# Isopach and Isoresource Maps for Oil Shale Deposits in the Eocene Green River Formation for the Combined Uinta and Piceance Basins, Utah and Colorado

Scientific Investigations Report 2012–5076

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

**Cover.** Aerial image of Uinta and Piceance Basins, northeast Utah and northwest Colorado.
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**U.S. Geological Survey**
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# Isopach and Isoresource Maps for Oil Shale Deposits in the Eocene Green River Formation for the Combined Uinta and Piceance Basins, Utah and Colorado

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## Abstract

The in-place oil shale resources in the Eocene Green River Formation of the Piceance Basin of western Colorado and the Uinta Basin of western Colorado and eastern Utah are estimated at 1.53 trillion barrels and 1.32 trillion barrels, respectively. The oil shale strata were deposited in a single large saline lake, Lake Uinta, that covered both basins and the intervening Douglas Creek arch, an area of comparatively low rates of subsidence throughout the history of Lake Uinta. Although the Green River Formation is largely eroded for about a 20-mile area along the crest of the arch, the oil shale interval is similar in both basins, and 17 out of 18 of the assessed oil shale zones are common to both basins. Assessment maps for these 17 zones are combined so that the overall distribution of oil shale over the entire extent of Lake Uinta can be studied. The combined maps show that throughout most of the history of Lake Uinta, the richest oil shale was deposited in the depocenter in the north-central part of the Piceance Basin and in the northeast corner of the Uinta Basin where it is closest to the Piceance Basin, which is the only area of the Uinta Basin where all of the rich and lean oil shale zones, originally defined in the Piceance Basin, can be identified. Both the oil shale and saline mineral depocenter in the Piceance Basin and the richest oil shale area in the Uinta Basin were in areas with comparatively low rates of subsidence during Lake Uinta time, but both areas had low rates of clastic influx. Limiting clastic influx rather than maximizing subsidence appears to have been the most important factor in producing rich oil shale.

## Introduction

The in-place oil shale resources in the Eocene Green River Formation of the Piceance Basin of western Colorado and the Uinta Basin of western Colorado and eastern Utah are estimated at 1.53 trillion barrels and 1.32 trillion barrels, respectively (Johnson, Mercier, Brownfield, and others, 2010; Johnson, Mercier, Brownfield, and Self, 2010). The oil shale strata were deposited in a single large saline lake, Lake Uinta, that covered both basins and the intervening Douglas Creek arch (figs. 1 and 2). Although the Green River Formation is largely eroded for about a 20-mile area along the crest of the arch, the oil shale interval is similar in both basins, and 17 of the 18 assessed oil shale zones are common to both basins. The Greater Green River Basin of Wyoming, Utah, and Colorado also contains significant oil shale resources in the Green River Formation, recently estimated at 1.44 trillion barrels of oil in place (Johnson and others, 2011); however, these oil shale resources were deposited in a separate Eocene lake, Lake Gosiute, that underwent a different depositional history from that of Lake Uinta. There has been little success thus far correlating the oil shale deposits of Lake Gosiute to those of Lake Uinta; therefore, the oil shale deposits of Lake Gosiute are excluded from this report.

The oil shale interval in the Uinta and Piceance Basins is divided into 18 rich and lean zones (fig. 3), 17 of which are recognized in both basins, and one zone, bed 76, is unique to the Uinta Basin. Four maps are presented here for each assessed zone: (1) isopach, (2) variations in gallons per ton (GPT), (3) variations in barrels per acre (BPA) oil yield, and (4) total in-place oil in each 6-mi by 6-mi township. Gallons per ton maps depict variations in the richness of oil shale deposited in a particular oil shale zone, whereas BPA maps depict variations in the total amount of oil. In this report, the individual assessment results for the Uinta and Piceance Basins are combined into a single set of maps for the 17 oil shale zones common to both basins. The maps are identical to those published by Johnson, Mercier, Brownfield, and others (2010) and Johnson, Mercier, Brownfield, and Self (2010), except the contoured intervals are changed so that both basins use the same intervals for each map. Some detail on a few of the Uinta Basin maps originally published by Johnson, Mercier, Brownfield, and Self (2010) is lost due to the new contour intervals. Combined maps depicting total oil in each township were considered of limited usefulness and are not presented here.

Maps showing variations in weight-percent oil for each zone are presented for the first time. This step was taken because weight-percent oil is used instead of GPT to measure variations in oil shale richness by most countries; thus, these

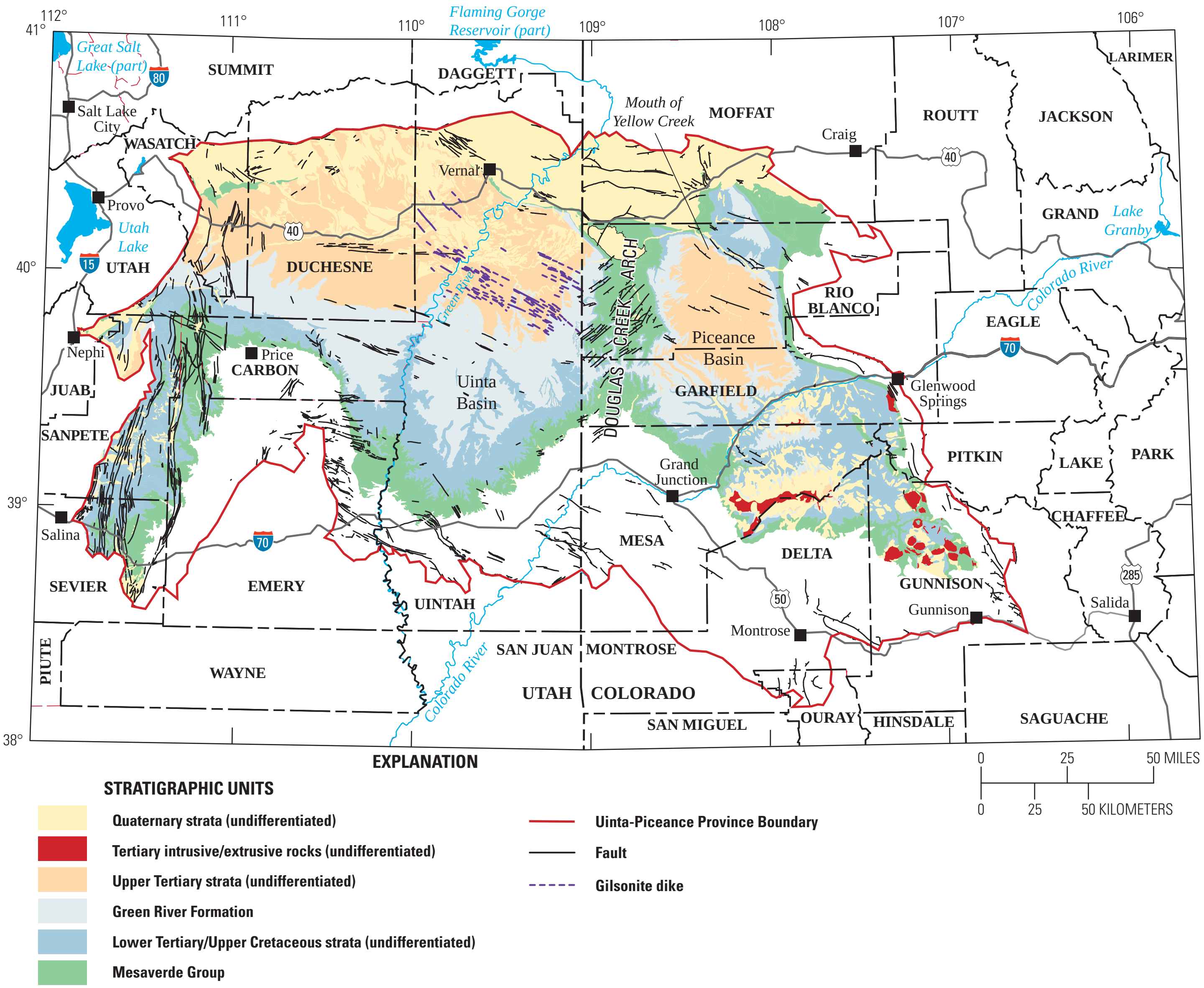


**Figure 1.** Generalized geologic map of the Uinta and Piceance Basins, northeastern Utah and northwestern Colorado, showing Upper Cretaceous and lower Tertiary stratigraphic units.

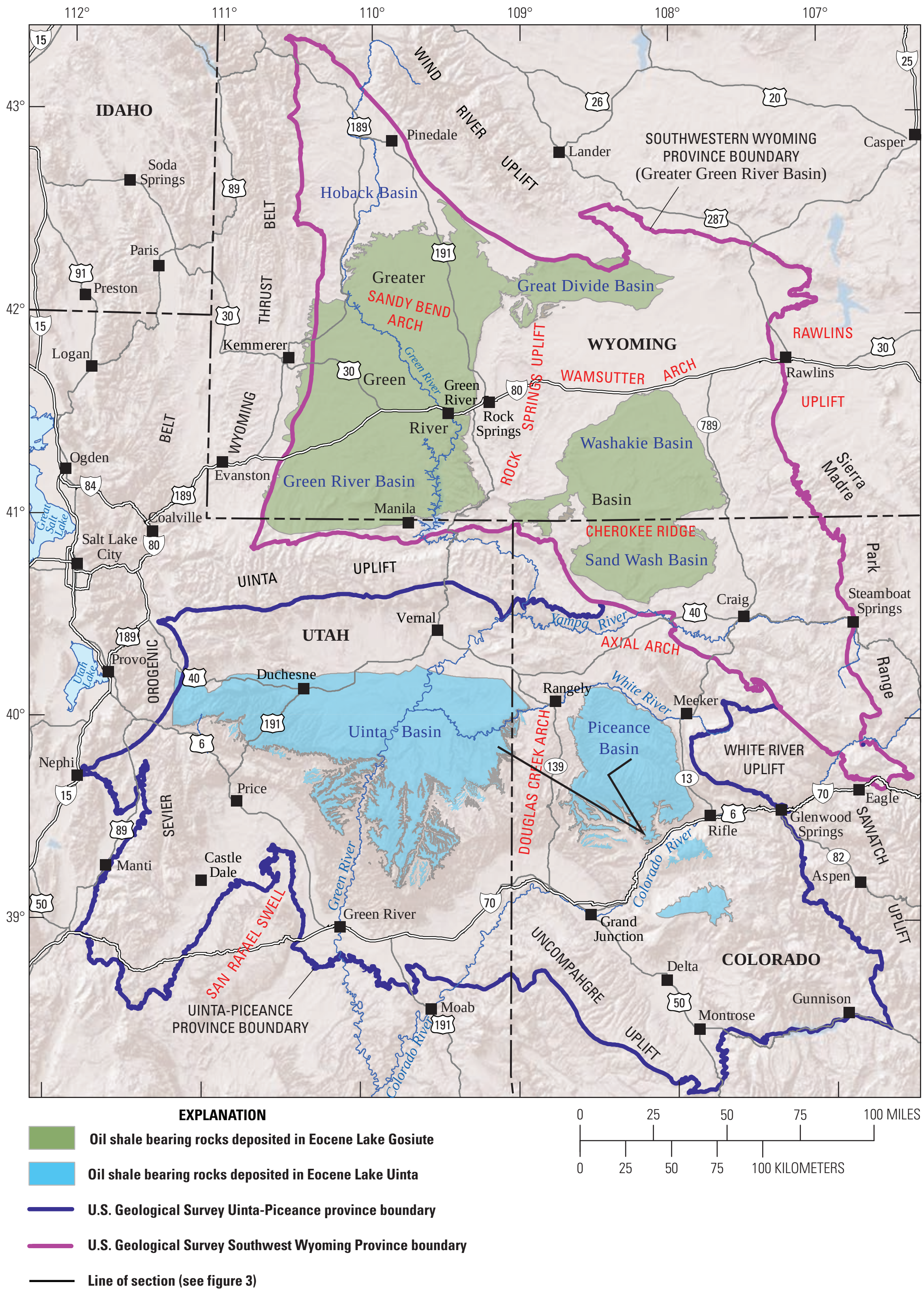
112°
111°
110°
109°
108°
107°
43°
42°
41°
40°
39°
IDAHO
WYOMING
UTAH
COLORADO
SOUTHWESTERN WYOMING PROVINCE BOUNDARY (Greater Green River Basin)
UINTA-PICEANCE PROVINCE BOUNDARY
Hoback Basin
Greater Green River Basin
Great Divide Basin
Washakie Basin
Sand Wash Basin
Uinta Basin
Piceance Basin
WIND RIVER UPLIFT
SANDY BEND ARCH
WAMSUTTER ARCH
ROCK SPRINGS UPLIFT
RAWLINS UPLIFT
CHEROKEE RIDGE
AXIAL ARCH
UINTA UPLIFT
DOUGLAS CREEK ARCH
WHITE RIVER UPLIFT
SAN RAFAEL SWELL
UNCOMPAHGRE UPLIFT
SAWATCH UPLIFT
Sierra Madre
Park Range
THRUST BELT
WYOMING
OROGENIC BELT
SEVIER
Pinedale
Lander
Casper
Soda Springs
Paris
Preston
Logan
Kemmerer
Green River
Rock Springs
Rawlins
Ogden
Evanston
Coalville
Manila
Salt Lake City
Provo
Vernal
Duchesne
Rangely
Meeker
Craig
Steamboat Springs
Nephi
Price
Manti
Castle Dale
Green River
Moab
Grand Junction
Rifle
Glenwood Springs
Eagle
Aspen
Delta
Montrose
Gunnison
Great Salt Lake
Utah Lake
Green River
Yampa River
White River
Colorado River
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
Line of section (see figure 3)
0 25 50 75 100 MILES
0 25 50 75 100 KILOMETERS

**Figure 2.** Extent of Uinta and Piceance Basins and Greater Green River Basin and approximate extent of oil shale in the Eocene Green River Formation. Extent of the Uinta and Piceance Basins is the same as the Uinta-Piceance Province boundary (USGS Uinta-Piceance Assessment Team, 2003). Extent of the Greater Green River Basin (which includes the Hoback, Great Divide, Green River, Washakie, and Sand Wash Basins) is the same as the Southwest Wyoming Province boundary (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005). For the extent of oil shale in the Piceance Basin, the base of the Parachute Creek Member of the Green River Formation as mapped by Tweto (1979) was used for all but the northwest part of the basin where the base of the lower member of the Green River Formation is used. For the extent of oil shale in the eastern part of the Uinta Basin, the base of the Parachute Creek Member as mapped by Cashion (1973) and Rowley and others (1985) was used. In the western part of the Uinta Basin, the top of the Mahogany oil shale bed as mapped by Witkind (1995) was used. In the northern part of the Uinta Basin, only those areas where oil shale is at a depth of 6,000 ft or less are shown, based on a structure contour map of the top of the Mahogany oil shale bed compiled by Johnson and Roberts (2003a). For the Sand Wash, Washakie, and Great Divide Basins and southeastern part of the Green River Basin, the base of the Tipton Shale Member of the Green River Formation as mapped by Tweto (1979) and Love and Christiansen (1985) was used as the extent of oil shale. For the western part of the Green River Basin, the base of the Wilkins Peak Member of the Green River Formation, and for the northern part of the Green River Basin, the base of the Laney Shale Member of the Green River Formation as mapped by Love and Christiansen (1985) was used. Location of cross section in figure 3 shown in black.

maps will make our assessments more readily understandable to workers worldwide. These maps were created by applying a hillshade function to the Esri GeoStatistical models instead of the Esri GRIDs to visually enhance the displayed contours creating the illusion that the maps are three-dimensional. Weight-percent oil is measured with the standard Fischer assay analysis used to determine the oil content of oil shale, and the maps were generated by substituting weight-percent oil for gallons per ton oil using the assessment methodology outlined in Mercier and others (2010).

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

The Fischer assay method does not determine the total amount of hydrocarbons in an oil shale sample nor does it measure the amount or composition of the gases released during the heating of the sample. These gases—chiefly light hydrocarbons, hydrogen, and carbon dioxide—are reported as “gas plus loss.”

Fischer assay does not measure the maximum amount of oil that an oil shale can produce; there are retorting methods that yield more oil than Fischer assay (see Dyni, 2003, p. 195–196, for a discussion of methods to determine oil yields). However, the oil yields achieved by other technologies are typically reported as a percentage of the Fischer assay oil yield; thus, Fischer assay is still considered the standard by which other methods are compared.

# Stratigraphy of the Green River Formation and Definition of Rich and Lean Zones of the Oil Shale Section

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 Green River Formation in the Uinta and Piceance Basins was deposited in Lake Uinta, a large saline lake that formed in early Eocene time when two much smaller freshwater lakes, one in each basin, coalesced across the Douglas Creek arch to form one large lake during a major transgression called the Long Point transgression (pl. 1) (Johnson, 1985). The Douglas Creek arch was an area with relatively low subsidence rates throughout the Paleocene and Eocene, and pre-Long Point Paleocene and lower Eocene rocks thin and largely wedge out on both flanks of the arch (pl. 1). Lake Uinta sediments, in contrast, appear to have extended unbroken across the arch (pl. 1) (Johnson, 1985, 1989; Johnson and Roberts, 2003, their pl. 1), although there is significant thinning of these sediments toward the crest of the arch (pl. 1) (Johnson and Finn, 1986, their fig. 12). Johnson (1985) hypothesized that a relatively deep-water connection existed between the Uinta Basin and Piceance Basin parts of the lake along the northern part of the arch adjacent to this rich oil shale area in the Uinta Basin (fig. 4). However, this remains problematic because the Green River Formation has been largely eroded for an east-west distance of about 20 mi in this hypothesized connecting area (fig. 1).

The salinity of Lake Uinta increased through time (Johnson, 1985), ultimately leading to deposition of vast quantities of halite and the potentially valuable sodium bicarbonate mineral nahcolite ($NaHCO_3$) along with many other minerals such

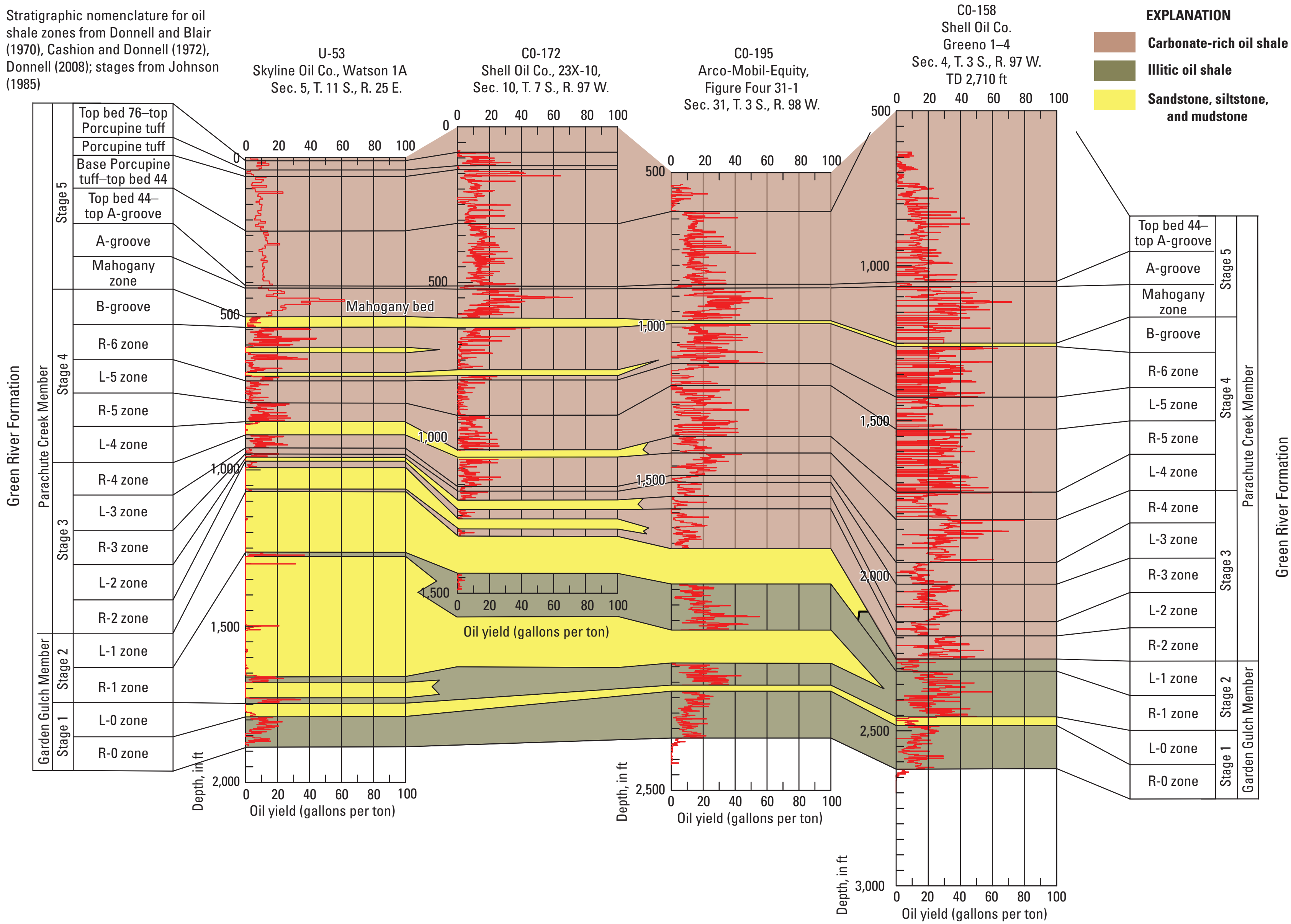


**Figure 3.** Cross section showing members of the Eocene Green River Formation, stages in the evolution of Lake Uinta, correlation of rich (R) and lean (L) oil shale zones of Cashion and Donnell (1972), and oil-yield histograms. Core hole U-53 is in the northeast corner of the Uinta Basin, core holes CO-172 and CO-195 are in the southeastern and central parts of the Piceance Basin respectively, and CO-158 is in the central part of the Piceance Basin. Location shown on figure 2.

