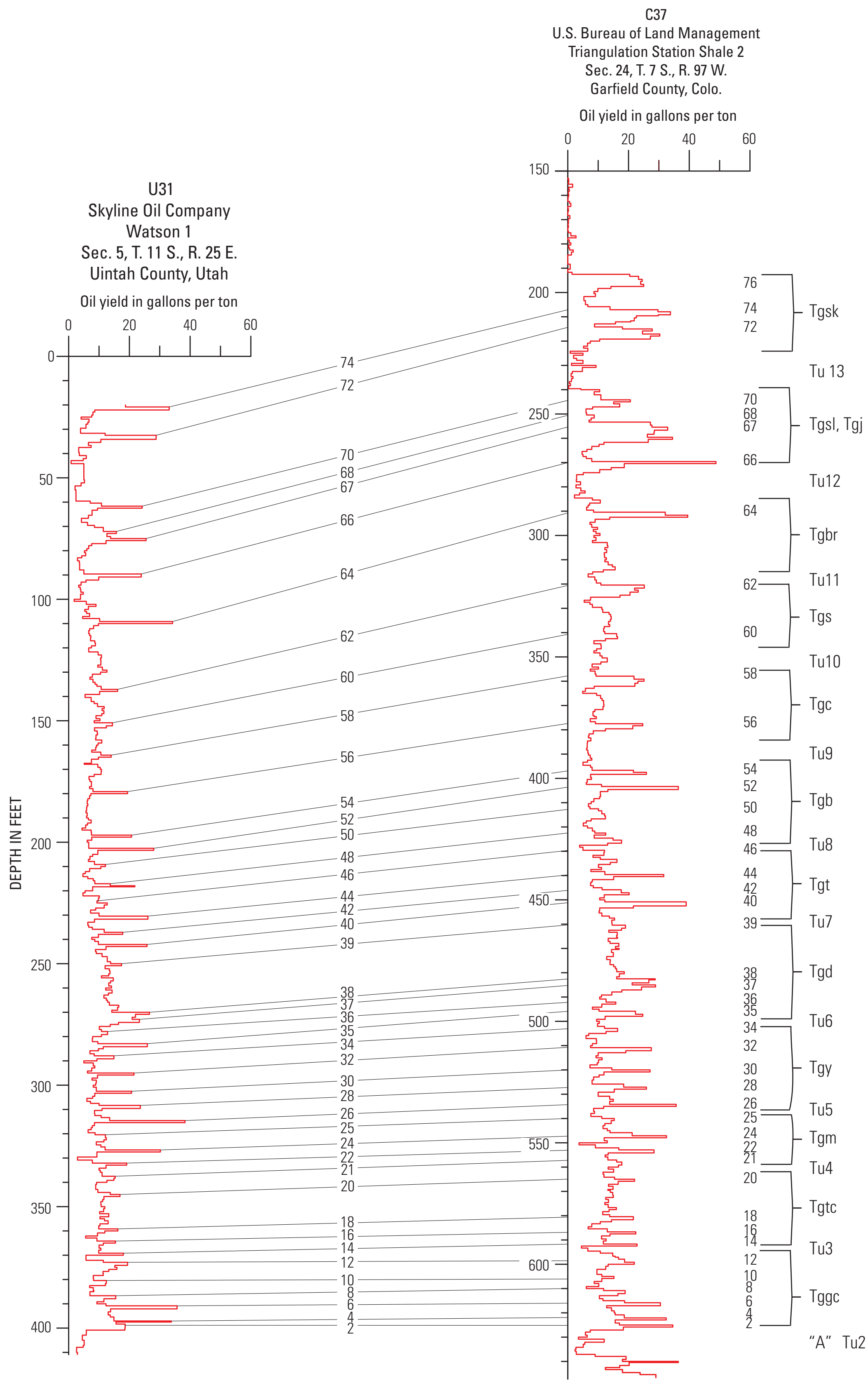


Figure 10. Correlation of individual oil shale beds and groups of beds forming formally and informally named tongues of the Green River Formation (indicated by stratigraphic-unit symbol beginning with Tg) in the interval above A-groove. Abbreviations used: "A", base of A-groove; Green River Formation units: 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 Sulphur 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. Uinta Formation units are numbered Tu2 through Tu13. Units evenly numbered 2 through 76 are persistent oil shale beds defined by Donnell (2008).

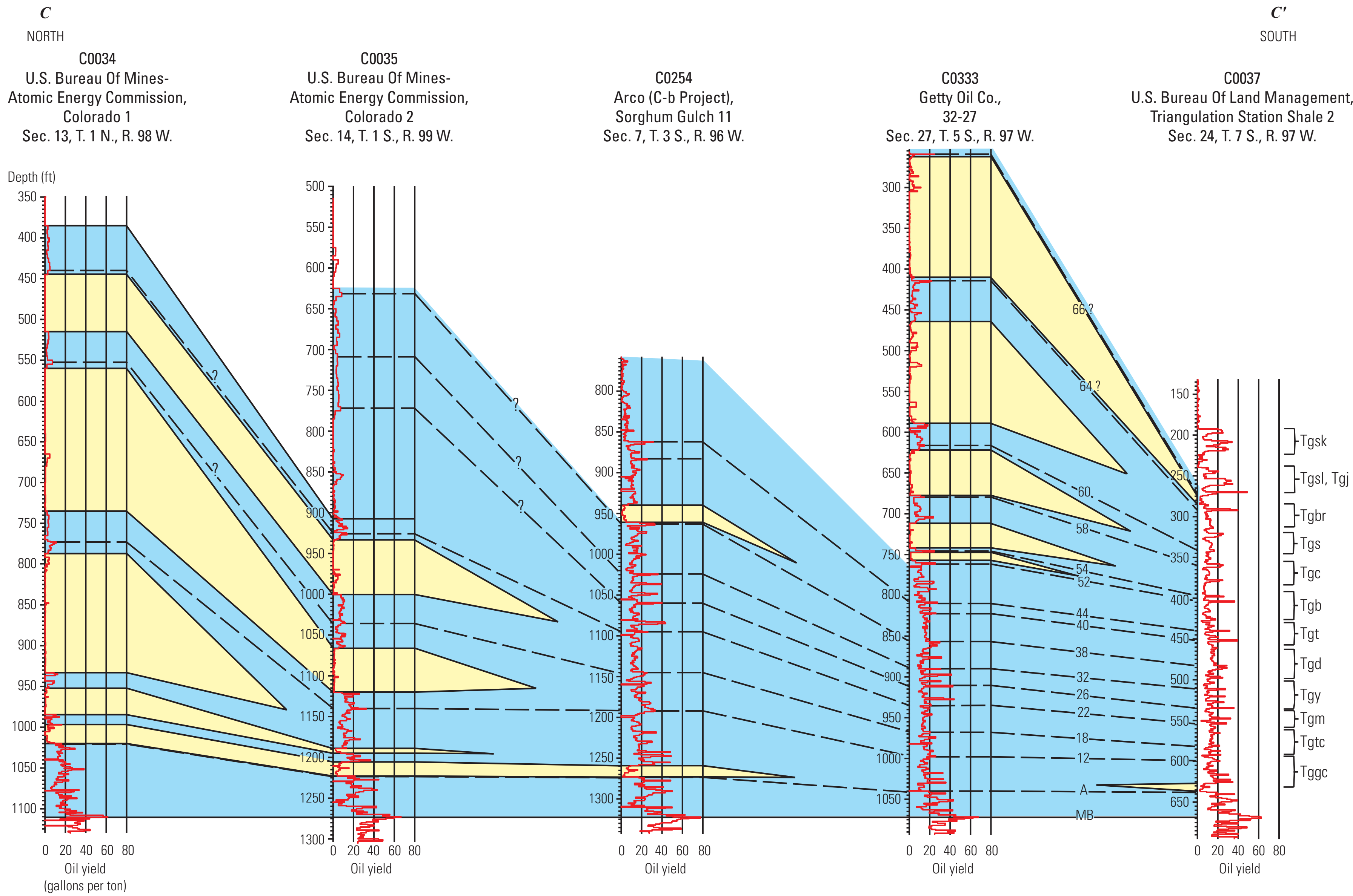


Figure 11. North-south cross section C-C′ showing intertonguing of the Uinta Formation (yellow) with the upper part of the Green River Formation (blue) in the Piceance Basin, Colorado (from Donnell, 2008, his fig. 3). Abbreviations used: MB, Mahogany bed; A, base of A-groove; Tggc, marlstone at Greasewood 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 Sulphur Tongue; Tgc, Coughs Creek Tongue; Tgs, Stewart Gulch Tongue; Tgbr, marlstone at Barnes Ridge; Tgsl, marlstone at Sleepy Ridge; Tgj, marlstone at Jackrabbit Ridge; Tgsk, marlstone at Skinner Ridge. Numbers 12 through 66 are persistent oil shale beds defined by Donnell (2008).