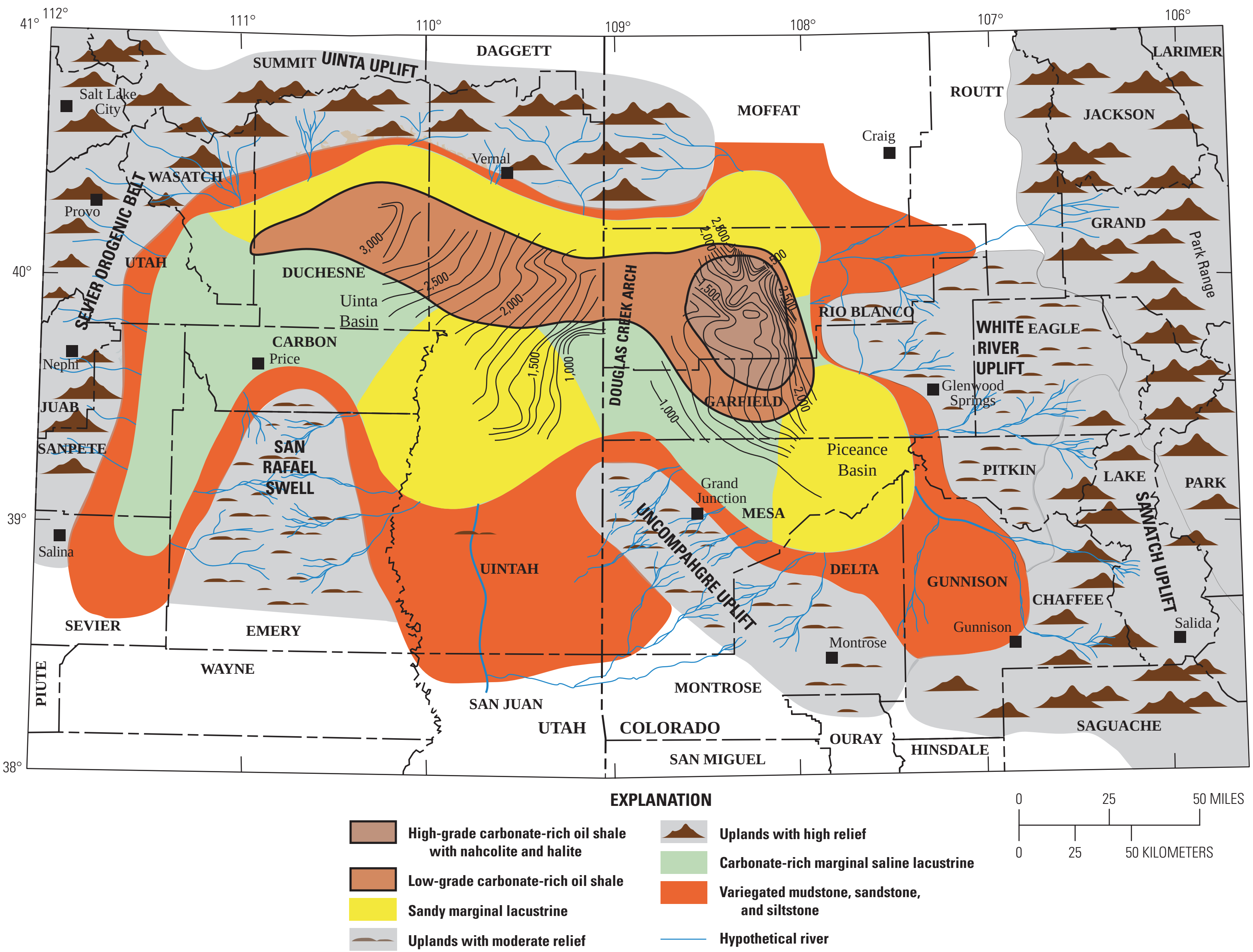


**Figure 4.** Paleogeographic map of the Uinta and Piceance Basins showing uplifts, depositional environments, and types of sediments being deposited during the period when vast amounts of halite and nahcolite (sodium bicarbonate) were being deposited along with rich oil shale in the north-central part of the Piceance Basin. Modified from Johnson (1985, his fig. 11). In central part of figure, isopachs show thickness from base of Long Point Bed of Green River Formation to top of Mahogany oil shale zone (from Johnson and Finn,1986, their fig. 12; contour interval is 100 ft).

as dawsonite ($NaAl(OH_2CO_3)$), eitelite ($Na_2CO_3 \cdot MgCO_3$), and shortite ($Na_2Ca_2(CO_3)_3$) (for a summary, see Dyni, 1996). Saline mineral deposition was confined to the depocenter in the north-central part of the Piceance Basin (pl. 1) throughout much of the history of Lake Uinta and only shifted to the Uinta Basin late in the lake's history after the Piceance depocenter had been filled with volcaniclastic sediments from the north (Brownfield, Johnson, and Dyni, 2010). Dyni (1996) believed that there was a net flow of water from the Uinta Basin across the Douglas Creek arch and into the Piceance Basin, thus confining saline mineral deposition to the Piceance Basin prior to infilling.

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-organic productivity and low-organic productivity (fig. 3 and pl. 1). Each of these divisions will be discussed briefly.

Four of the members of the Green River Formation—Parachute Creek, Douglas Creek, Garden Gulch, and Evacuation Creek—were originally defined by Bradley (1931) who recognized them in both the Uinta and Piceance Basins, thereby reinforcing the concept that Lake Uinta was a single, unbroken lake spanning the two basins and the intervening Douglas Creek arch throughout much of its history (pl. 1). The name Evacuation Creek was later abandoned (Cashion and Donnell, 1974) because it was determined to be lithologically and stratigraphically equivalent to the upper part of the Parachute Creek Member. In the oil shale section deposited in the offshore areas of the lake, the name Garden Gulch is applied to the illitic oil shale deposited early in the history of Lake Uinta, and the name Parachute Creek is applied to the dolomitic oil shales deposited later. The name Douglas Creek Member is applied to marginal lacustrine rocks along the east and south margins of the Uinta Basin and the west and south margins of the Piceance Basin (Bradley, 1931; Cashion, 1967). The name Uinta Formation is applied to a sequence of sandstones and siltstones containing abundant volcanic debris that interfingers with the upper part of the Green River Formation (Dane, 1954; Cashion and Donnell, 1974). Although Bradley (1931, his pl. 8) applied the name Garden Gulch Member to strata in the easternmost part of the Uinta Basin, subsequent mapping in the Uinta Basin did not use the name (for example, see Cashion, 1977, 1978, 1986; Pipiringos, 1978), and usage of Garden Gulch Member is now confined to the Piceance Basin.

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 a significant change in conditions in the lake (fig. 3 and pl. 1). The first two stages are equivalent to the illitic oil shales of the Garden Gulch Member, and the last three stages are generally equivalent to the dolomitic oil shales of the Parachute Creek Member (fig. 3 and pl. 1). The beginning of stage 1 is marked by the initial transgression of Lake Uinta, the Long Point transgression, that caused two comparatively small freshwater lakes—one in the Piceance Basin and one in the Uinta Basin—to form one large lake that spanned the intervening Douglas Creek arch (pl. 1). The illitic-rich oil shales from this stage that were deposited in the offshore areas of the lake generally average less than 15 GPT, and because of their great depth and low grade, they have received little economic interest. These shales, however, form one of the most widespread units recognized in both the Uinta and Piceance Basins. The unit is approximately equivalent to the "second lacustrine phase" in Bradley's (1931) Indian Canyon section in the western part of the Uinta Basin. In the subsurface, stage 1 strata extend from the base of the Long Point Bed and its equivalent rocks to the top of the carbonate marker in the Uinta Basin and to the top of the orange marker in the Piceance Basin. Distinctive electric log markers representing a slight increase in carbonate content can be traced throughout much of the offshore lacustrine areas of both basins (Fouch, 1975; Ryder and others, 1976; Johnson, 1985).

Average oil yields increased at the beginning of stage 2 in the Piceance Basin from less than 15 GPT to a maximum of about 27 GPT with some thin beds averaging nearly 60 GPT. This increase is more difficult to detect in the Uinta Basin because wedges of sandstone, siltstone, and mudstone are common in the interval deposited at that time (fig. 3) and because they are rarely cored and assayed. Stage 2 strata can be detected in a few of the deeper oil shale core holes in the eastern part of the basin (fig. 3).

A gradual shift from illitic-rich to carbonate-rich oil shales occurred at the beginning of stage 3 (fig. 3), and for the first time nahcolite was deposited in the central part of the Piceance Basin to the east. As noted above, nahcolite was not deposited in the Uinta Basin part of Lake Uinta until much later. Nahcolite is disseminated in oil shale as aggregates and as beds (Dyni, 1974, 1981; Brownfield, Johnson, and Dyni, 2010). Bedded nahcolite grades laterally into halite beds toward the middle of the saline depocenter. All oil shales deposited after the beginning of stage 3 are carbonate rich with dolomite the dominant carbonate (Robb and Smith, 1974).

Stage 4 began with a relatively minor transgression, represented by an increase in oil yield at the base of the R-4 zone (fig. 3 and pl. 1) that may have been caused by increased outflow from Lake Gosiute in the Greater Green River Basin into Lake Uinta (Johnson, 1985, 2007). The transgression at the start of stage 5 is represented by the base of the Mahogany oil shale zone (also referred to as Mahogany zone in this report and Mahogany ledge where exposed in outcrop) (fig. 3 and pl. 1). The Mahogany zone (ledge) is the most widely distributed and easily recognized oil shale zone in both the Uinta and Piceance Basins (pl. 1). This transgression was almost certainly related to increased outflow from Lake Gosuite because volcaniclastic sediments thought to be derived from the Absaroka volcanic field in northwestern Wyoming reached the north margin of Lake Uinta in the northern part of the Piceance Basin shortly after maximum transgression (Surdam and Stanley, 1980). These volcaniclastic sediments could only have reached Lake Uinta once Lake Gosiute was largely filled because prior to its infilling Lake Gosiute would have acted as a sediment sink. The volcaniclastic sediments gradually filled the Piceance Basin part of Lake Uinta, thus ending oil shale deposition there and shifting saline mineral deposition to the Uinta Basin (Johnson, 1985). A saline zone as much as 900 ft thick, where saline minerals have been leached, was deposited in the Uinta Basin after the saline depocenter in the Piceance Basin was filled (Dane, 1955; Brownfield, Johnson, and Dyni, 2010).

Trudell and others (1970) correlated individual oil shale beds throughout the central part of the Piceance Basin. Cashion and Donnell (1972) recognized that the entire Parachute Creek and Garden Gulch Members in the Piceance Basin could be subdivided into a sequence of oil-rich zones (R-0 through R-6 zones) and oil-lean zones (L-0 through L-5 zones) (fig. 3). The lower zones, from L-0 zone through L-1 zone, are clay-rich and contain little carbonate; they form the Garden Gulch Member. All zones above L-1 zone are dolomitic and form the Parachute Creek Member. Units above R-6 zone are (in ascending order) B-groove, which is a lean zone; Mahogany zone, the richest oil shale zone in the basin; and A-groove, another lean zone (fig. 3). On a finer scale, many individual rich and lean beds within each rich and lean zone can be traced for considerable distances as well. All of these oil shale zones grade into marginal lacustrine rocks toward the margins of the Piceance Basin, and their marginal equivalents are difficult to identify. Johnson and others (1988) were able to trace some of the rich and lean zones into their marginal lacustrine equivalents along the eastern margin of the Uinta Basin and western margin of the Piceance Basin.

Cashion and Donnell (1972) also traced R-4 and younger oil shale zones into the eastern part of the Uinta Basin (fig. 3), and Johnson (1985, 1989) subsequently traced them into the western part (pl. 1). The interval above A-groove is one of the easiest intervals to correlate in the two basins, and Donnell (2008) correlated many individual beds over wide areas. All of these oil shale beds and oil shale zones appear to closely represent time-stratigraphic units representing changing rates of organic matter production and preservation that occurred simultaneously throughout Lake Uinta.

Oil shale zones below R-4 zone are difficult to trace in the Uinta Basin because they are leaner than in the Piceance Basin, and many are thin (fig. 3). Johnson (1989) traced R-0, R-1, and L-0 zones throughout much of the eastern two-thirds of the Uinta Basin, but correlations were problematic in the western one-third of the basin. The R-2 through L-3 zones were traced into a 150- to 250-ft-thick interval, but Johnson (1989) did not distinguish the individual zones in that interval. These individual zones are traced here in a limited area of the easternmost part of the Uinta Basin where the zones could be identified in core drill holes and traced into nearby rotary drill holes.

The entire Green River Formation below the Mahogany zone becomes interbedded with clastic wedges of sandstone, siltstone, and mudstone toward the southern part of the Uinta Basin dividing the oil shale interval into thin, discrete oil shale intervals separated by intervals of barren rock that thicken toward the south (fig. 3). Many of these clastic wedges can be traced into the southwestern part of the Piceance Basin as well (fig. 3). Ultimately, these discrete oil shale intervals grade into marginal lacustrine and fluvial rocks toward the south margin of the Uinta Basin where the individual oil shale zones can no longer be identified. The R-0 zone, a part of stage 1 of Lake Uinta discussed earlier (fig. 3), can be identified much farther to the south than any other oil shale zone below the Mahogany zone. The Mahogany zone becomes split by clastic wedges toward the south margin of the basin with only the Mahogany oil shale bed (also referred to as Mahogany bed in this report), the richest bed in the zone, still present there.

# Detailed Description and Assessment Results of Oil Shale Zones

## R-0 Zone

The R-0 and L-0 zones compose the first stage of Lake Uinta as defined by Johnson (1985) (pl. 1 and fig. 3). The R-0 oil shale zone is the first oil shale zone deposited after the Long Point transgression when two much smaller freshwater lakes in the Piceance and Uinta Basins expanded and connected across the Douglas Creek arch to form one large lake, Lake Uinta (pl. 1) (Johnson, 1985). It is one of the most widespread oil shale zones in both basins. A transgressive, mollusk-rich bed named the Long Point Bed of the Douglas Creek, Anvil Points, or Garden Gulch Members of the Green River Formation (Johnson, 1984) commonly marks the base of the R-0 zone in marginal areas of both basins where it overlies variegated mudstones of the fluvial Wasatch Formation (Johnson, 1989). The base of the R-0 zone can be identified throughout much of the deeper parts of the Piceance Basin as a distinctive resistivity “kick” on electric logs (for example, see Johnson, 1989). Along the northwest margin of the Piceance Basin, the R-0 zone overlies freshwater lacustrine rocks of the Cow Ridge Member of the Green River Formation, and in this area the base of the R-0 zone is marked by a change from mollusk-bearing freshwater lacustrine rocks below to low-grade oil shale above (Johnson, 1985; Johnson and others, 1988). The R-0 zone grades into sandstones toward the eastern margin of the Piceance Basin.

The upper 30 to 75 ft of the R-0 zone is marked in the central part of both basins by a distinctive increase in resistivity on electric logs known informally in the Piceance Basin as the orange marker, named for the color of a pen used to mark it on geophysical logs (Chancellor and others, 1974; Ziemba, 1974), and in the Uinta Basin it is referred to as the carbonate marker (Fouch, 1975; Ryder and others, 1976; Johnson, 1989). The increase in resistivity is caused by a slight increase in carbonate in the illitic strata.

In the Piceance Basin, the R-0 zone is thinnest in the westernmost part of the basin along the Douglas Creek arch (fig. 2) where it is about 75 ft thick (fig. 5). It thickens and becomes sandy to the southeast, east, and northeast, reaching a maximum thickness of about 585 ft thick at Anvil Points, just west of Rifle, Colo. (fig. 2), in the southeast part of the basin where it is predominantly fluvial and consists of variegated mudstone and lenticular sandstone. The R-0 zone is included in the Anvil Points Member of the Green River Formation in the eastern part of the Piceance Basin where it is sandy. The R-0 zone generally thickens to the north and west across the Uinta Basin from a minimum of 89 ft in one well near the crest of the Douglas Creek arch to 340 ft near the west margin of the study area (fig. 5).

Oil yields for the R-0 zone in the Piceance Basin range from 10 to 20 GPT throughout a broad area of the central part of the basin with yields decreasing in a regular fashion toward the basin margins (fig. 6). Oil yields are low along the east margins of the basin where the zone is predominantly sandstone. In the Uinta Basin, oil yields are greatest in the northeastern part of the basin where they are as much as 9.8 GPT (fig. 6). Maximum oil yield in weight percent is 9.2 percent in the central part of the Piceance Basin decreasing to less than 4.0 percent around the basin margins. Maximum weight-percent oil in the Uinta Basin is 4.0 in the northeast part of the basin (fig. 7). Barrels of oil per acre in the central part of the Piceance Basin range from 150,000 to 250,000 and decrease in a regular fashion outward (fig. 8). Barrels of oil per acre in the Uinta Basin range from 27,000 to 95,000 throughout much of the basin; two rotary drill holes in the central part of the Uinta Basin indicated yields of 130,000 and 140,000 BPA (fig. 8). Values approach 0 BPA toward the south margin (fig. 8).

## L-0 Zone

The L-0 zone is a thin, lean zone with a thickness range of 13 to 35 ft throughout most of the Piceance Basin (fig. 9). It thickens in an irregular fashion toward the east margin of the basin where it grades into sandstone. In the Uinta Basin, the L-0 zone thickens from 30 to 43.3 ft along the west flank of the Douglas Creek arch to a maximum of about 120 ft in the western part of the assessed area (fig. 9). Oil yields for the L-0 zone in the Piceance Basin range from 5.0 to 14.3 GPT in the central part of the basin and decrease in a regular fashion toward the basin margins (fig. 10). In the Uinta Basin, maximum oil yields range from 3–4 GPT in the northeast corner of the basin (fig. 10). Weight-percent oil reaches a maximum of 14.6 percent in limited areas in the central part of the Piceance Basin. Maximum values for the Uinta Basin are about 4 weight-percent oil in the northeast part of the basin (fig. 11). In the Piceance Basin, maximum in-place resources range from 7,500 to 32,000 BPA in the central part of the Piceance Basin and decrease outward toward the basin margins (fig. 12). Maximum in-place resources in the Uinta Basin are about 12,000 BPA in the northeast part of that basin.

## R-1 Zone

The R-1 zone consists of illite-rich oil shale similar to the underlying R-0 zone but is much richer. In the Piceance Basin, the R-1 zone ranges in thickness from about 100 to 125 ft in the central part of the basin to more than 350 ft along much of the eastern, southeastern, and southwestern margins (fig. 13). Much of the thickening toward the southwest is due to the presence of discrete, southwestward-thickening, kerogen-poor, mudstones and sandstones wedging into the oil shale interval (fig. 3) (Johnson, 1985, 1989; Johnson and others, 1988; Pitman and others, 1989). The wedges appear to be predominantly lacustrine consisting of nonlaminated to laminated carbonate-rich mudstone in the center of the basin grading to the southwest into sandstone and mudstone that is, in part, highly contorted and then grading into carbonate-rich mudstone and ripple-laminated sandstone with stromatolitic, ostracodal, and oolitic limestone (Johnson, 1985; Johnson and others, 1988). These wedges can be traced into the Uinta Basin where they thicken and coalesce toward the south margin of the basin replacing much of the oil shale in the R-1 zone, ultimately grading into fluvial rocks of the Renegade Tongue of the Wasatch Formation (Cashion, 1967). In the Uinta Basin, the R-1 interval thickens from about 400 ft on the west flank of the Douglas Creek arch to 910 ft in the eastern part of the assessed area (fig. 13).

In the Piceance Basin, estimated oil yield for the R-1 zone ranges from about 20 to 29 GPT in the central part of the basin with oil yields decreasing markedly toward the margins of the basin (fig. 14). In the limited area in the Uinta Basin where the R-1 zone was assessed, oil yield ranges from a maximum of 4.3 GPT in the northeast corner of the basin to a minimum 1.9 GPT in the northwest corner of the assessed area (fig. 14). Weight-percent oil reaches a maximum of 11.8 percent in the central part of the Piceance Basin (fig. 15). Maximum weight-percent oil for the R-1 zone in the Uinta Basin is about 4 percent in the northeast part of that basin (fig. 15). In the Piceance Basin, estimated in-place oil ranges from 300,000 to 435,000 BPA through a broad crescent-shaped depocenter (fig. 16) that is somewhat south of the depocenter for the underlying R-0 and L-0 zones. Oil yields are lower in this depocenter than farther to the north, but this is due largely to the presence of clastic wedges into the R-1 interval discussed earlier. In the Uinta Basin, estimated BPA ranges from 87,000 to 160,000 in the limited area that was assessed (fig. 16).