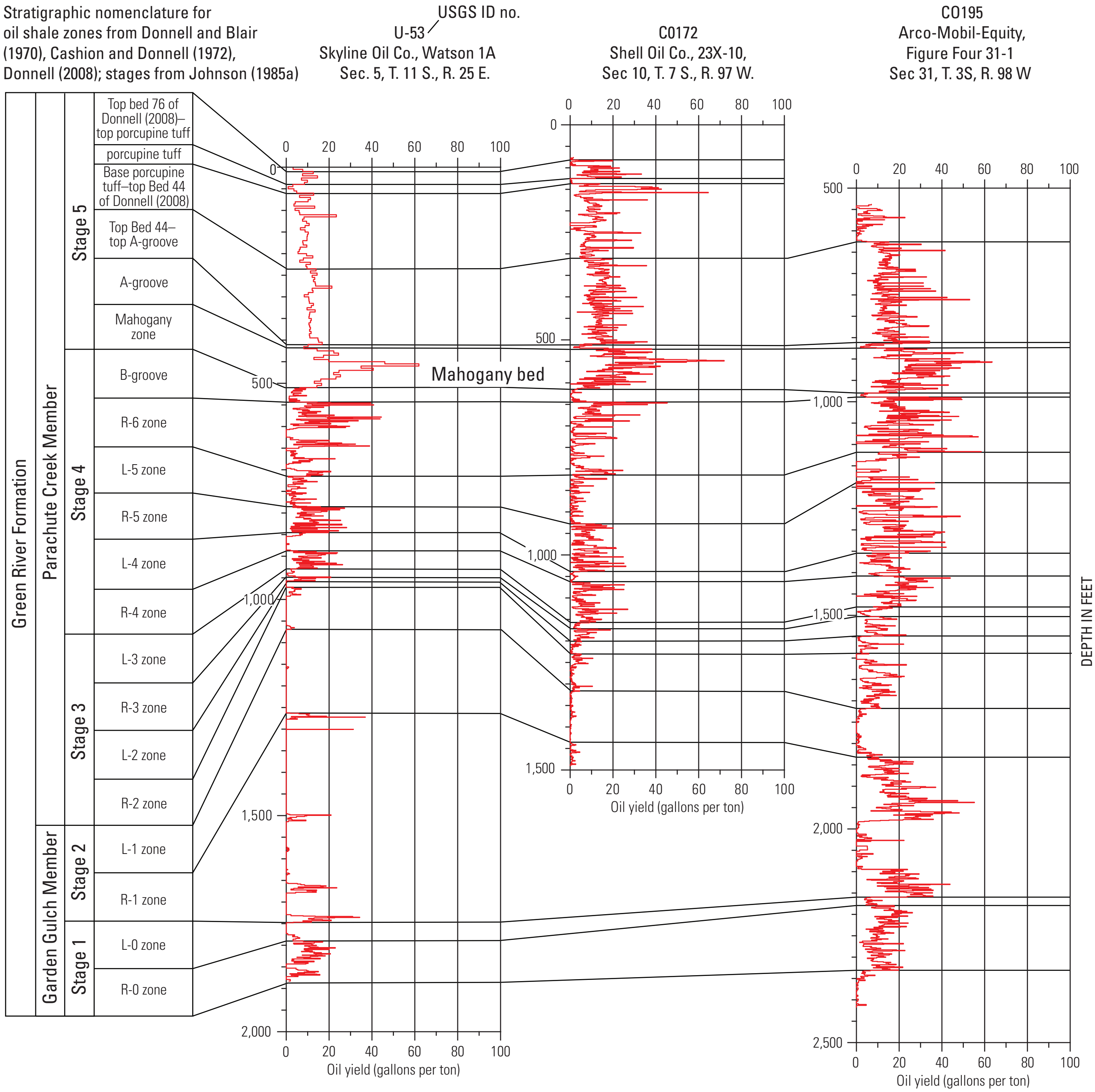


Figure 12. Cross section showing oil-yield histograms, members of the Eocene Green River Formation, correlation of rich and lean oil shale zones of Cashion and Donnell (1972), and stages in the evolution of Lake Uinta (Johnson, 1985a). Core hole U-53 is in the northeast corner of the Uinta Basin and core holes CO-172 and CO-195 are in the southeastern and central parts of the Piceance Basin, respectively.

Discussion

There are clearly problems with the definitions of the four members of the Green River Formation—Evacuation Creek, Garden Gulch, Parachute Creek, and Douglas Creek Members—originally defined by Bradley (1931). These problems led to inconsistencies in how these names have been applied throughout the basin, owing primarily to the lack of both subsurface and surface information at the time the members were defined. Such problems did not become apparent until the extensive coring and mapping programs in the 1960s, 1970s, and 1980s.

The name Evacuation Creek Member was abandoned when it was recognized as being equivalent to the Uinta Formation as used in the Piceance Basin by Cashion and Donnell (1974). However, the name was used on five of the earliest quadrangles mapped in the basin (Cashion, 1969; Cullins, 1968, 1969; Roehler, 1972a,b, 1973a,b). The Douglas Creek Member as originally defined by Bradley was later determined to include an interval of the underlying Wasatch Formation and rocks deposited in the freshwater lake that predated the formation of Lake Uinta. These two sequences were removed from the definition of the Douglas Creek Member, with the freshwater lake deposits given a new name, the Cow Ridge Member (Johnson, 1984), but not before the name Douglas Creek Member had been applied to these deposits on some of the early maps (Cashion, 1969; Cullins, 1968, 1969; Roehler, 1972a,b, 1973a,b).

A particularly large stratigraphic problem involves the original definition of the Garden Gulch Member by Bradley (1931). As previously discussed, the term Garden Gulch Member in the oil shale depocenter of the Piceance Basin is now applied to the illitic-rich oil shale interval that extends from the base of the R-0 zone to the base of the R-2 zone (fig. 12). However, Bradley (1931) defined the member for outcrops near the basin margin before drill data were available to study the subsurface stratigraphy. He was thus unaware of the relatively sharp transition between illitic oil shale below and dolomitic oil shale above that is at the base of the R-2 zone in the depocenter. By 1970, a significant number of core holes had penetrated the entire oil shale section in the basin interior, and the illitic and dolomitic zones were fairly well defined. The name Garden Gulch was applied to the illitic oil shale zone at the base of the section (R-0 through L-1 zones) (Trudell and others, 1970; Dyni, 1974; Ziemba, 1974), and the name Parachute Creek Member was applied to the overlying dolomitic oil shale zone (R-2 and above; fig. 12) based on Bradley's descriptions of these two members.

As detailed mapping progressed and correlations between the depocenter and the margins of the basin improved, inconsistencies between the Garden Gulch as defined in outcrop by Bradley and the Garden Gulch as defined by the R-zone stratigraphy became apparent. Mapping around the margins of the basin shows that the lower contact of the Garden Gulch Member varies from the base of the R-0 to about the middle of the R-1 zone, whereas the upper contact varies from the top of the R-0 zone to as high as the top of the R-5 zone (pl. 1).