## L-1 Zone

The L-1 zone is lithologically similar to the clastic wedges that split the underlying R-1 zone and is essentially the highest of these clastic wedges. In the Piceance Basin, it generally thickens toward the south and west from 60 to 270 ft, and in the Uinta Basin, in the limited area where the L-1 zone is assessed, it generally thickens toward the south and west from 60 to 270 ft (fig. 17). Maximum oil yields in the Piceance Basin are from

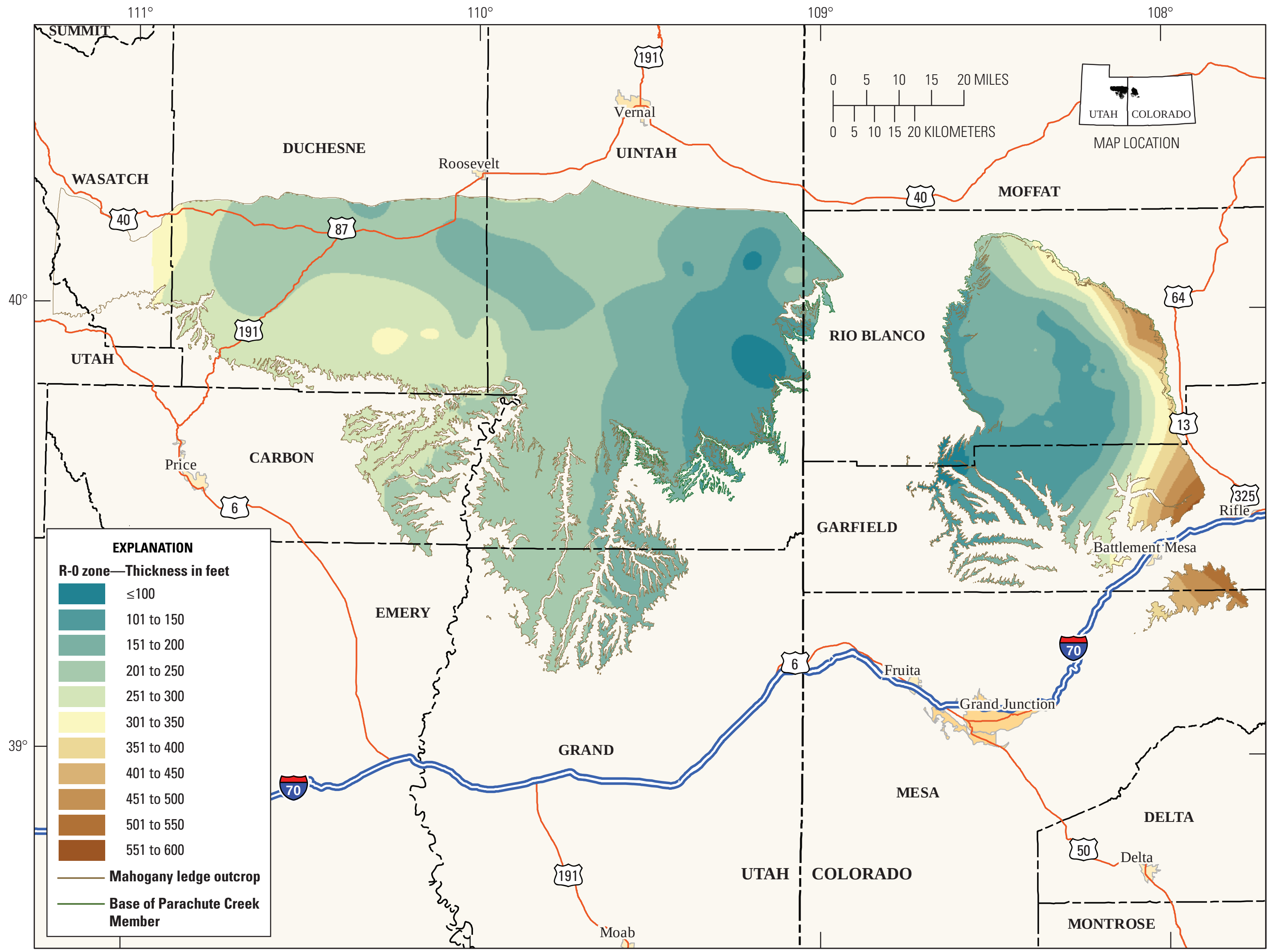


**Figure 5.** Isopach map of R-0 zone in Uinta and Piceance Basins using Radial Basis Function method for contouring. Contour interval in feet is variable.

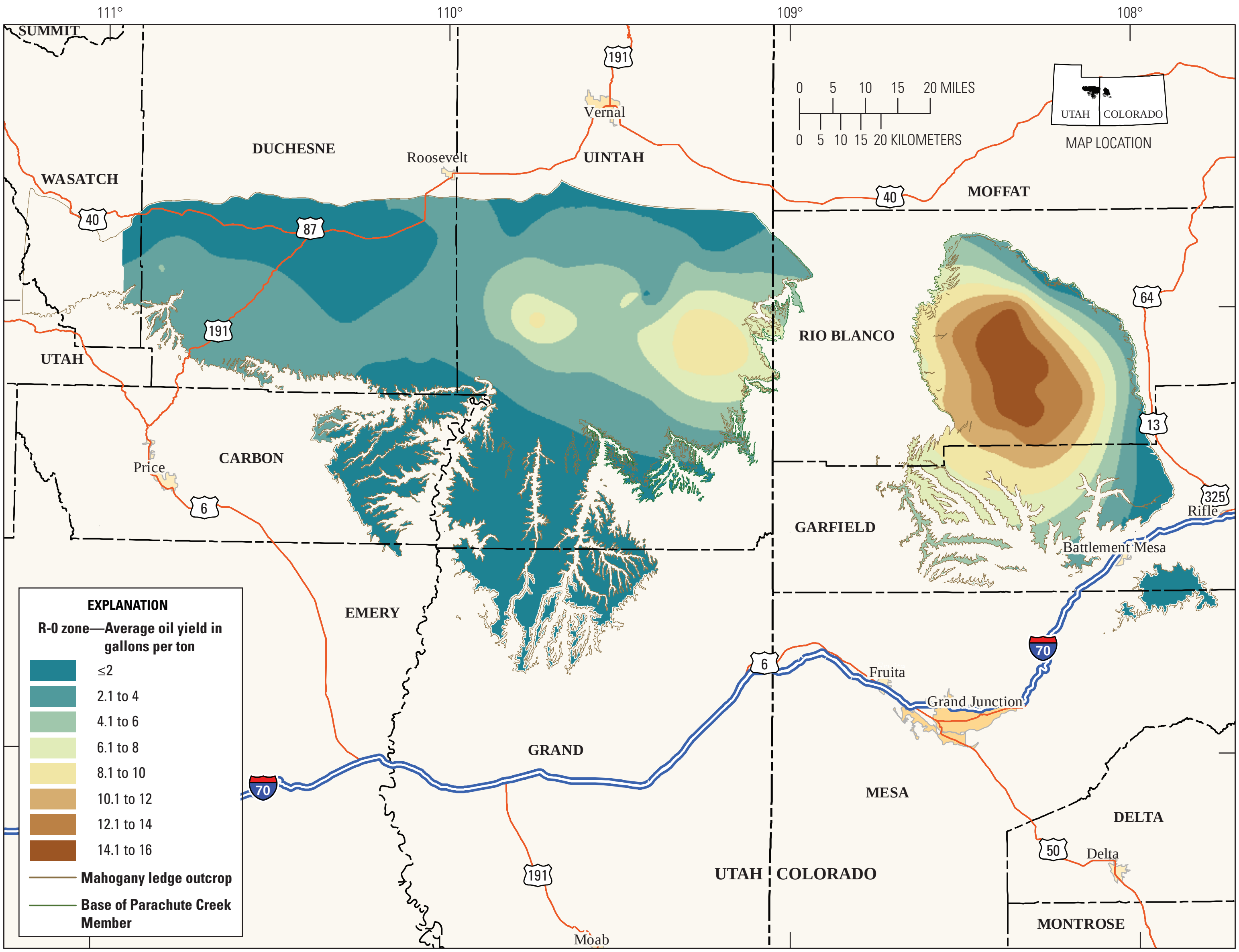


**Figure 6.** Isoresource map of R-0 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

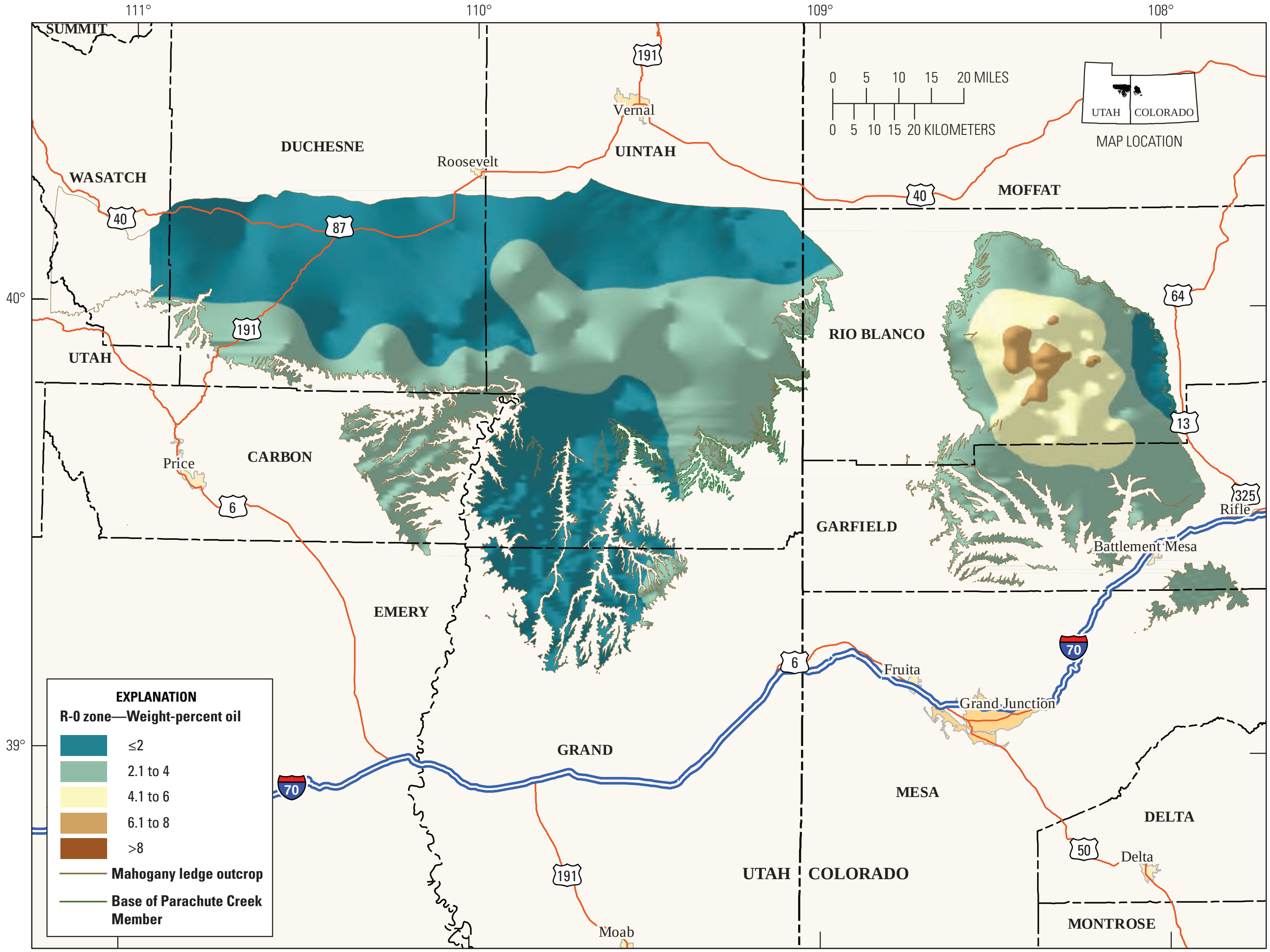


**Figure 7.** Isoresource map of R-0 zone in Uinta and Piceance Basins showing oil yield in weight percent.

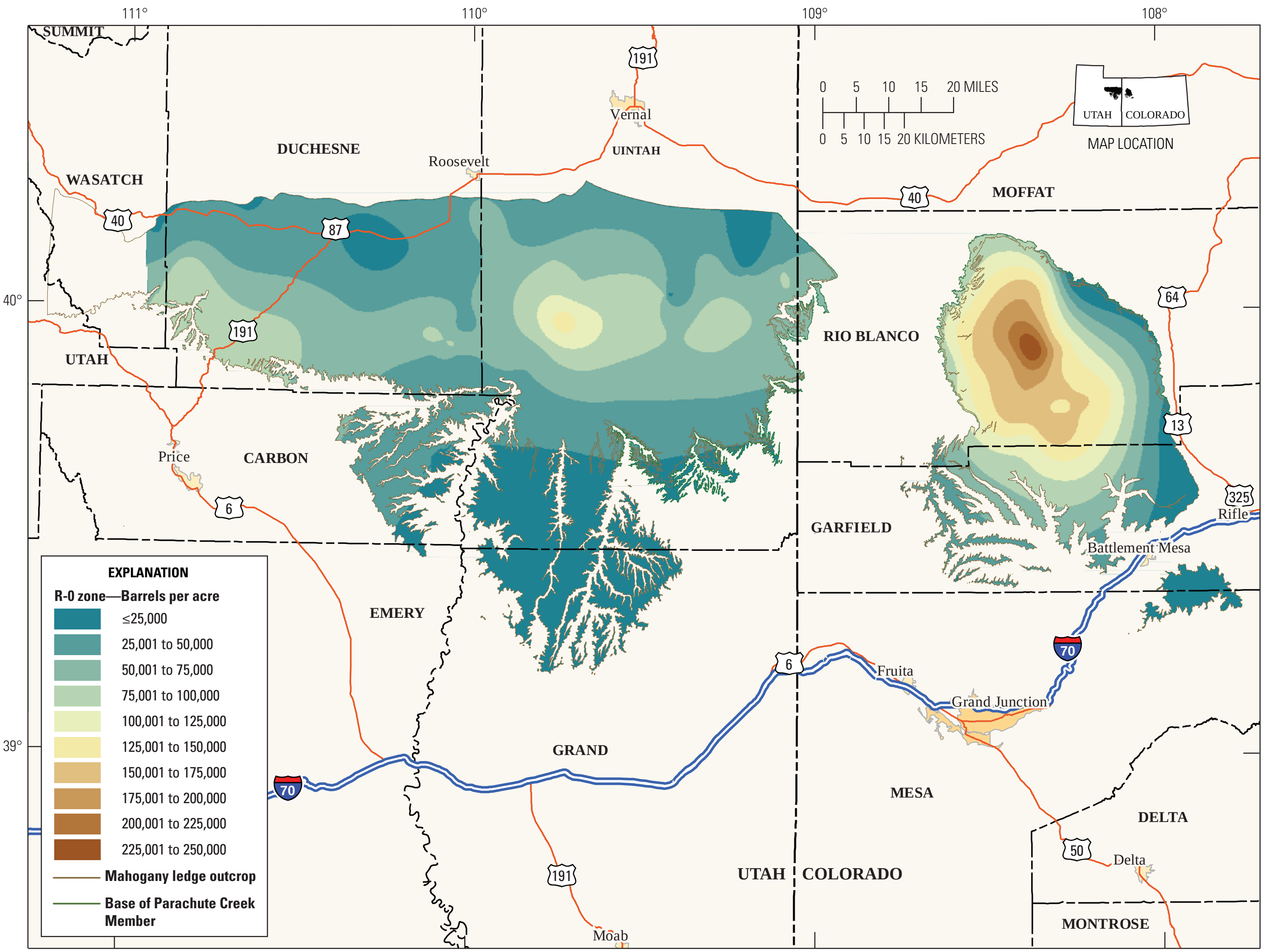


**Figure 8.** Isoresource map of R-0 zone in the Uinta and Piceance Basins showing oil yield in barrels per acre. The Radial Basis Function method was used for contouring.

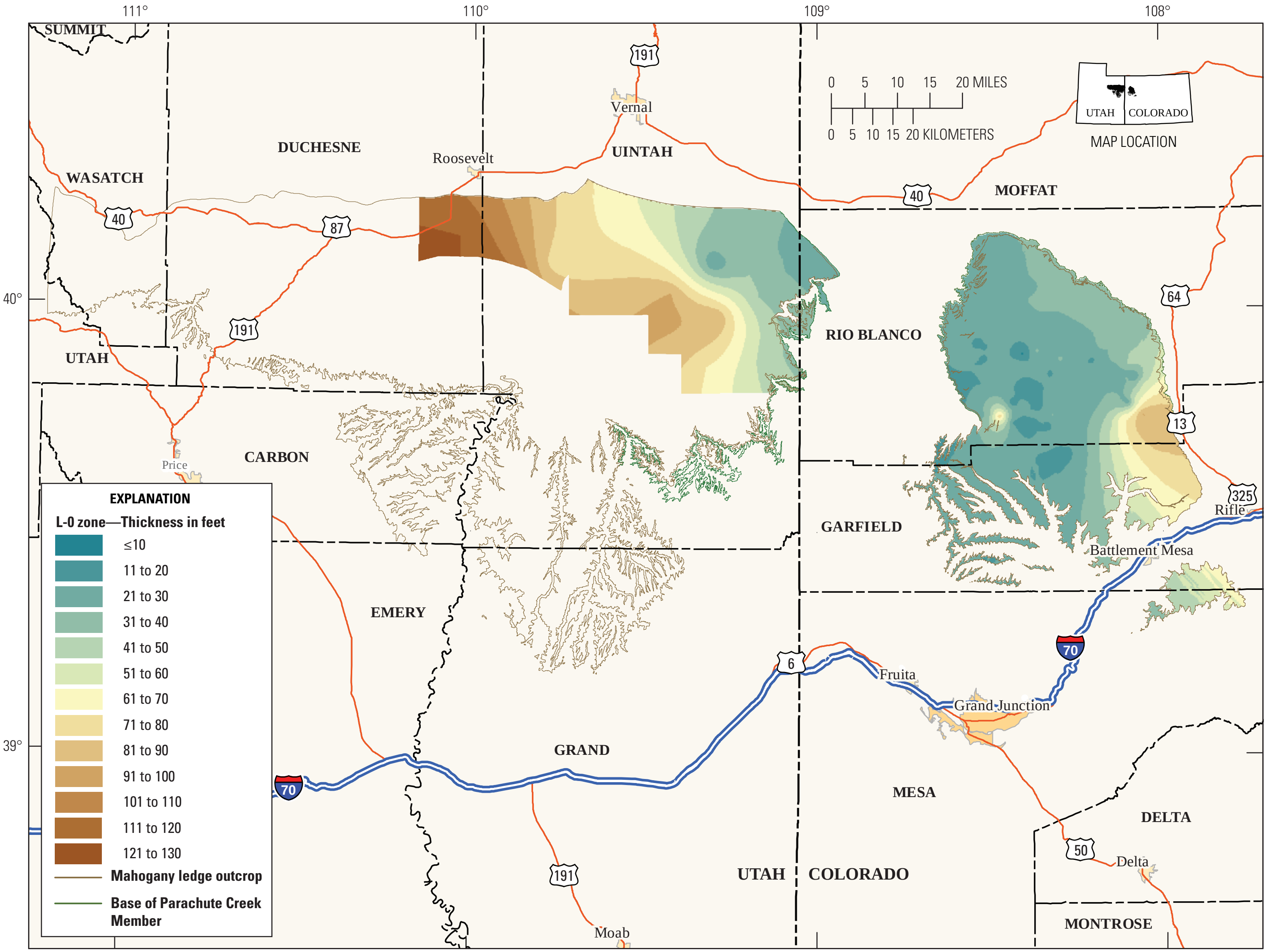


**Figure 9.** Isopach map of L-0 zone in Uinta and Piceance Basins using the Radial Basis Function method for contouring. Contour interval in feet is variable.

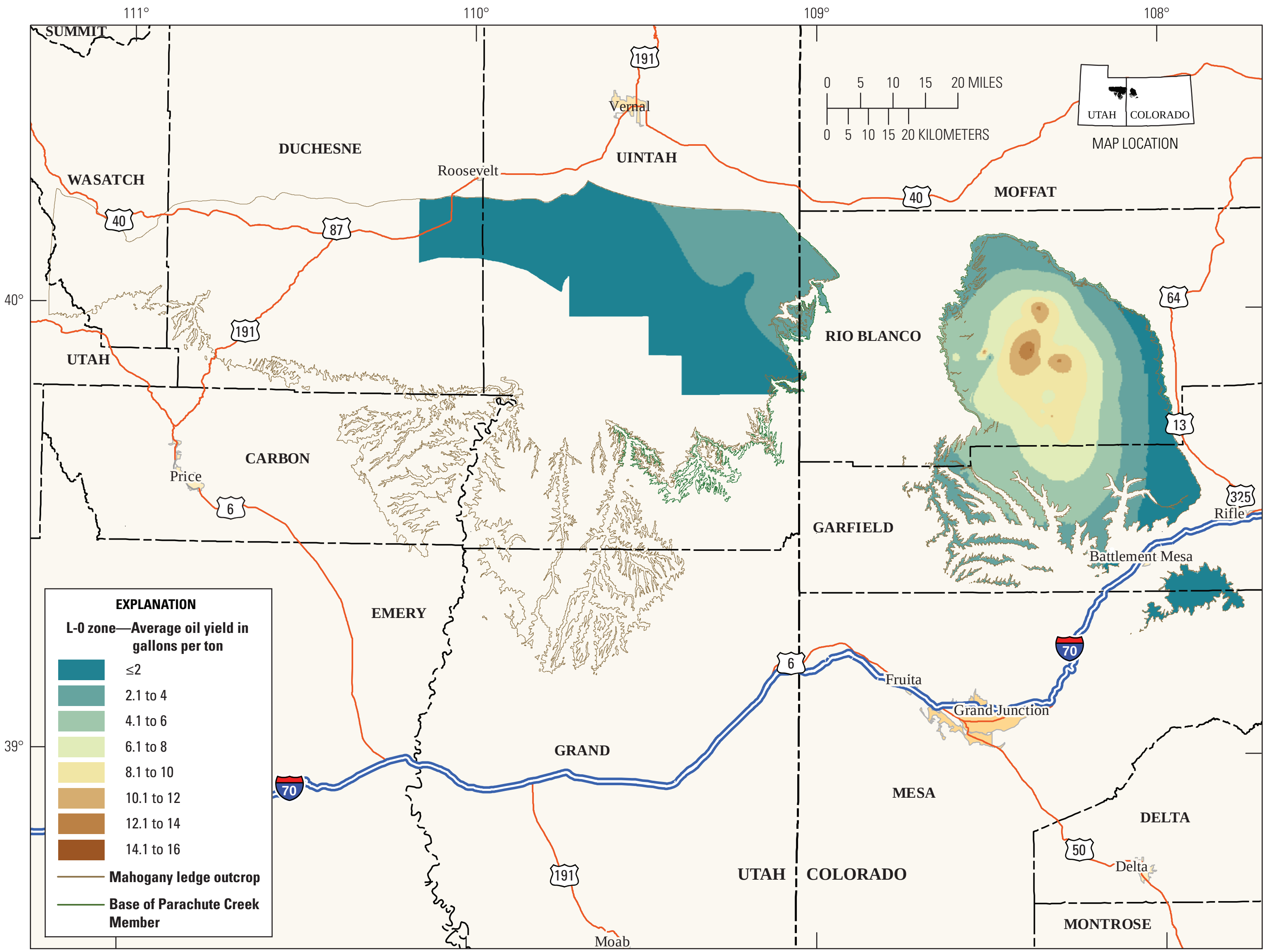


**Figure I0.** Isoresource map of L-0 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

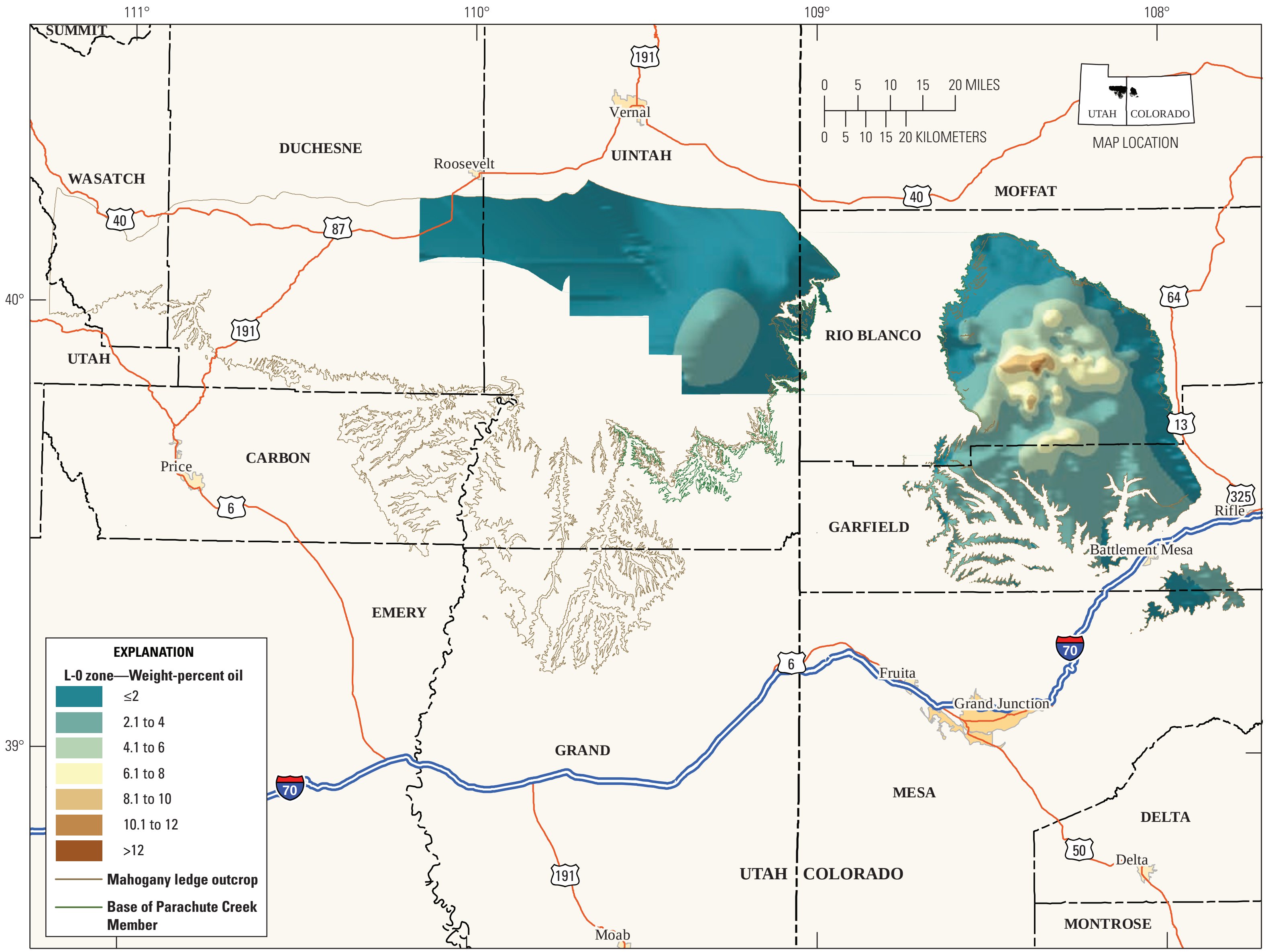


**Figure 11.** Isoresource map of L-0 zone in Uinta and Piceance Basins showing oil yield in weight percent.

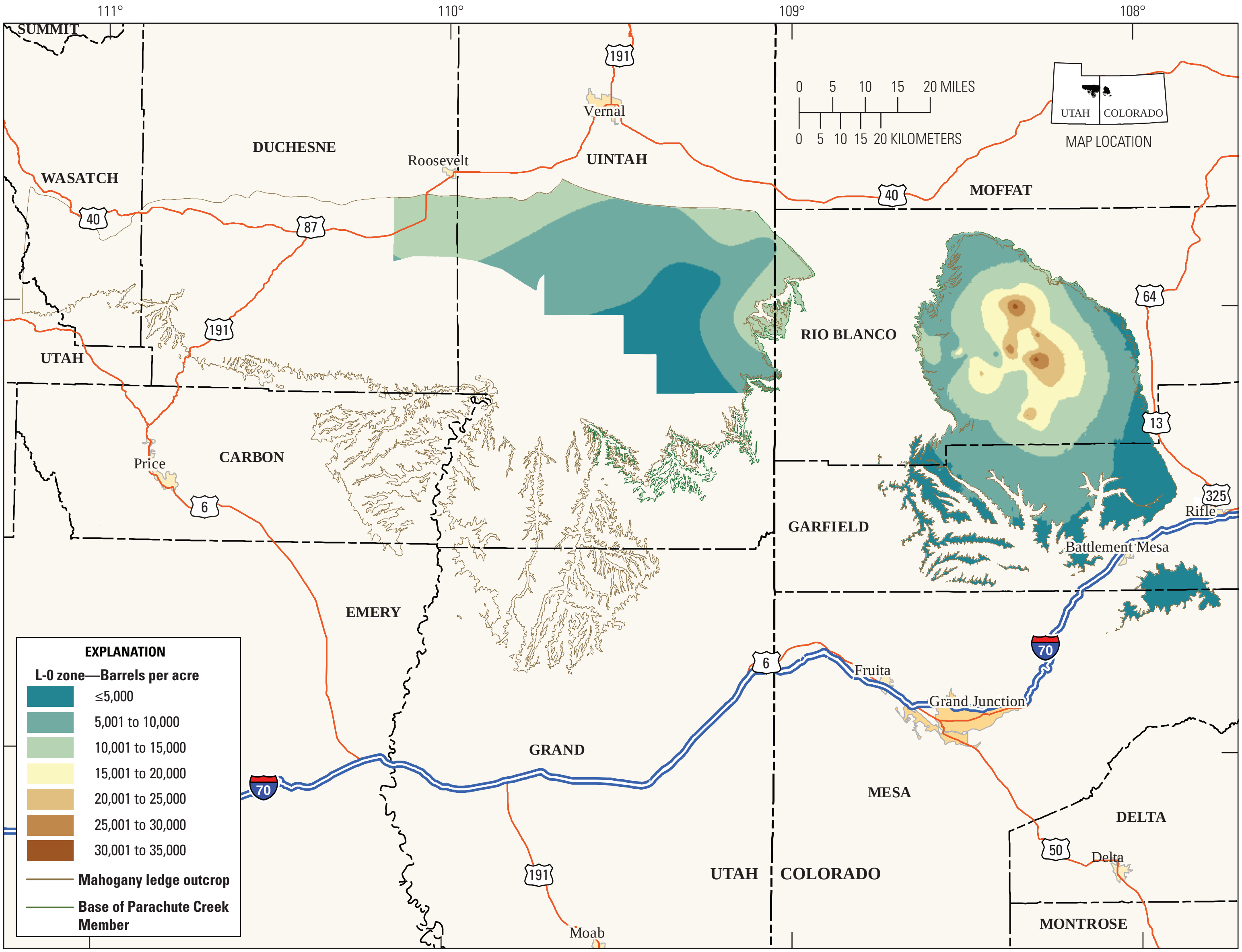


**Figure 12.** Isoresource map of L-0 zone in Uinta and Piceance Basins showing oil yield in barrels per acre. The Radial Basis Function method was used for contouring.

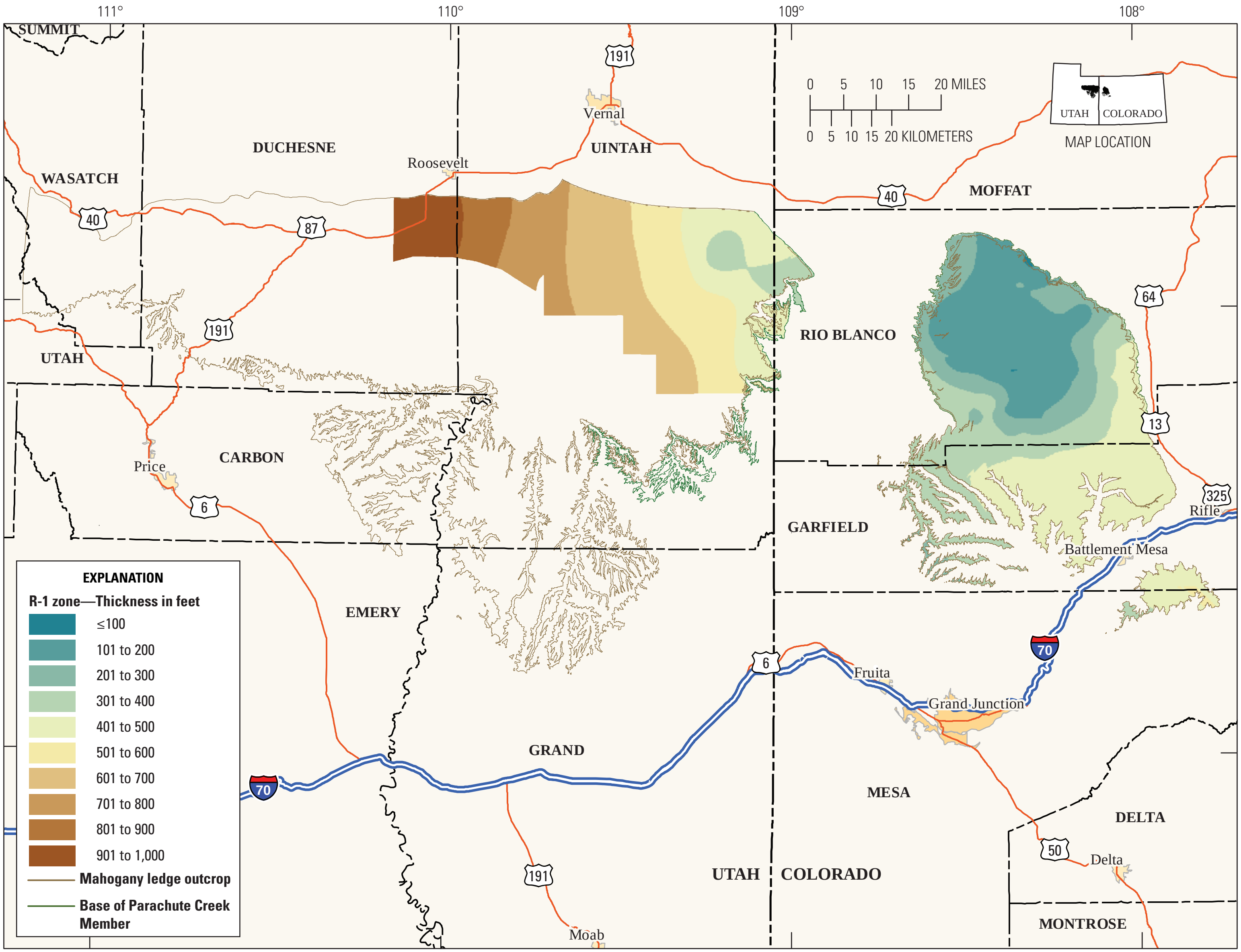


**Figure 13.** Isopach map of R-1 zone in the Uinta and Piceance Basins using the Radial Basis Function method for contouring. Contour interval in feet is variable.