The lower contact of the Garden Gulch Member progressively climbs stratigraphically toward the east margin of the basin as the lower part of the Garden Gulch grades into the sandy Anvil Points Member (pl. 1). Along Parachute Creek, where the Garden Gulch Member was originally defined by Bradley (1931), the R-0 zone has graded into the sandy Anvil Points Member, and about 3 miles to the southeast, the remaining Garden Gulch grades into Anvil Points (O'Sullivan and Hail, 1987) (pl. 1). Toward the west, in contrast, the lowest part of the Garden Gulch Member (about the R-0 zone) persists farther marginward than any other part of the Garden Gulch (pl. 1). Thus, marginal lacustrine rocks of the Anvil Points *underlie* the Garden Gulch Member toward the east margin of the basin, whereas marginal lacustrine rocks of the Douglas Creek Member *overlie* the Garden Gulch Member to the west. Remnants of the R-0 zone extend farther toward the southern margins of the Uinta Basin to the west than any oil shale zone below the R-4 zone (Johnson and others, 2010b).

The stratigraphic variability in the mapped position of the upper contact of the Garden Gulch with respect to the R-zone stratigraphy is complex. In Bradley's original Garden Gulch section along Parachute Creek, the contact with the overlying Parachute Creek Member is placed at about the base of the R-4 zone, which is much higher stratigraphically than the base of the R-2 zone in the oil shale depocenter. The base of the R-4 zone represents a period of expansion of Lake Uinta during which the area of oil shale deposition expanded to cover much of the area that had previously been marginal lacustrine (Johnson, 1986). Bradley (1931) considered the Parachute Creek Member to be "the oil-shale facies of the Green River Formation" stating (p. 11) that the Parachute Creek Member "contains all the large groups of rich beds, most of the individual rich beds, and a very large proportion of the low-grade oil shale." Although Bradley's Garden Gulch Member is characterized by the presence of papery fissile oil shale, he does not place the contact with the overlying Parachute Creek Member at the top of the highest interval of paper shale but rather about 60 ft above, at the base of the lowest major oil shale interval, or about the base of the R-4 zone (Bradley, 1931, his pl. 7). Thus, the Garden Gulch-Parachute Creek contact, where originally described, is primarily defined by the presence or absence of significant oil shale and only secondarily by the presence of papery shale. As previously discussed, the Garden Gulch as defined by Bradley (1931) also includes calcareous mudstone and oolitic and algal limestone more typical of the marginal lacustrine Anvil Points and Douglas Creek Members and thus occupies a position that is transitional between offshore lacustrine and marginal lacustrine.

The base of the R-4 zone is mapped as the base of the Parachute Creek Member in 21 of the quadrangles in the basin. Of these, the Garden Gulch Member is mapped below the Parachute Creek in 8 quadrangles, the Douglas Creek or Anvil Points Member is mapped below the Parachute Creek in 10, and in the remaining 3 quadrangles, the Garden Gulch Member is mapped below the Parachute Creek/base R-4 zone in parts of the quadrangles and Douglas Creek or Anvil Points in other parts.

The assumption that a high degree of fissility on outcrop indicates high illite/clay content and low dolomite content may not be entirely true. Although the Garden Gulch Member in the depocenter is predominantly illitic, it contains some dolomite as well (Robb and Smith, 1974). Similarly, the Parachute Creek Member also contains some illite in the depocenter. Green River Formation exposures along the lower part of Piceance Creek in the north-central part of the basin probably represent the most basinward oil shale facies cropping out anywhere in the basin, and thus represent the best place to study rocks similar to those in the depocenter (figs. 2 and 3). Nahcolite vugs are present in some stratigraphic intervals, and there is abundant nahcolite in the subsurface a short distance to the south. The rich and lean zones are better defined here than in any other outcrops, and the approximate positions of all of the rich and lean zones have been identified (Self and others, 2010, their pl. 13). The stratigraphically highest fissile oil shale interval, the top of which was used by Pipiringos and Johnson (1976) as the Garden Gulch-Parachute Creek contact, is near the base of the R-5 zone or much higher than the base of the R-2 zone.