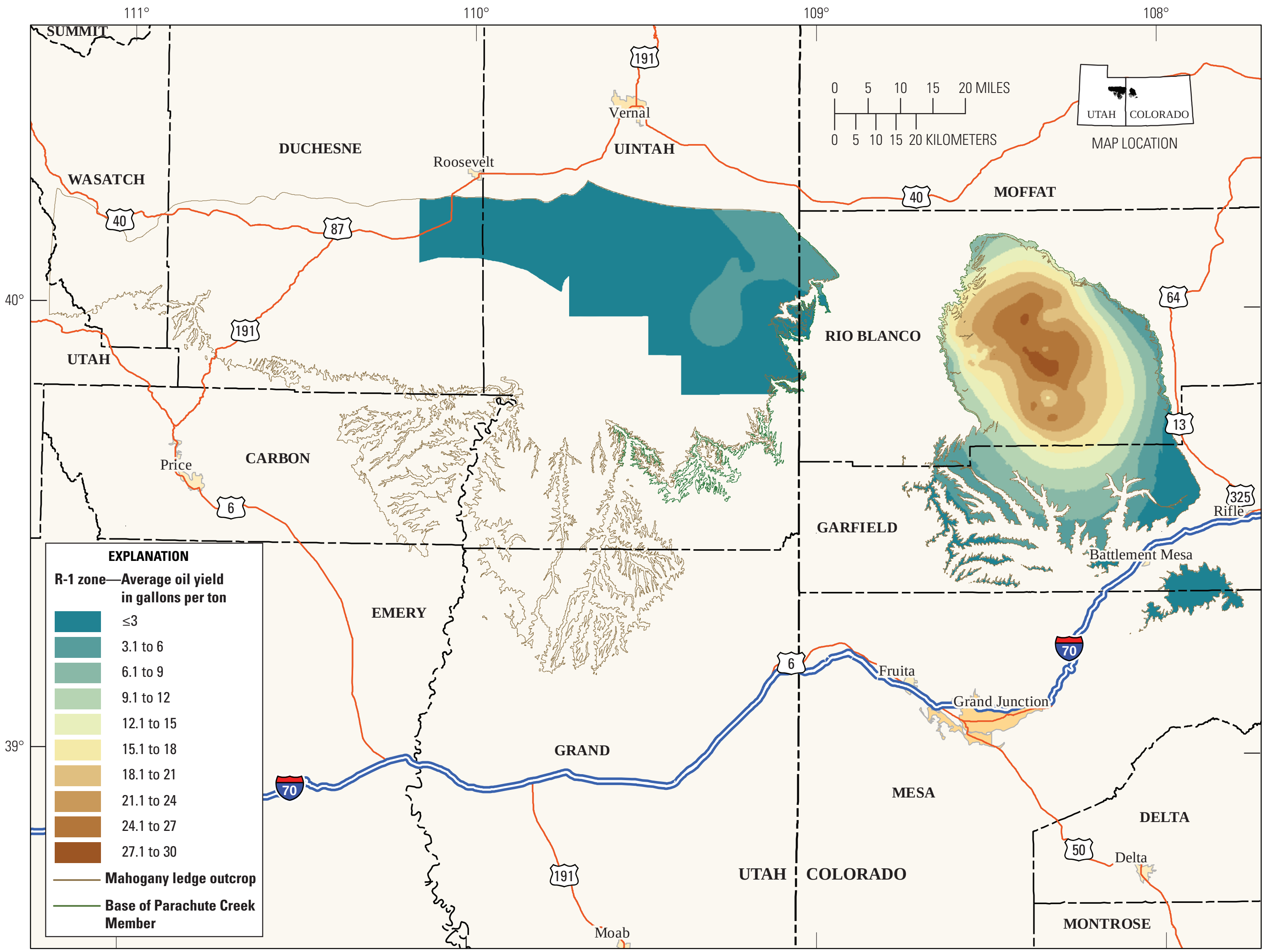


**Figure 14.** Isoresource map of R-1 zone in the Uinta and Piceance Basins showing oil yield in gallons per ton.

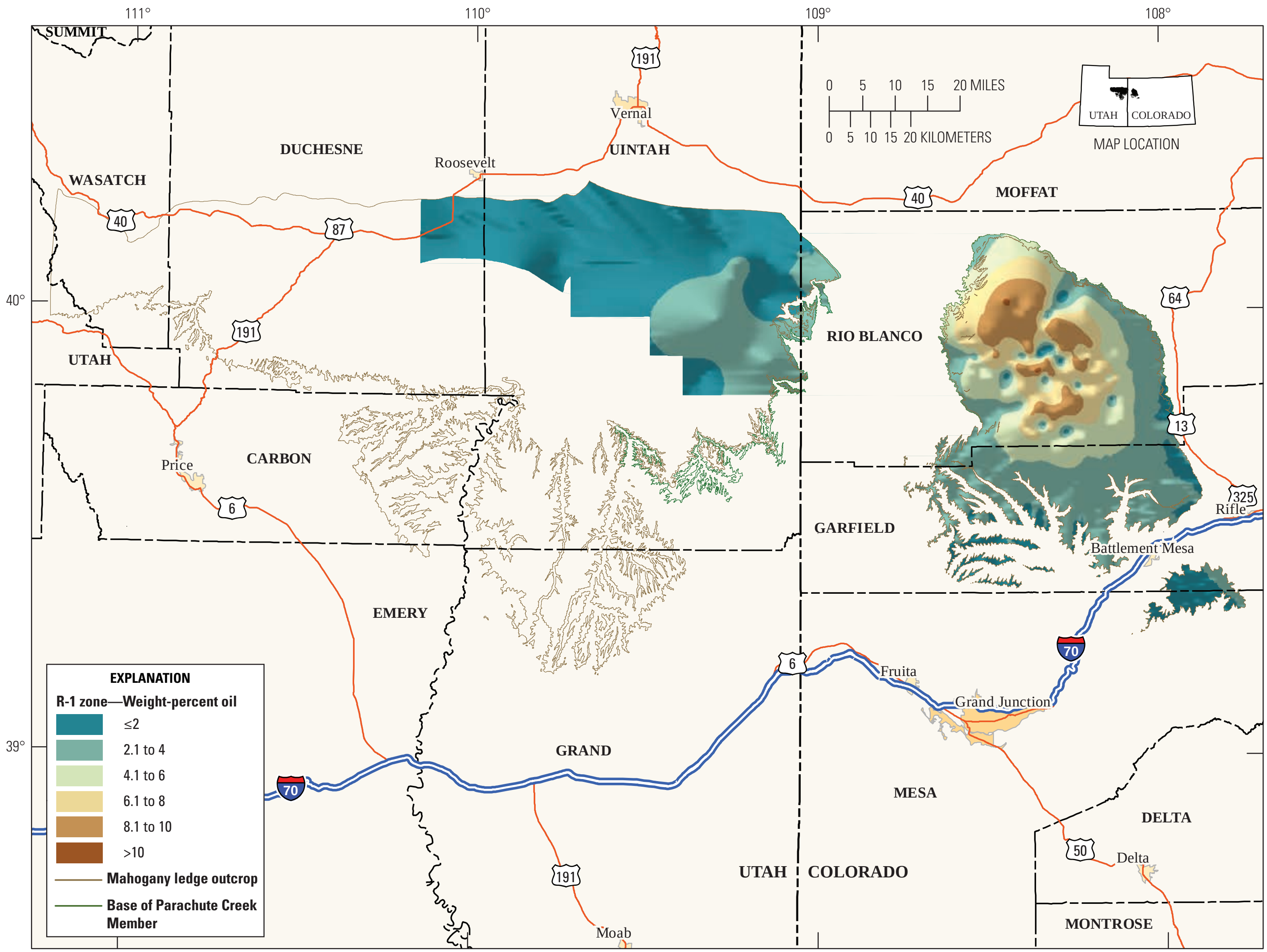


**Figure 15.** Isoresource map of R-1 zone in Uinta and Piceance Basins showing oil yield in weight percent.

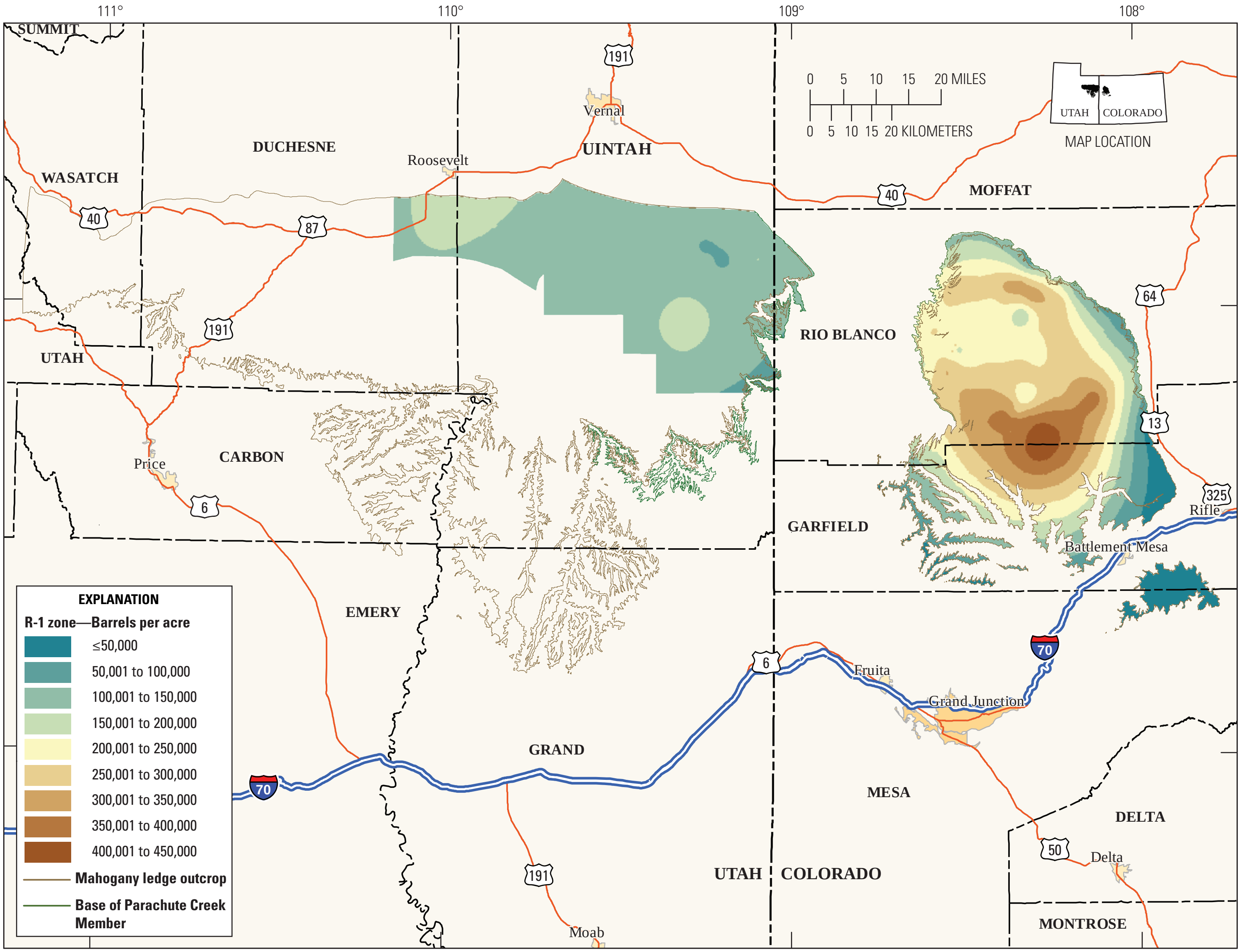


**Figure 16.** Isoresource map of R-1 zone in the Uinta and Piceance Basins showing oil yield in barrels per acre.

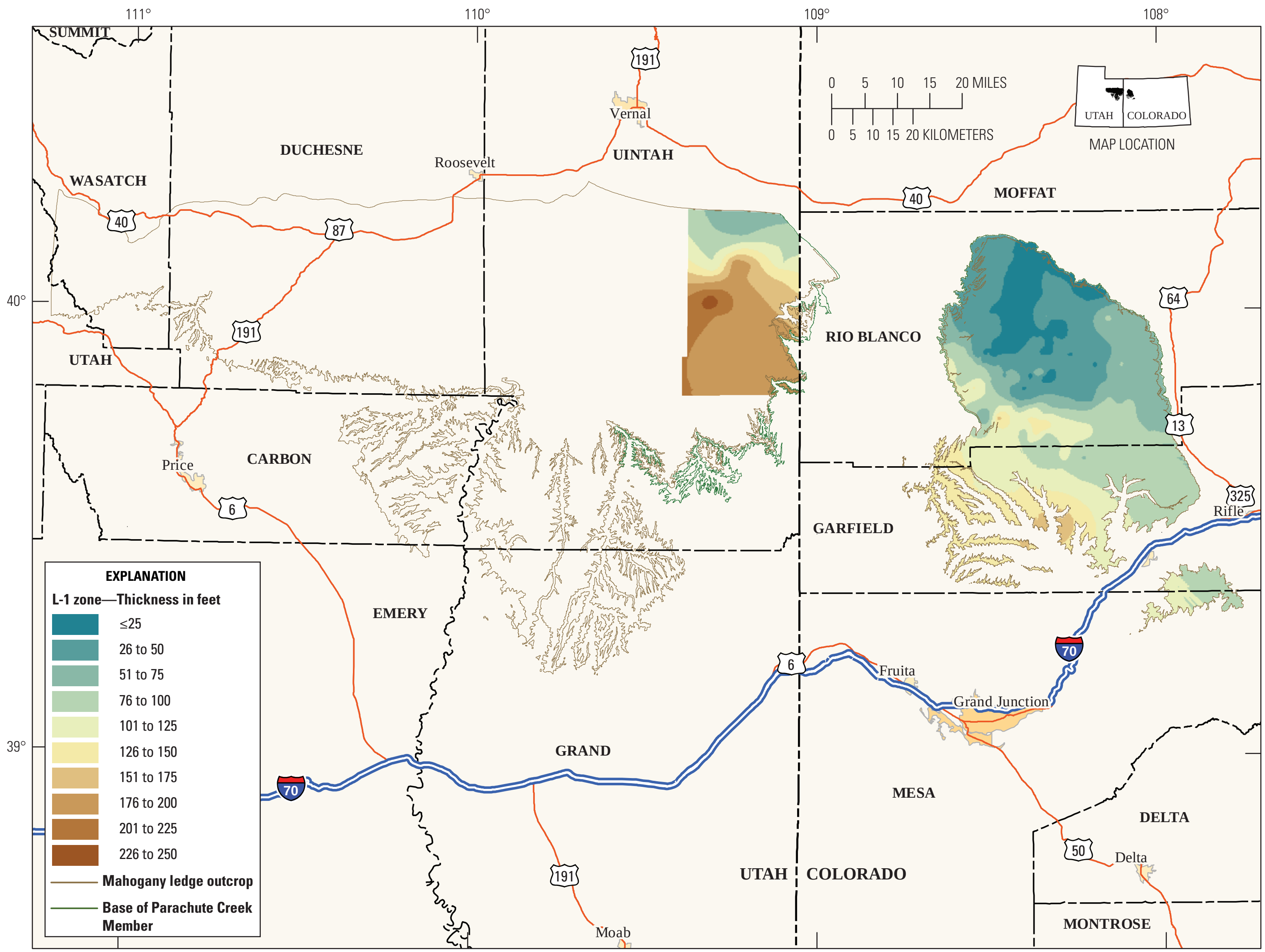


**Figure 17.** Isopach map of L-1 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

about 5 to 25 GPT in the north-central part of the basin (fig. 18). In the limited area of the Uinta Basin where the L-1 zone is assessed, estimated oil yields range from 0.8 to 2.5 GPT (fig. 18). Maximum weight-percent oil for the L-1 zone in the Piceance Basin is 12.2 percent, whereas weight-percent oil in the Uinta Basin is less than 4 (fig. 19). The BPA map (fig. 20) shows a depocenter with from 20,000 to 80,000 BPA in the south-central part of the Piceance Basin, the same area as the depocenter during the previous R-1 zone, but several much smaller areas with high in-place oil are scattered throughout the northern part of the basin. Estimated BPA in the Uinta Basin range from 7,000 to 39,000 (fig. 20), but control is sparse in the limited area assessed.

## R-2 through L-3 Zones

The R-2, L-2, R-3, and L-3 zones compose the third stage of Lake Uinta as defined by Johnson (1985). In the Piceance Basin, the R-2 zone marks a transition from illitic-rich oil shales to carbonate-rich oil shales. On electric logs, this shift is represented by a distinctive increase in resistivity informally known as the blue marker (Ziemba, 1974). The first occurrence of disseminated nahcolite, a sodium bicarbonate mineral ($NaHCO_3$), is in the upper part of the L-2 zone in the north-central part of the Piceance Basin (Dyni, 1974, 1981). Dawsonite, a hydrated aluminum carbonate mineral ($NaAl(OH)_2CO_3$), appears for the first time in the lower part of the R-2 zone, about 65–75 ft below the first occurrence of nahcolite in that same area (Dyni, 1981) and increases in abundance upward. Illite correspondingly decreases in abundance upward though the R-2 zone (Dyni, 1974, 1981; Robb and Smith, 1974). Dyni (1981) suggested that the alkaline lake waters destroyed much of the fine-grained detritus in the sediments, including the clays, replacing them with a suite of authigenic minerals including feldspars, quartz, and dawsonite.

The R-2 through L-3 interval is poorly correlated and poorly understood in the Uinta Basin. Johnson and others (1988) traced these zones from the central part of the Piceance Basin into a comparatively thin interval of stromatolites, sandstones, and mudstones ranging from about 110 to 150 ft thick in outcrops along the east margin of the Uinta Basin but could not distinguish them individually. Johnson (1989) then traced this combined interval from outcrops at the east margin of the Uinta Basin westward along the trough of the basin where it gradually thickens to a maximum of about 400 ft in the western part of the basin. The interval consists mainly of mudstone with varying amounts of carbonate. Dyni (2008) published a cross section along the trough of the Uinta Basin that included some of the same wells used by Johnson (1989) but included Fischer assay results from cuttings. The R-2 through L-3 interval along Dyni's line of section contains little kerogen. In their recent assessment of oil shale in the Uinta Basin, Johnson, Mercier, Brownfield, and Self (2010) could identify only the individual R-2, L-2, R-3, and L-3 zones in a limited area of the northeastern part of the basin.

### R-2 Zone

The R-2 zone in the Piceance Basin is thickest along an east- to northeast-trending belt across the south-central and northeastern parts of the basin where it ranges from about 90 to 155 ft thick (fig. 21). The interval thins generally toward the southwest in the direction that the previous R-1 and L-1 zones had thickened markedly. Along the south and west margins of the Piceance Basin, the R-2 zone cannot be separated from the overlying L-2, R-3, and L-3 zones, and all four zones are generally lumped together (Johnson and others, 1988), have a combined thickness of about 75 to 155 ft, and consist of marlstone oil shale beds and stromatolites. In the Uinta Basin, the R-2 zone ranges from 95 to 150 ft thick in the limited area that was assessed (fig. 21).

The oil shale depocenter during deposition of the R-2 zone is in the north-central part of the Piceance Basin and north of the area where the zone is thickest (figs. 22 to 24). Maximum oil yield there reaches 45 GPT and decreases in a radial pattern outward. Oil yields reach near zero along the southeastern and southwestern margins and about 10–15 GPT along the northern and northwestern margins (fig. 22). Weight-percent oil reaches a maximum of 17 percent in this depocenter (fig. 23). Estimated in-place oil reaches a maximum of 240,000 BPA in this depocenter and decreases outward (fig. 24). In the Uinta Basin, estimated oil yield ranges from 1.1 to 5.0 GPT (fig. 21) or a maximum of about 4.0 weight percent (fig. 23), and estimated oil in place ranges from about 15,000 to 5,000 BPA (fig. 24).

### L-2 Zone

In the Piceance Basin, thickness and oil shale richness patterns for the L-2 zone are similar to those for the R-2 zone with the area of maximum thickness rimming the south end of the oil shale depocenter (fig. 25). The L-2 zone reaches a maximum thickness of 115 ft in this area. Maximum oil yield for the L-2 zone is about 34 GPT in the oil shale depocenter, with oil yields decreasing in a radial pattern outward (fig. 26). Maximum weight-percent oil reaches 12.7 in the depocenter (fig. 27). Maximum BPA in the L-2 zone is 112,000 (fig. 28). In the limited area of the Uinta Basin where the L-2 zone is recognized, the L-2 zone ranges in thickness from 10 to 50 ft (fig. 25), with estimated oil yield ranges from 0.5 to 8.9 GPT (fig. 26), 2 to 4 weight-percent oil (fig. 27), and estimated in-place oil ranges from 1,000 to 22,000 BPA (fig. 28).

### R-3 Zone

The saline depocenter in the north-central part of the Piceance Basin became well established during deposition of the R-3 zone, and several thick beds consisting of predominantly nahcolite are dispersed throughout the zone in this area (Dyni, 1974, 1981; Brownfield, Mercier, and others, 2010). Unlike the underlying R-2 and L-2 zones in which maximum thicknesses were south and east of the oil shale and saline

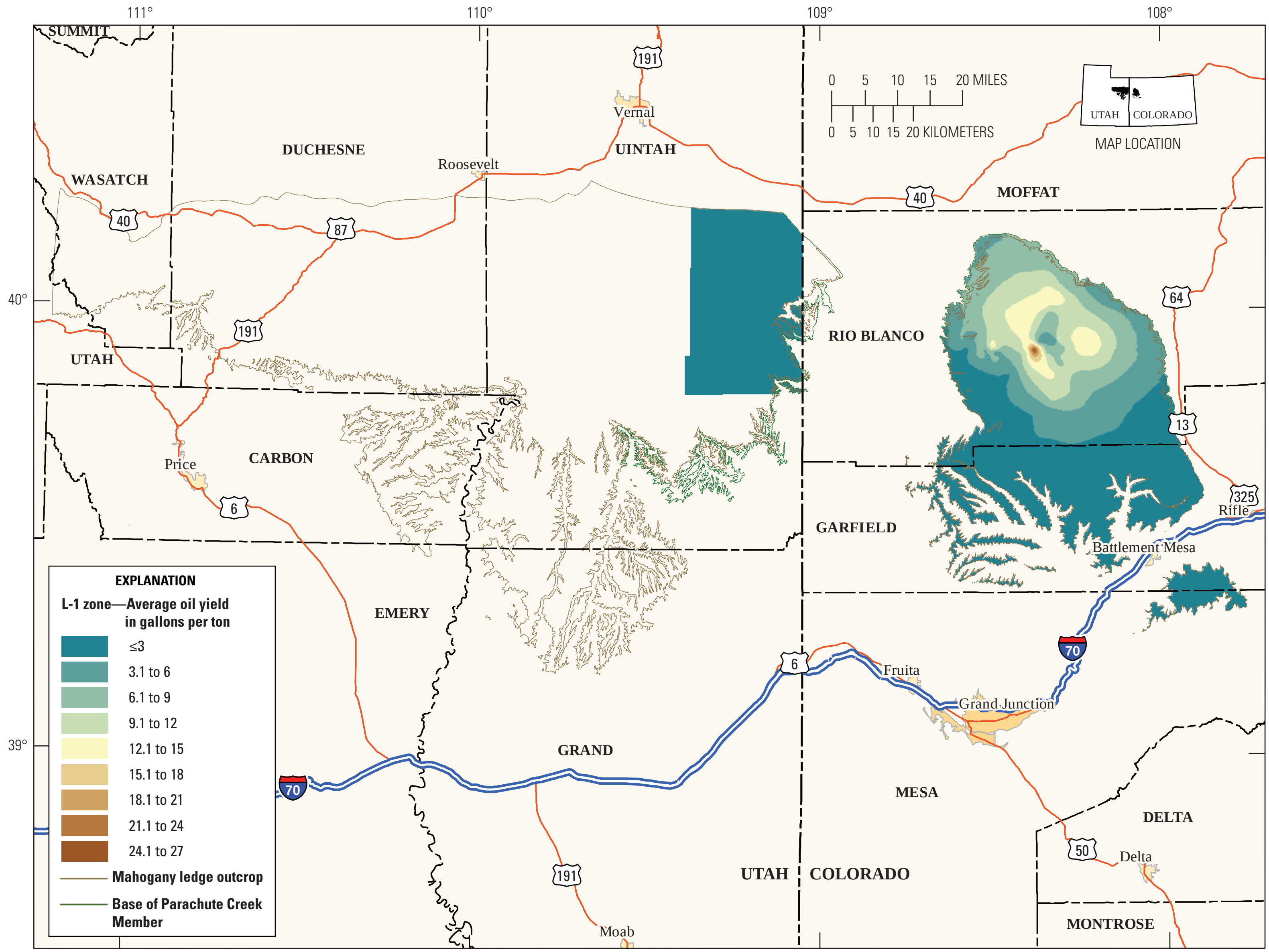


**Figure 18.** Isoresource map of L-1 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

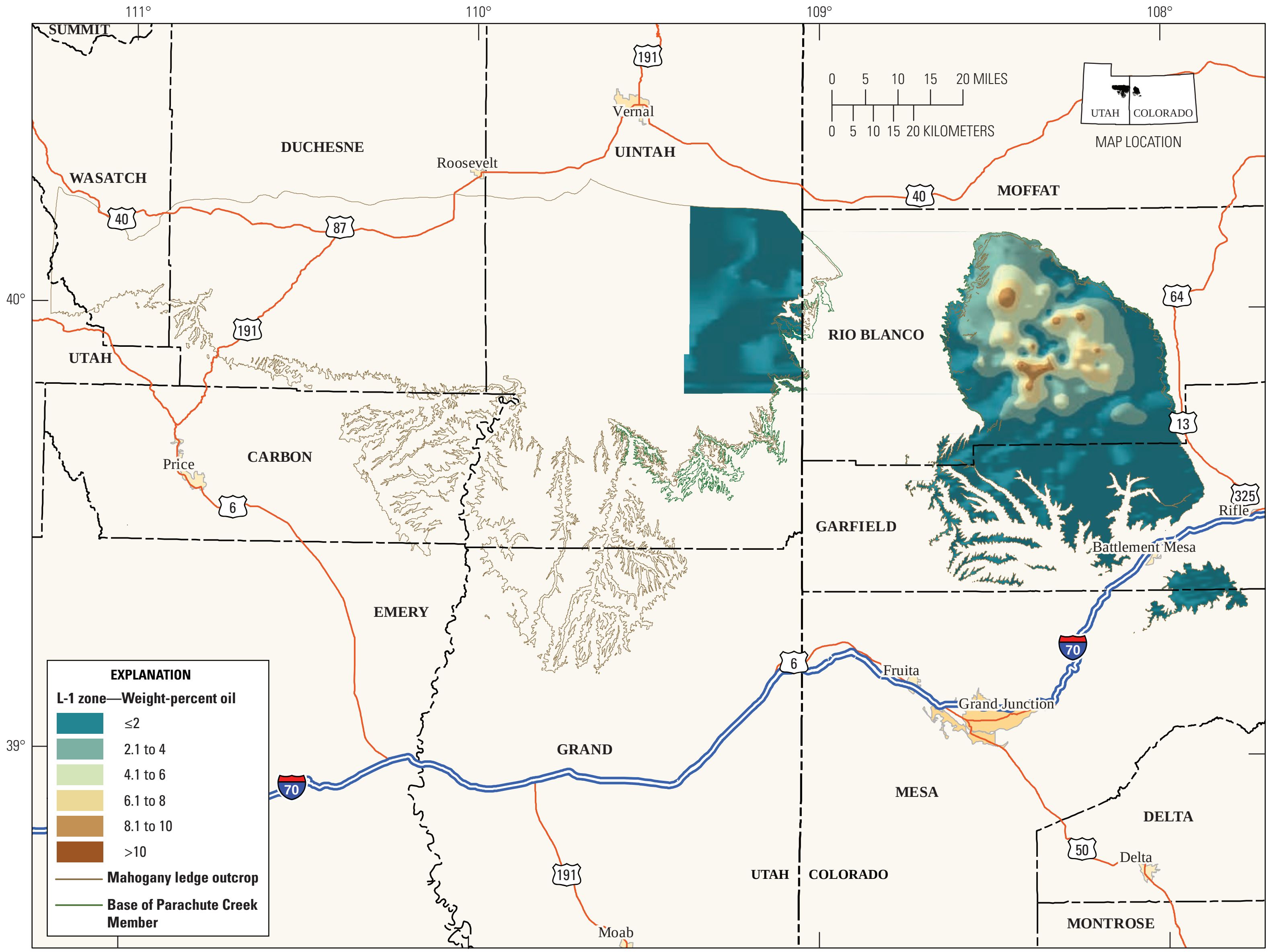


**Figure 19.** Isoresource map of L-1 zone in Uinta and Piceance Basins showing oil yield in weight percent.

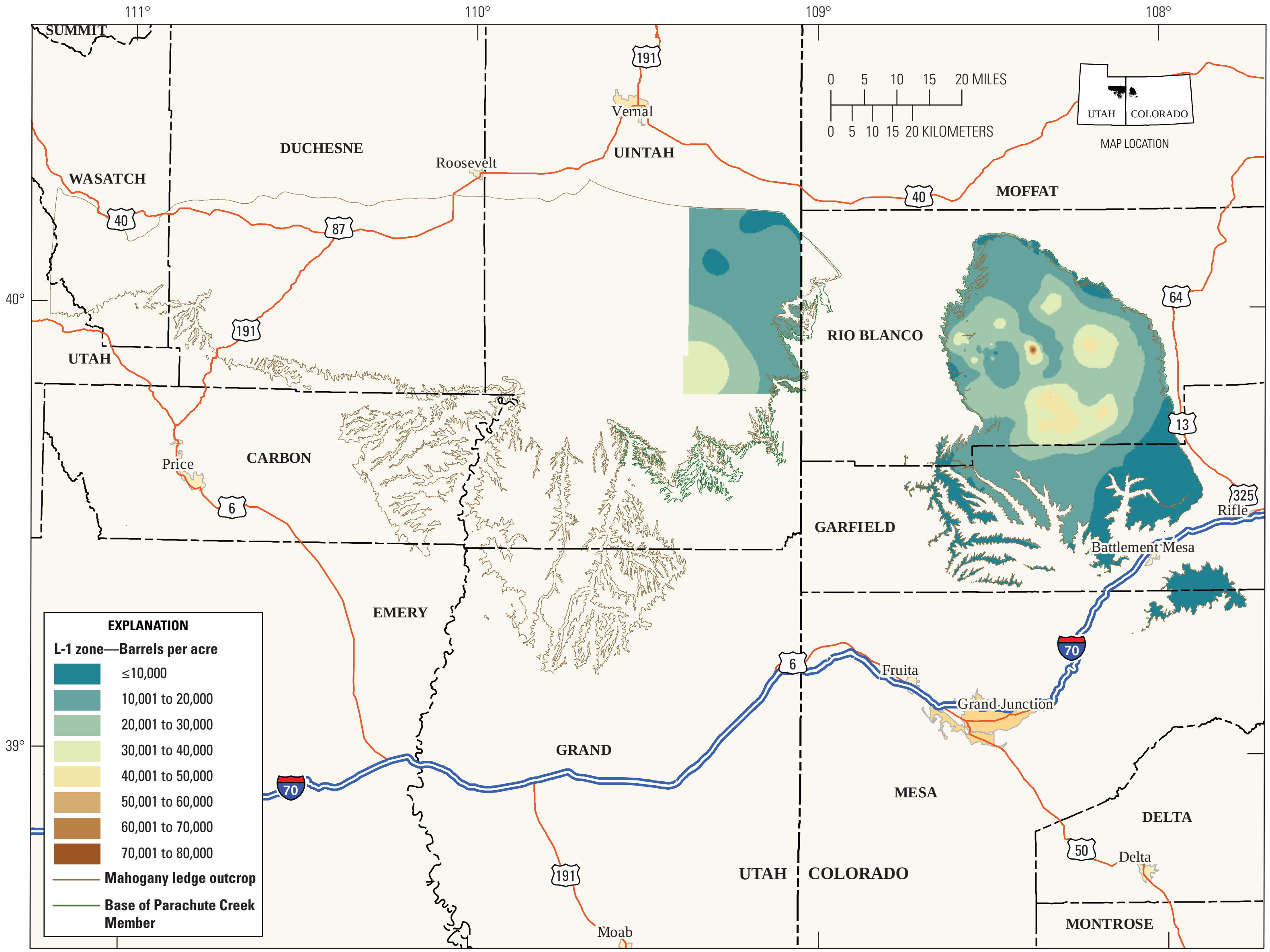


**Figure 20.** Isoresource map of L-1 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

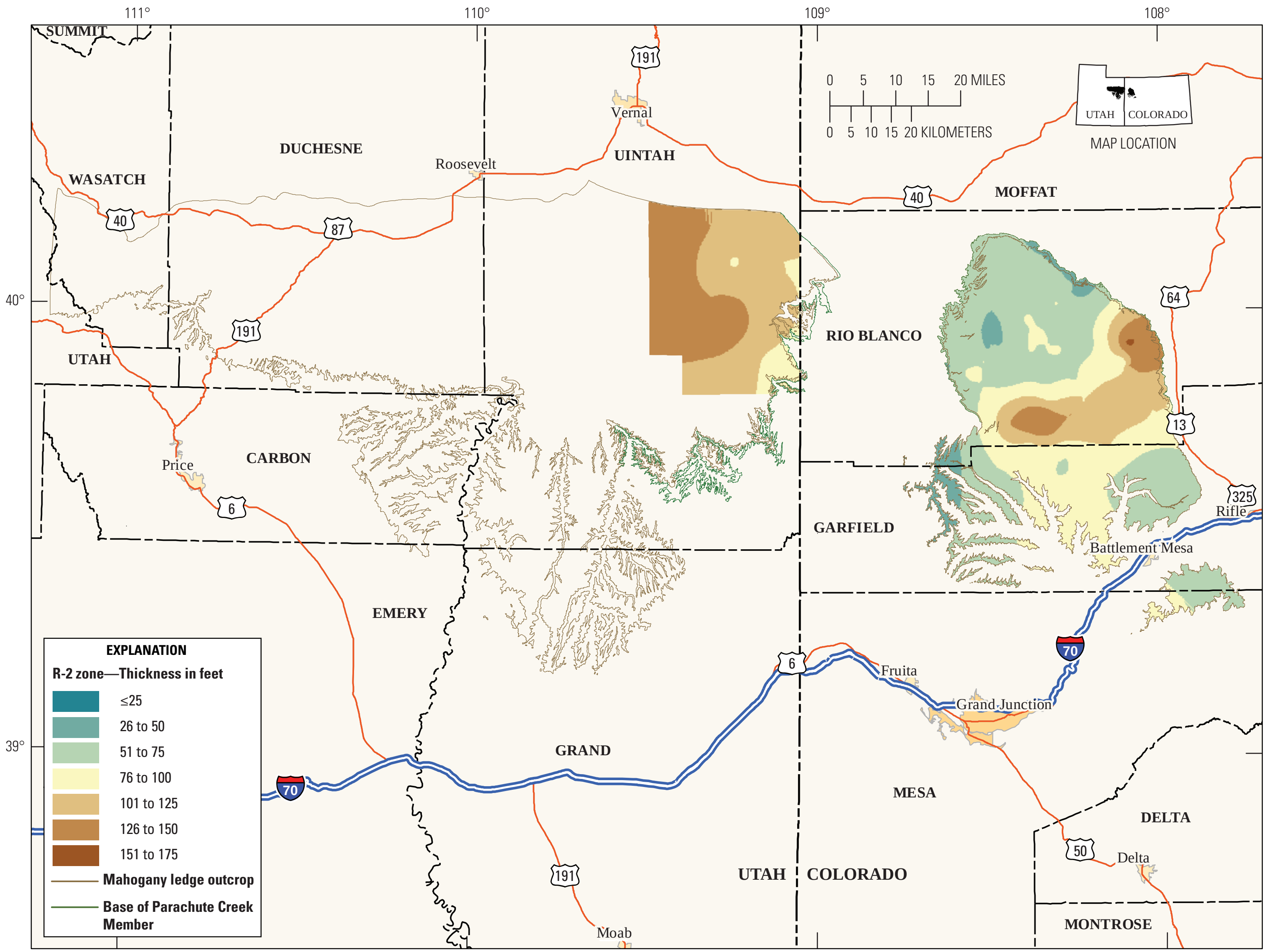


**Figure 21.** Isopach map of R-2 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

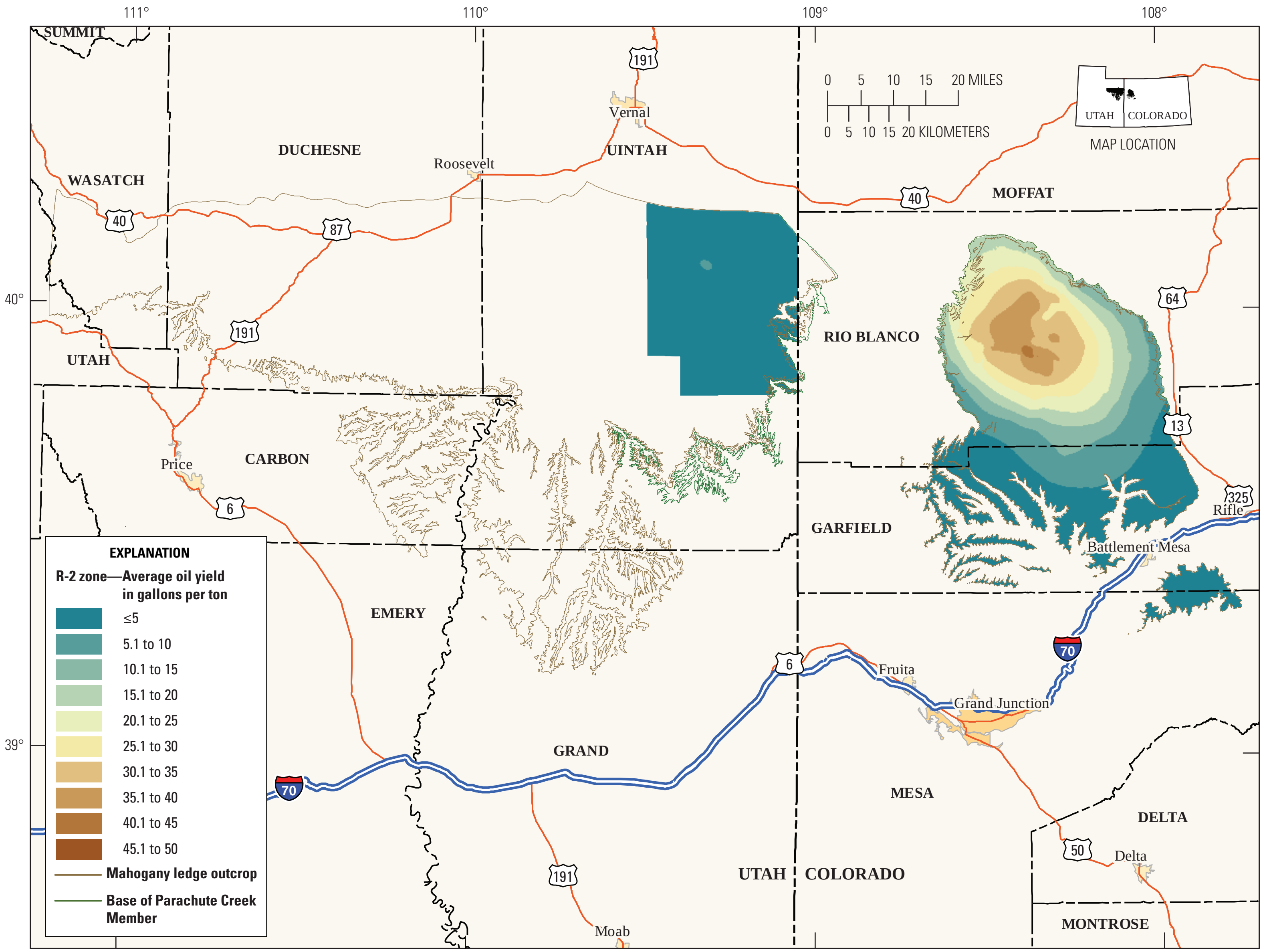


**Figure 22.** Isoresource map of R-2 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

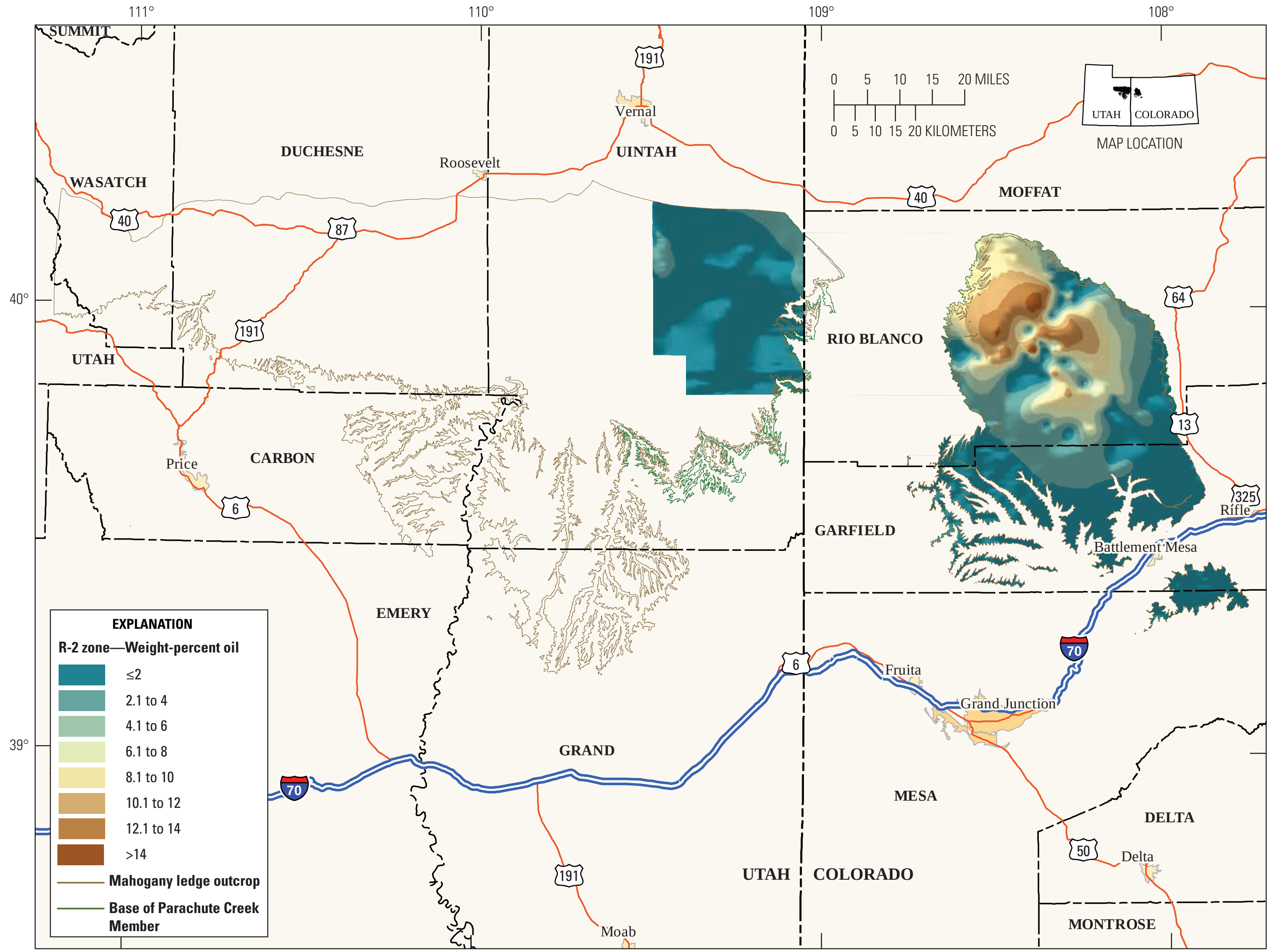


**Figure 23.** Isoresource map of R-2 zone in the Uinta and Piceance Basins showing oil yield in weight percent.

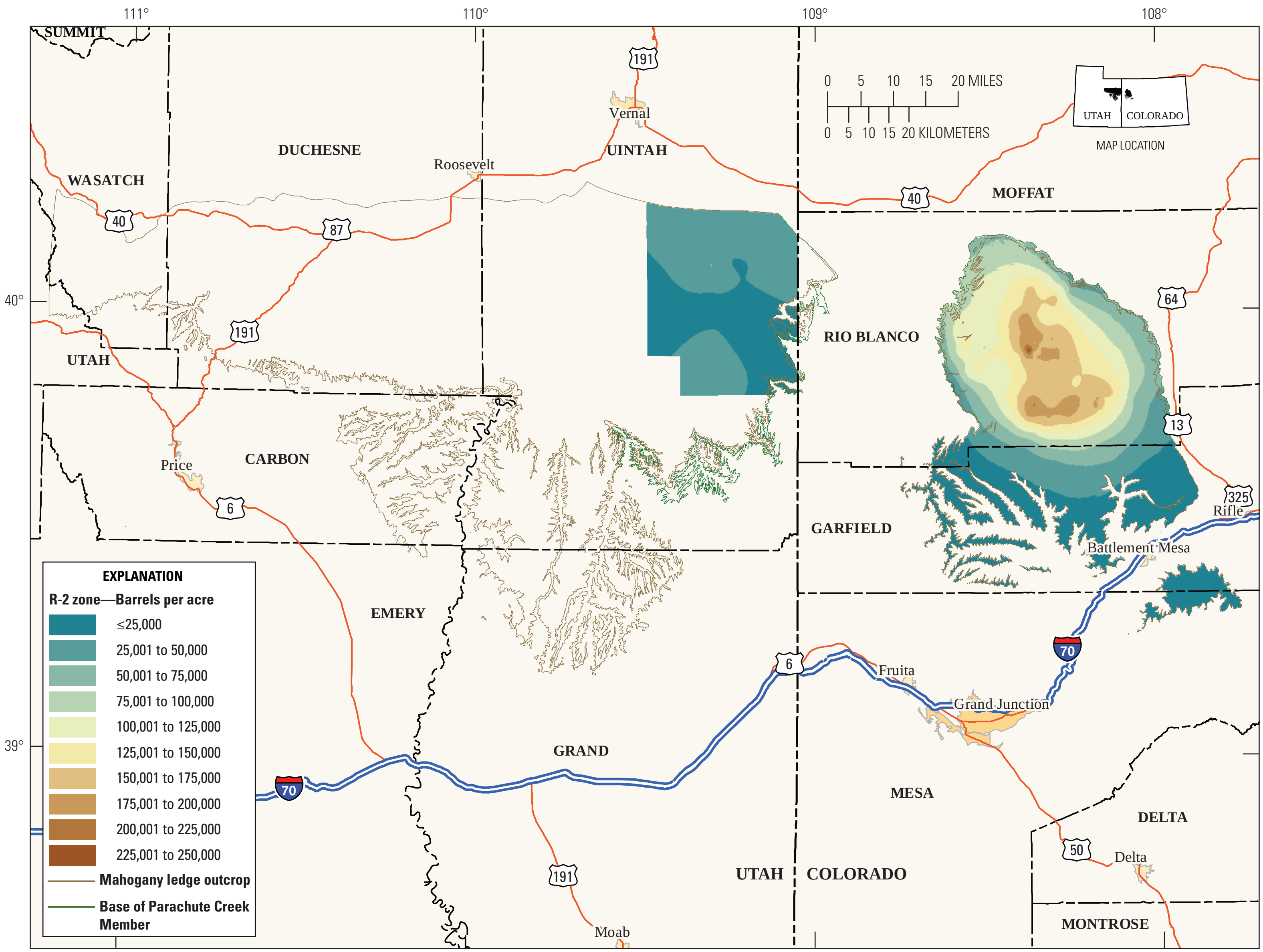


**Figure 24.** Isoresource map of R-2 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

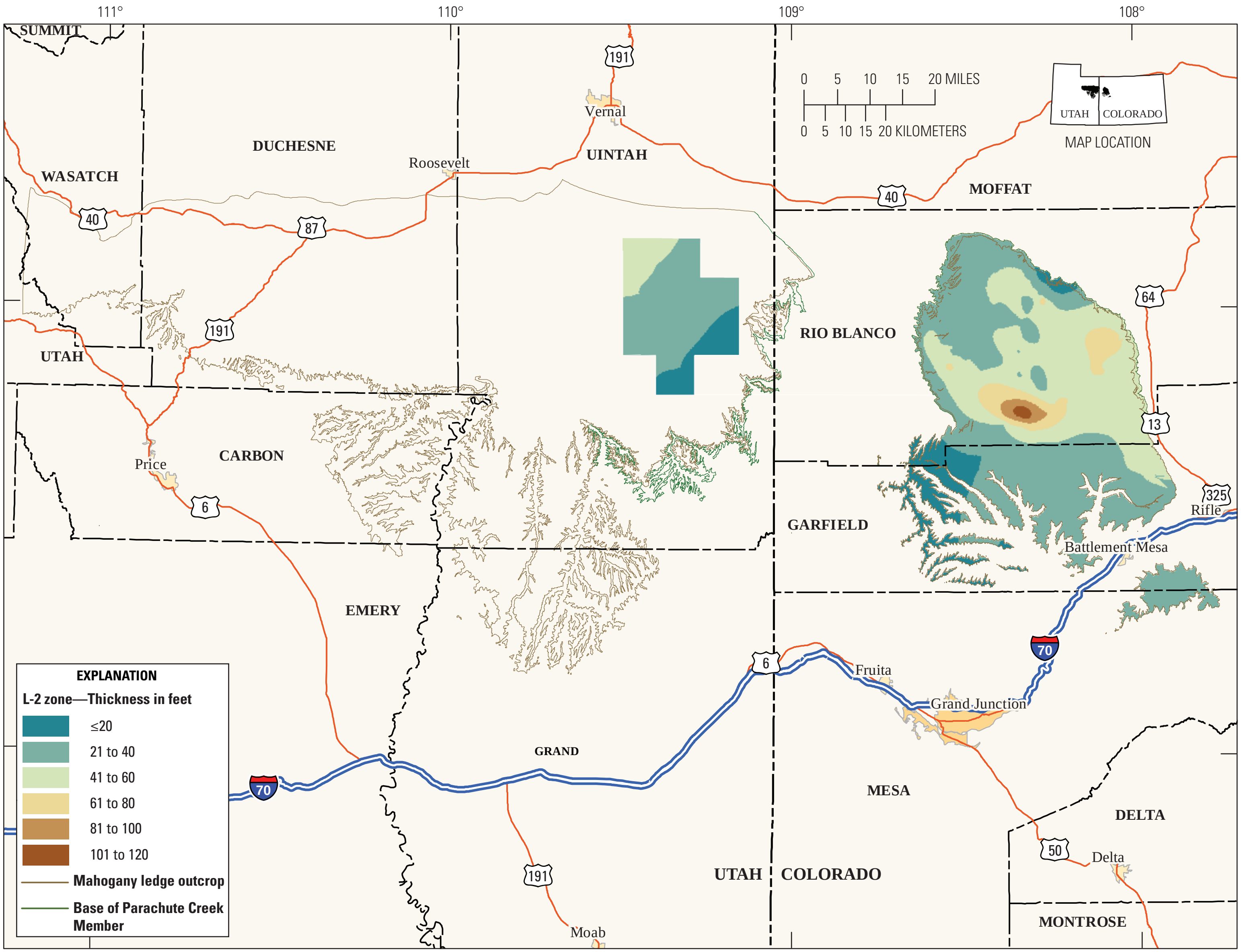


**Figure 25.** Isopach map of L-2 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

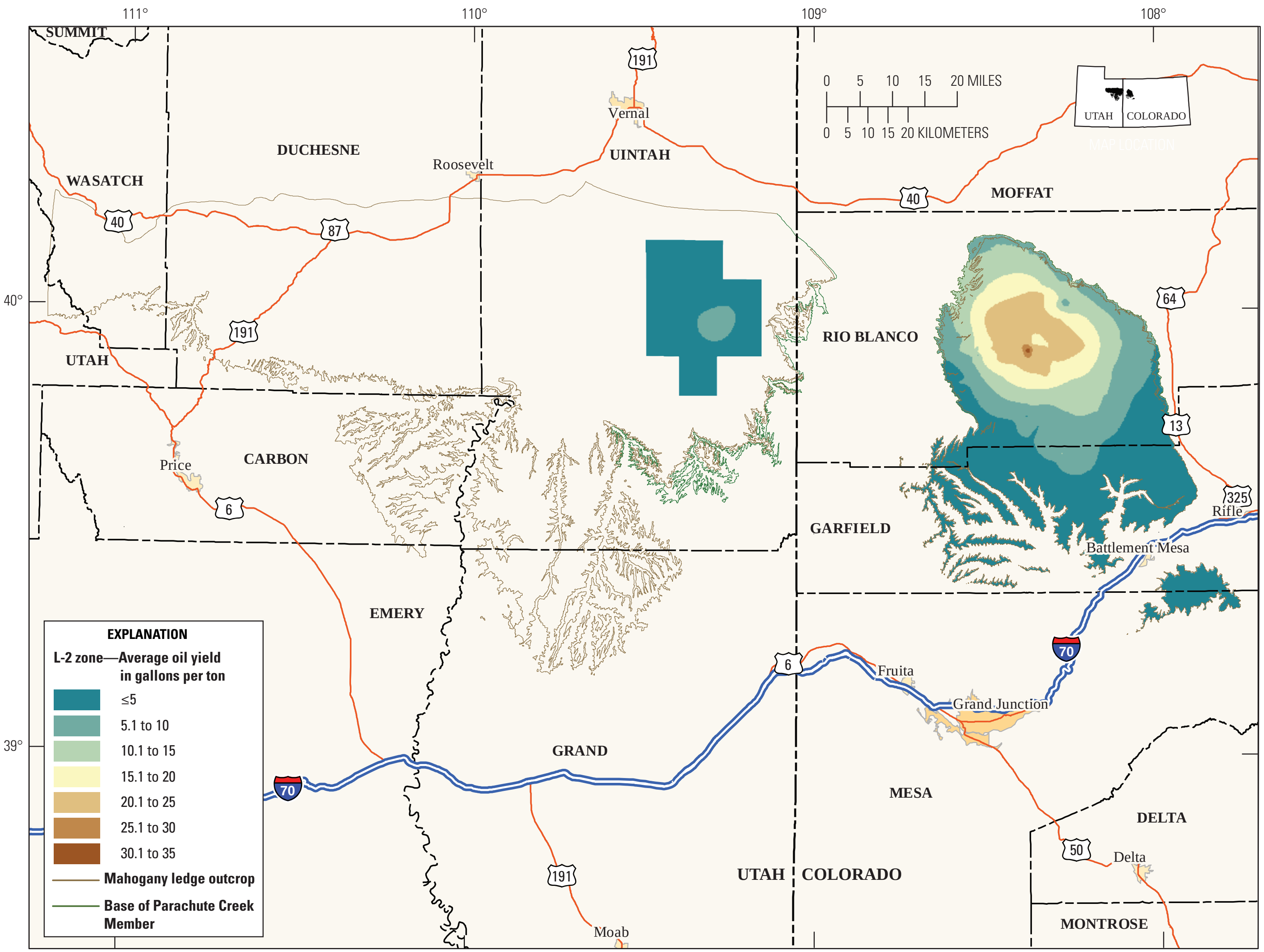


**Figure 26.** Isoresource map of L-2 zone in the Uinta and Piceance Basins showing oil yield in gallons per ton.

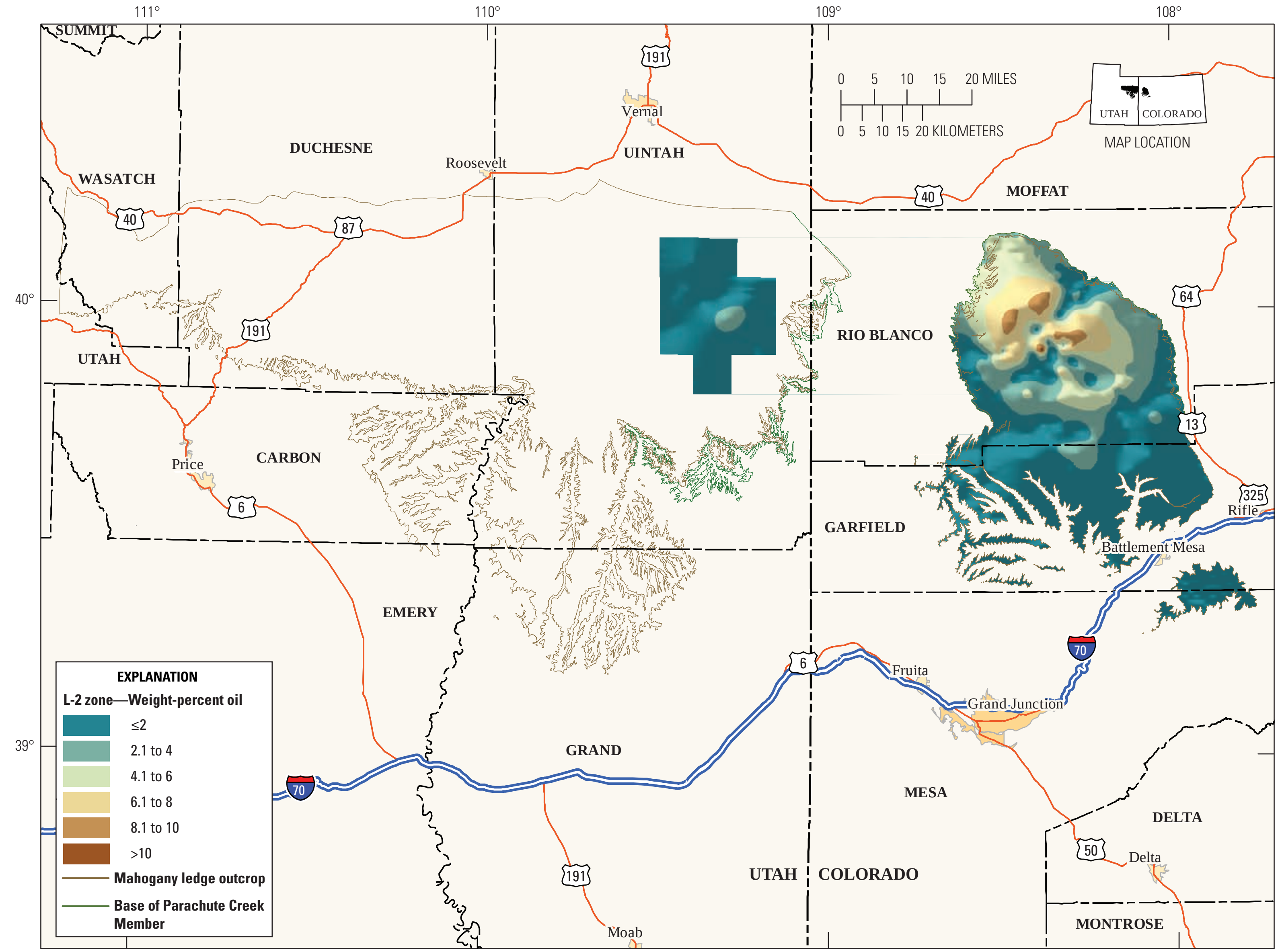


**Figure 27.** Isoresource map of L-2 zone in Uinta and Piceance Basins showing oil yield in weight percent.

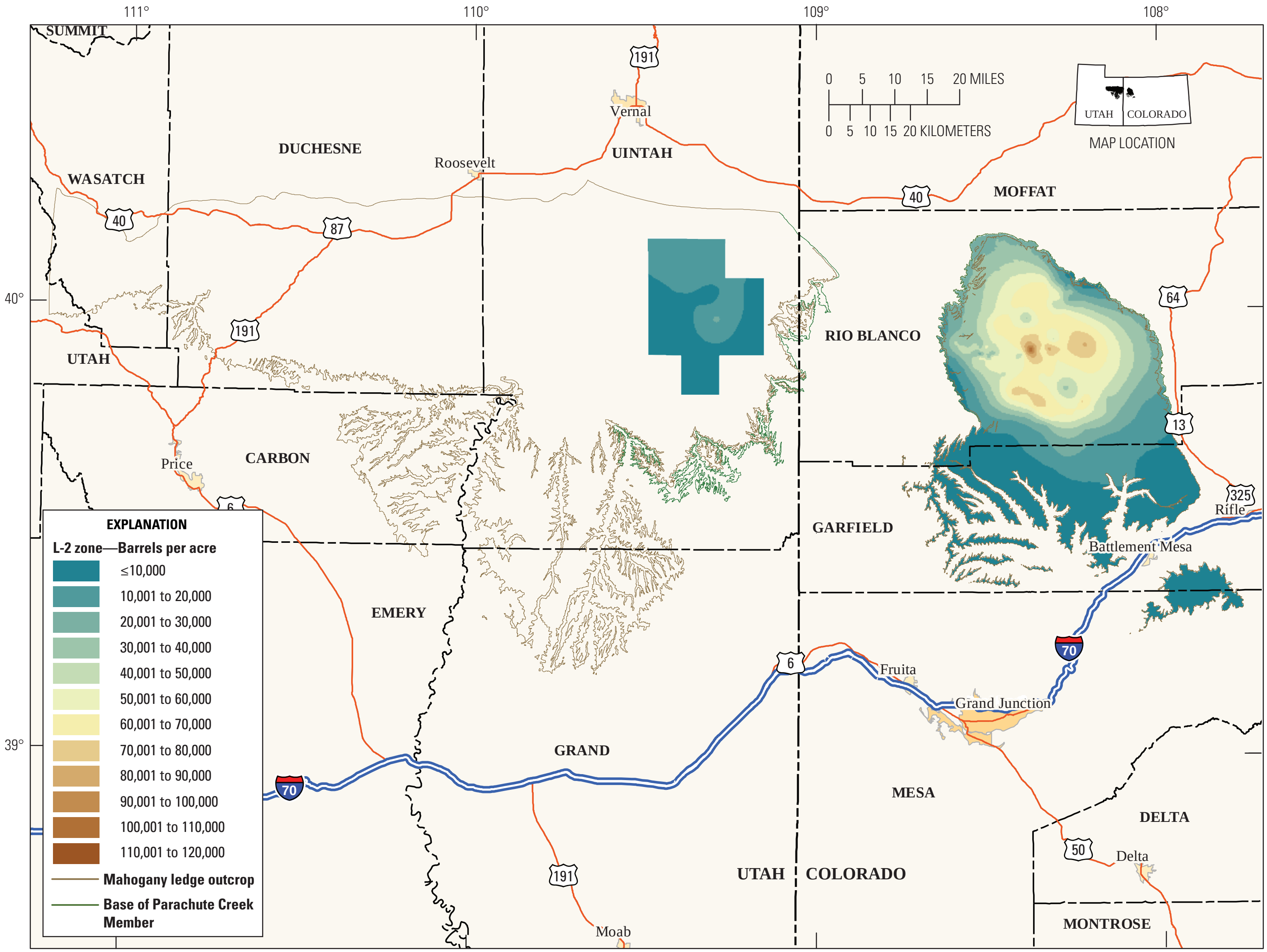


**Figure 28.** Isoresource map of L-2 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

depocenter, the R-3 zone is thickest in the depocenter itself where it is over 150 ft thick and thins in a radial pattern outward (fig. 29). The presence of several thick nahcolite beds in the R-3 zone is at least in part responsible for this thickening trend. The R-3 zone reaches a maximum of over 43 GPT, 16.4 weight-percent oil, and 381,000 BPA in this depocenter (figs. 30 to 32). In the limited area of the Uinta Basin where the R-3 zone is recognized, the zone ranges in thickness from 10 to 40 ft (fig. 29), with estimated oil yields ranging from 1.3 to 20.4 GPT (fig. 30), estimated weight-percent oil ranging from less than 2 to nearly 8 (fig. 31), and in-place oil ranging from 8,000 to 46,000 BPA (fig. 32).

## L-3 Zone

The L-3 zone is a comparatively thin oil shale zone in the Piceance Basin that represents a near cessation of nahcolite deposition. Interestingly, the zone is thickest along the south margin of the oil shale depocenter in the Piceance Basin, similar to the R-2 and L-2 zones. There, the L-3 zone reaches a maximum thickness of 68 ft (fig. 33). The oil shale depocenter during deposition of the L-3 zone occupies the same area in the north-central part of the basin as the previous R-3 zone (figs. 34 to 36). Maximum oil yields in this depocenter are about 35 GPT (fig. 34), maximum weight-percent oil is 13.1 (fig. 35), and maximum in-place oil is about 94,000 BPA (fig. 36). In the limited area of the Uinta Basin where the L-3 zone is recognized, the zone ranges in thickness from 7 to 20 ft (fig. 33). Estimated oil yield in this limited area ranges from 0.6 to 12.9 GPT (fig. 34), estimated weight-percent oil ranges from less than 2 to about 6 (fig. 35), and in-place oil ranges from 0 to 15,000 BPA (fig. 36).