Fissility as high as at least the R-5 zone could be the result of one or more of the following: (1) dolomitic oil shale contains enough clay to cause fissility, (2) the finely laminated nature of much of the dolomitic oil shale causes fissility, and (3) the mineralogy of the dolomitic interval changes toward the basin margins, due to changes in water chemistry, and these mineralogical changes promote the development of fissility in outcrop. Lake Uinta is believed to have been a stratified lake with two largely non-mixing layers (Bradley, 1929; Smith, 1974). The change from illitic-rich oil shale to dolomitic oil shale that takes place in the oil shale depocenter near the base of the R-2 zone was the result of changes in the chemistry and pH of the lower highly saline water layer (Smith, 1974). The mineralogical changes that are evident through the oil shale column have been well documented in the oil shale depocenter, but much less mineralogic information is available for lake-margin areas where the Garden Gulch and Parachute Creek Members were mapped. Mappers thus had little mineralogical data to help with defining their units. A north-south cross section through the depocenter of the basin (pl. 2), constructed by Johnson and others (in press) in their study of water-bearing mineral phases in the Green River Formation, uses some of the limited mineralogic data for basin margin areas. Only water-bearing phases are shown on the cross section, but mineralogical changes from the center of the depocenter outward are apparent, and these almost certainly reflect variations in water chemistry. The early illitic phase is shown extending across the entire basin at the base of the cross section. In the dolomitic zone above, the water-bearing phases grade outward from nahcolite and dawsonite in the middle of the depocenter, to just dawsonite, and finally to analcime and clay. The section exposed along lower Piceance Creek was remeasured for this study and is included in the cross section along with mineralogical data for the lower Piceance Creek section from Brobst and Tucker (1973). In this section, dawsonite-bearing oil shale extends from near the base of the R-3 zone to above the R-4 zone, with analcite and clay-bearing rocks both above and below (pl. 2).

The Uinta Formation represents a classic deltaic system that prograded from north to south into relatively deep Lake Uinta (Johnson, 1981a) (fig. 3). In an east-west direction, Uinta tongues are wedge-shaped as a result of a constantly shifting locus of clastic deposition (pl. 1) (Donnell, 2008, his figs. 10–16). The resulting complex pattern of the merging and splitting of sandstone and shale units is difficult to map, and only the most prominent Green River and Uinta Formations tongues have been named and mapped. Additionally, the lowest volcaniclastic unit of the Uinta Formation, which is present near the mouth of Yellow Creek (fig. 2), has been placed at two different stratigraphic positions by different workers: (1) at the Mahogany marker, a tuffaceous bed within the Mahogany zone just above the Mahogany bed (Johnson, 1981a; Donnell, 2008; Self and others, 2010, their pl. 13) or (2) somewhat higher, just above the top of the Mahogany oil shale zone (Hail, 1973, 1988). It may not be possible to resolve this issue, as the Mahogany zone (or Mahogany ledge on outcrop) grades into a silty and sandy interval in the vicinity of Yellow Creek (fig. 2, pl. 1, Rough Gulch and Smizer Gulch quadrangles) and cannot be recognized. Core-hole information, however, shows a marked thickening of the silty and sandy tuffaceous Mahogany marker toward the mouth of Yellow Creek, suggesting that the lowest Uinta tongue may be at that stratigraphic position. The lowest Uinta tongue is thus placed at the stratigraphic position of the Mahogany marker in this report (pl. 1). This placement, however, requires that the top of the Mahogany ledge as mapped by Hail (1973, 1974a, 1978) in the vicinity of Yellow Creek is too low, as these maps show the lowest Uinta tongue as being above the top of the Mahogany zone. More work is needed to resolve this problem.

In summary, an understanding of the geology of the oil shale strata in the Piceance Basin improved as the systematic geologic quadrangle program progressed. As a result, some of the geologic units that were defined prior to this detailed mapping were modified or discarded, and many of these inconsistencies that became evident after completion of the earliest maps were subsequently corrected on later regional compilations of the basin (Hail and Pipiringos, 1990; Hail and Smith, 1994, 1997). The extensive body of geologic data provided by the detailed quadrangle 7 ½-minute quadrangle maps, however, still represent the most detailed mapping available for this important area, and it is hoped that this investigation has contributed to a better understanding of this important body of work.

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