## R-4 Zone

The base of the R-4 zone through the base of the Mahogany zone represents the fourth stage of Lake Uinta of Johnson (1985). The R-4 zone is recognized throughout most of the Piceance Basin and is the first oil shale zone above the R-0 zone to be recognized throughout much of the Uinta Basin as well (Johnson, 1989). A comparatively minor transgression marks the beginning of this stage, extending oil shale deposition into areas of the lake where deposition of a marginal lacustrine facies previously predominated (Johnson, 1985; Johnson and others, 1988). In some areas along the south and west margins of the Piceance Basin and the east margin of the Uinta Basin, the transgression is marked by a shift from a marginal lacustrine sequence containing abundant thick stromatolite units to oil shale interbedded with marlstone and thin stromatolites. In other places the transgression is marked by a shift from interbedded oil shale and marlstone to predominantly oil shale (Johnson and others, 1988). At Renegade Canyon along the extreme southern exposure of the Green River Formation in the Uinta Basin, all but the uppermost part of the interval from the base of the R-4 zone to the base of the Mahogany zone grades into fluvial rocks of the Renegade Tongue of the Wasatch Formation (Cashion, 1967, his pl. 3, Renegade Canyon measured section).

The presence of stromatolites both above and below the base of the R-4 zone in some sections indicates that the increase in average water depth after this transgression may not have been great. It should be noted that water level probably fluctuated constantly throughout the history of this closed saline lake, but average water levels appear to have been somewhat higher beginning with the deposition of the R-4 zone than previously. Nahcolite is mostly absent from the lower part of the R-4 zone in the saline depocenter in the north-central part of the Piceance Basin, and only a few comparatively thin, persistent beds high in nahcolite content are in the R-4 zone (Dyni, 1974, 1981) suggesting that lake water was less saline after the transgression than before.

In the Piceance Basin, the R-4 zone is thickest along a southeast-trending belt extending from the oil shale depocenter in the north-central part to the east margin of the basin, reaching a maximum thickness of about 165 ft along this trend (fig. 37). In the Uinta Basin, the R-4 zone ranges from about 35 to 50 ft thick in the northeast part, adjacent to the crest of the Douglas Creek arch, and thickens to the north and west to a maximum of about 200 ft (fig. 37). In the Piceance Basin, oil yield reaches a maximum of about 43 GPT and 16.3 weight percent in the saline depocenter (figs. 38 and 39). The area containing at least 20 GPT extends farther toward the margins of the basin during R-4 deposition than any of the previous oil shale zones except the R-1 zone. Maximum BPA is about 424,000 in the middle part of the saline and oil shale depocenter in the north-central part of the basin (fig. 40). In the Uinta Basin, estimated oil yields are as much as 24 GPT (fig. 38) or 10 weight percent (fig. 39), and in-place oil ranges from about 50,000 to 104,000 BPA (fig. 40).

## L-4 Zone

In the Piceance Basin, the L-4 zone is thickest in about the same southeast-trending belt as the underlying R-4 zone, reaching a maximum thickness of 184 ft in the saline depocenter (fig. 41). The L-4 zone contains large amounts of nahcolite in the saline depocenter, and several persistent nahcolite beds have been traced throughout the depocenter (Dyni 1974, 1981). Oil yields are significantly lower overall in the L-4 zone than in the underlying R-4 zone with a maximum of about 34 GPT or 12.7 weight percent in the saline depocenter and lower values throughout the marginal areas of the basin (figs. 42 and 43). Maximum BPA is about 426,000 in the saline depocenter (fig. 44). In the Uinta Basin, the L-4 zone thickens from about 24 to 43 ft along the west flank of the Douglas Creek arch to a maximum of about 130 ft in the central part of the basin (fig. 41). Estimated oil yields are as much as 8.2 GPT (fig. 42) or about 4 weight percent (fig. 43), and estimated in-place oil varies from about 12,000 to 35,000 BPA (fig. 44).

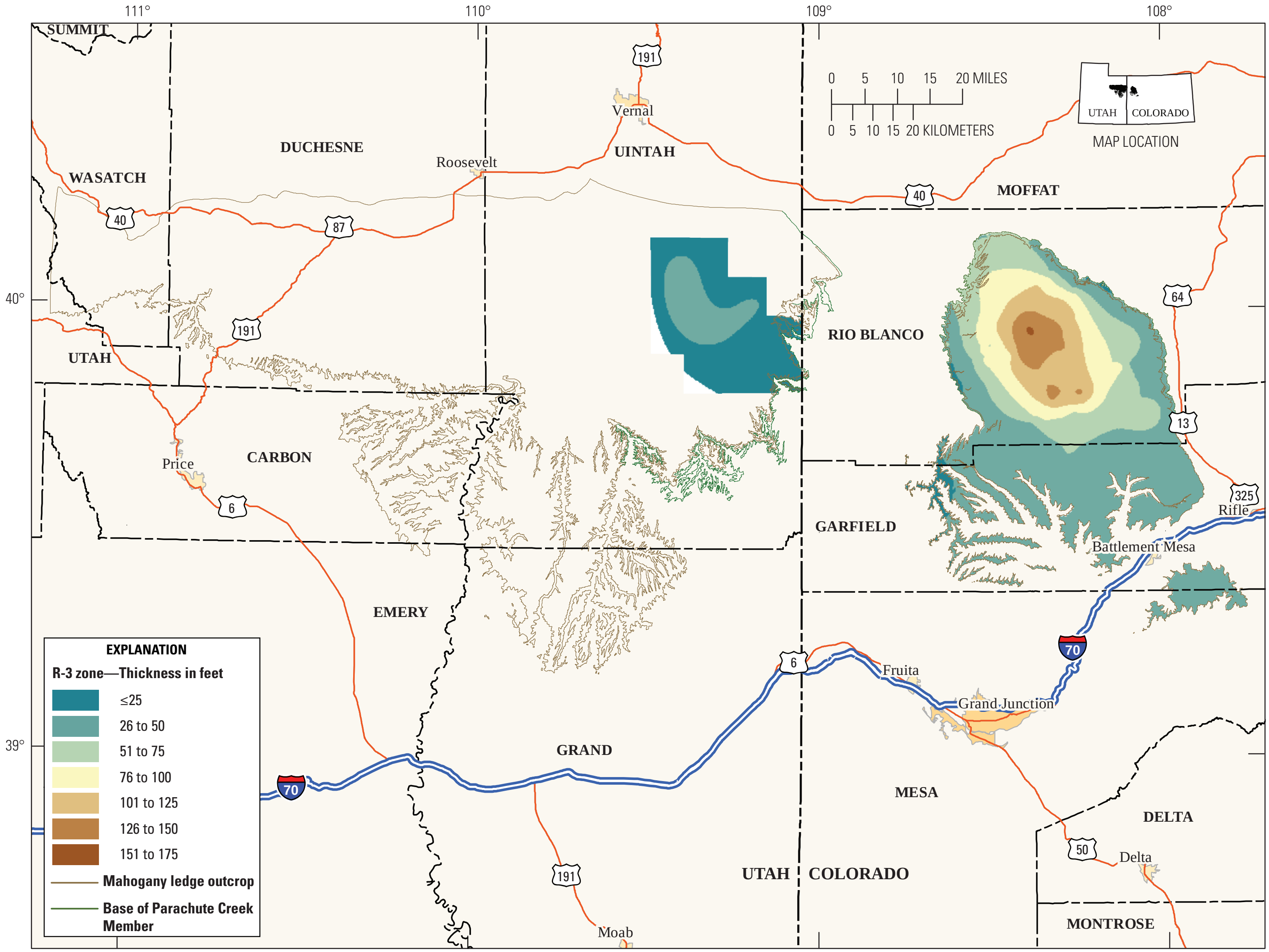


**Figure 29.** Isopach map of R-3 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

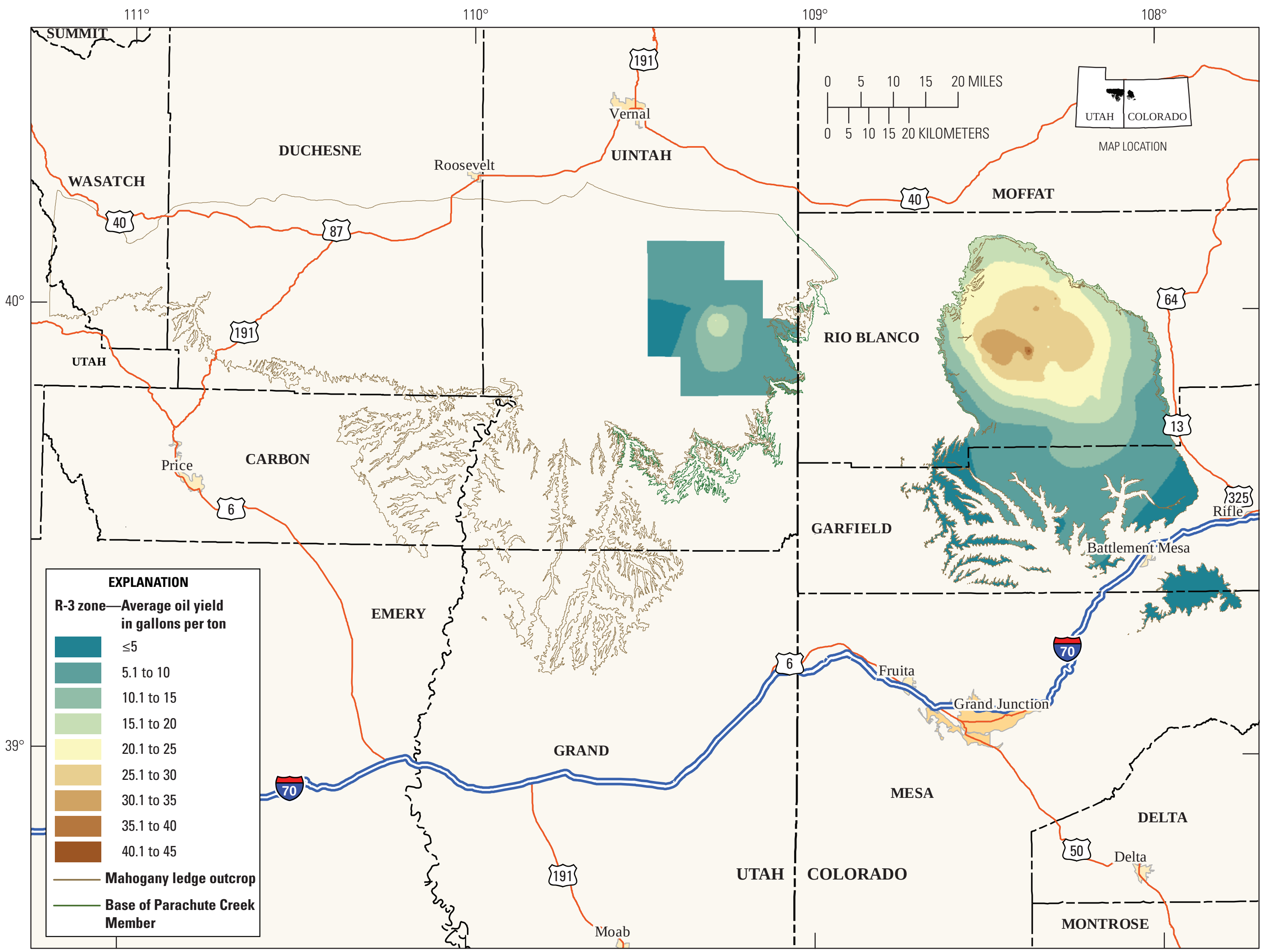


**Figure 30.** Isoresource map of R-3 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

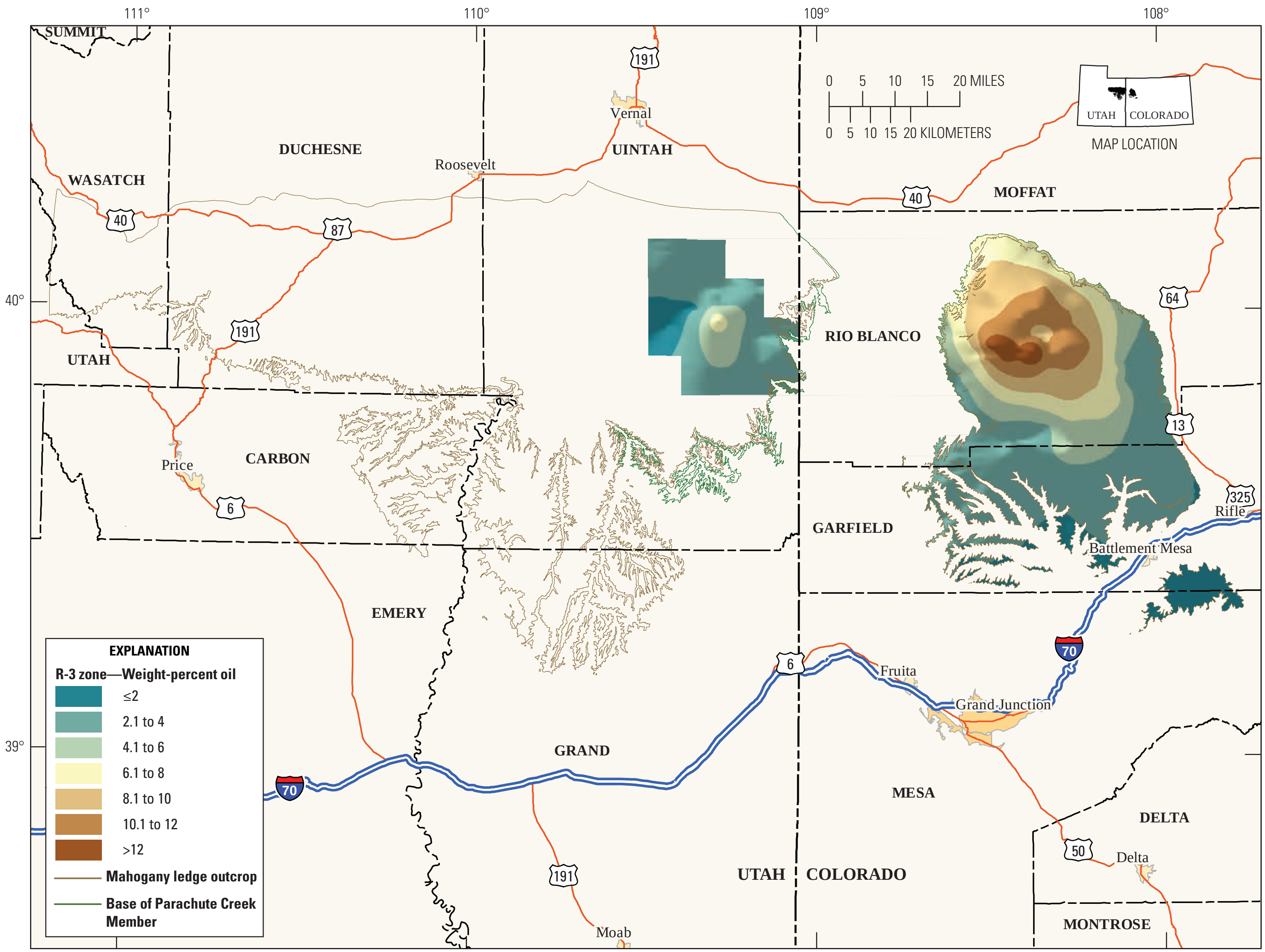


**Figure 31.** Isoresource map of R-3 zone in Uinta and Piceance Basins showing oil yield in weight percent.

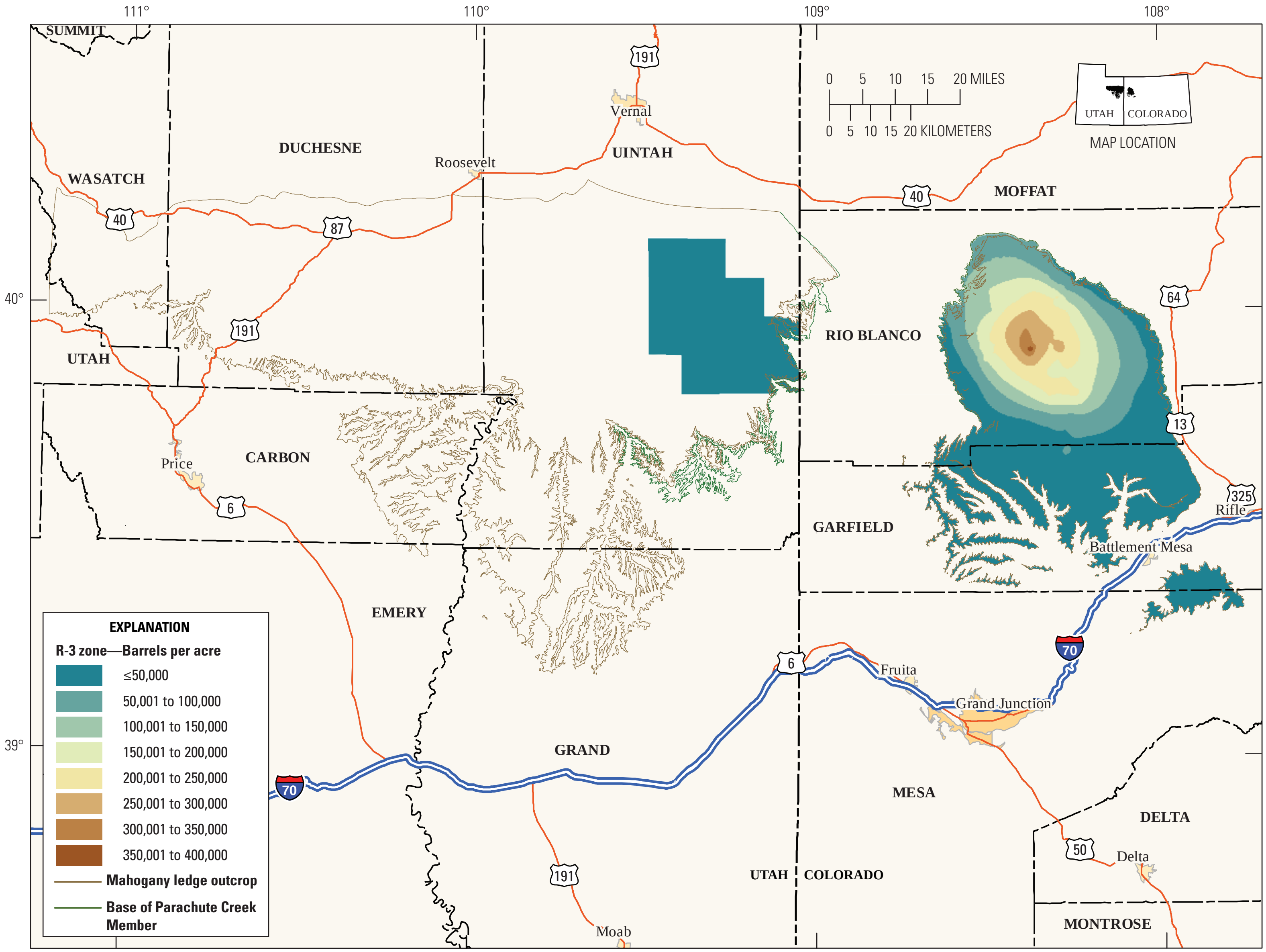


**Figure 32.** Isoresource map of R-3 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

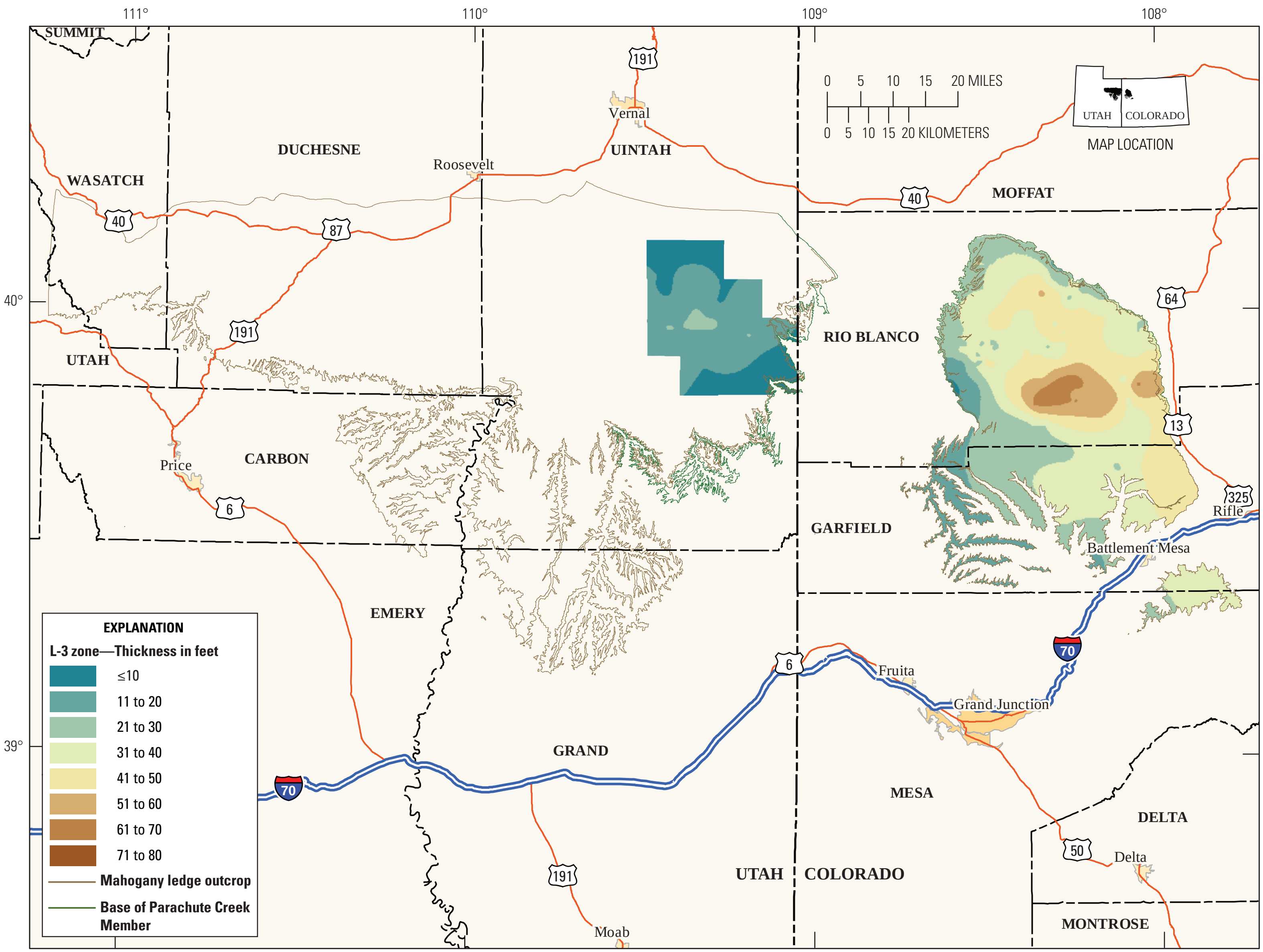


**Figure 33.** Isopach map of L-3 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

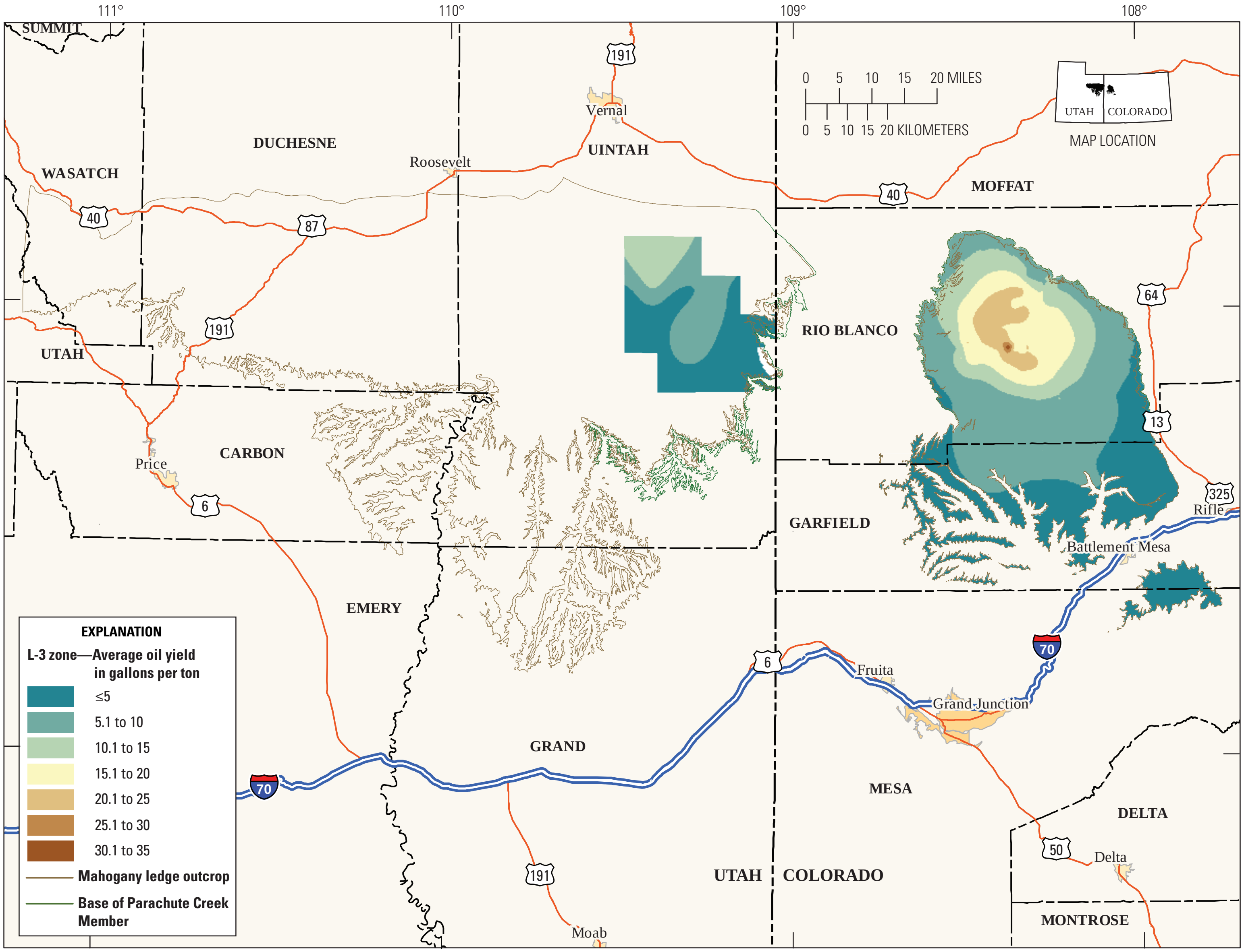


**Figure 34.** Isoresource map of L-3 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

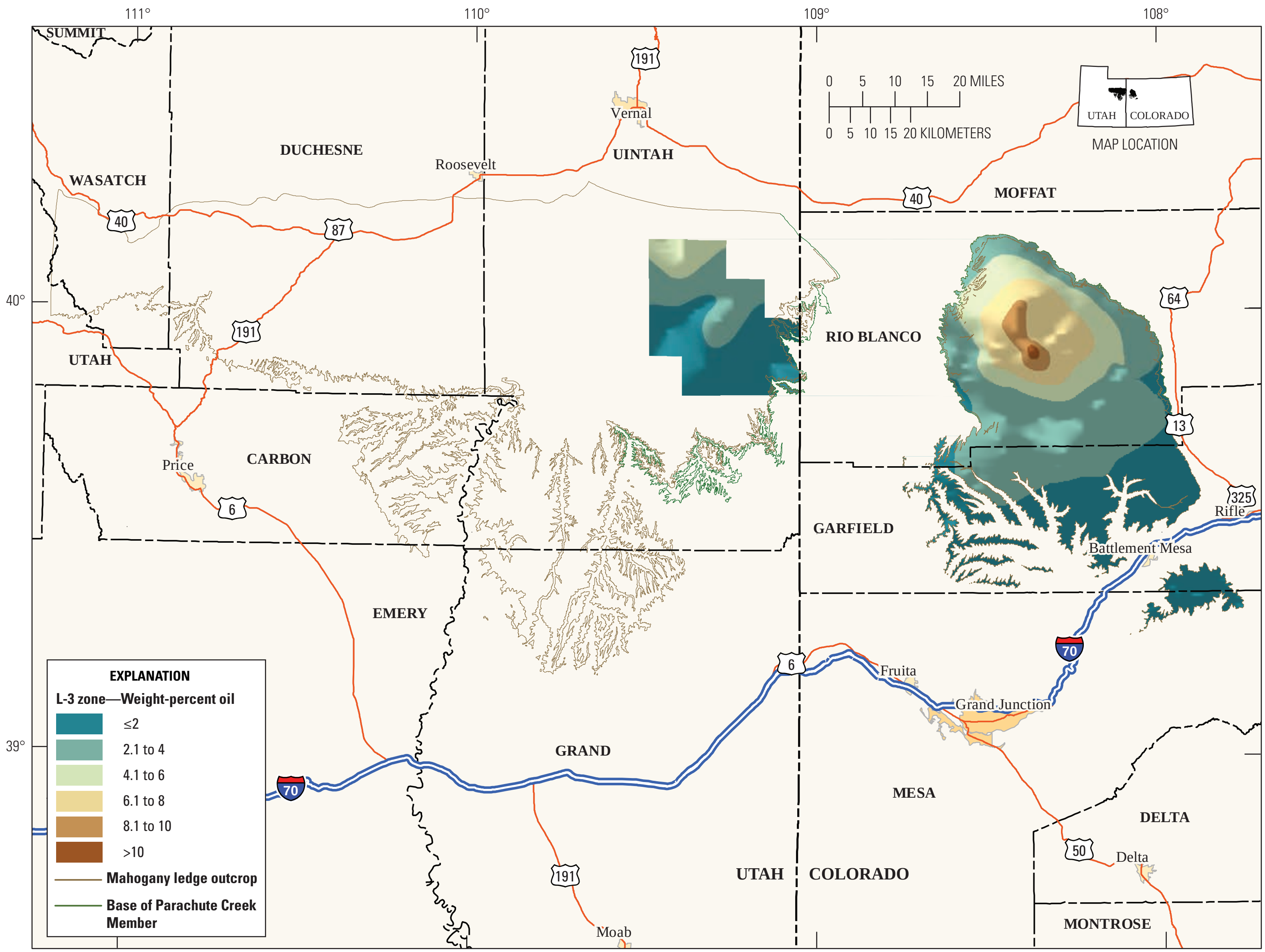


**Figure 35.** Isoresource map of L-3 zone in Uinta and Piceance Basins showing oil yield in weight percent.

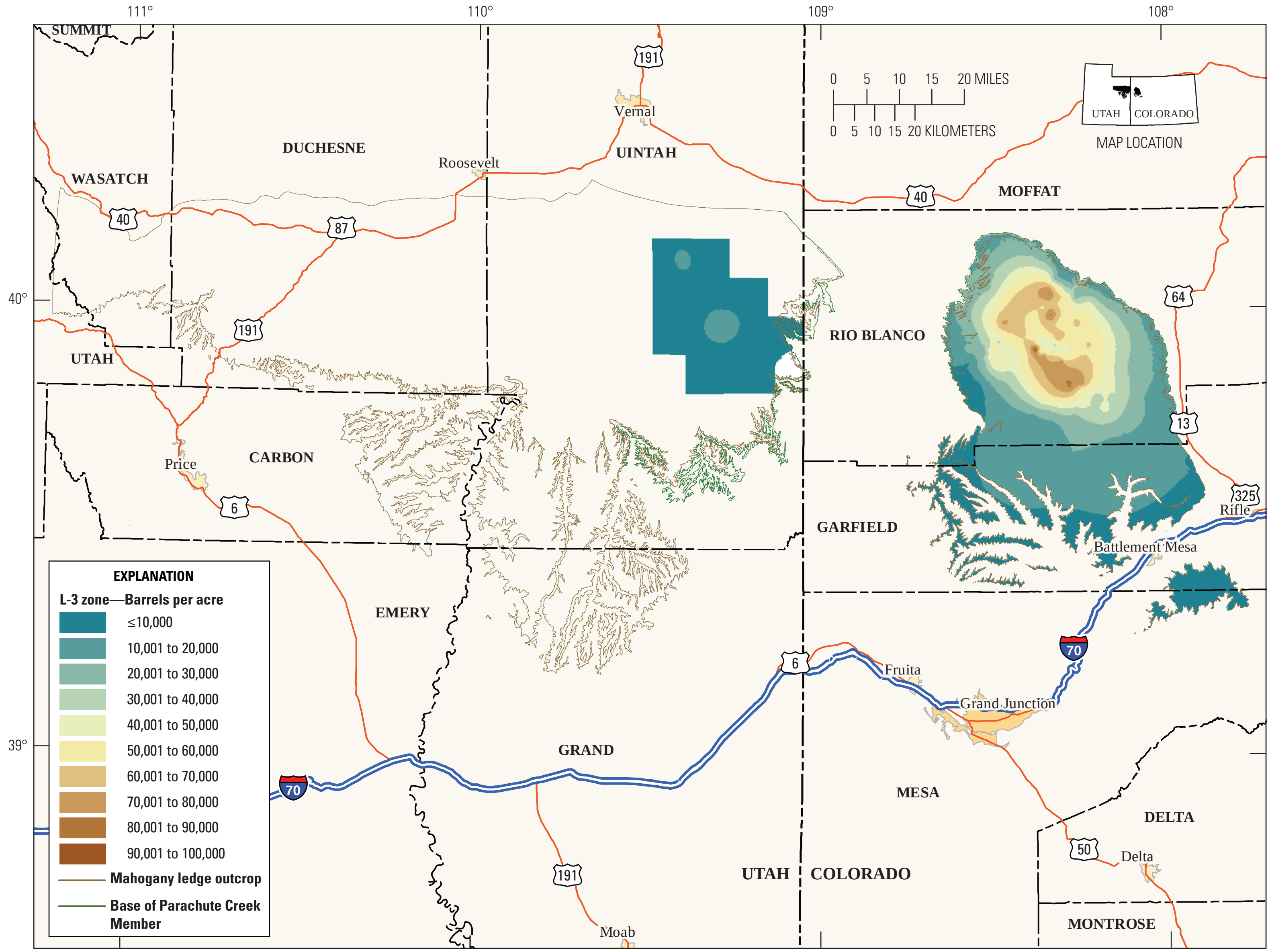


**Figure 36.** Isoresource map of L-3 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

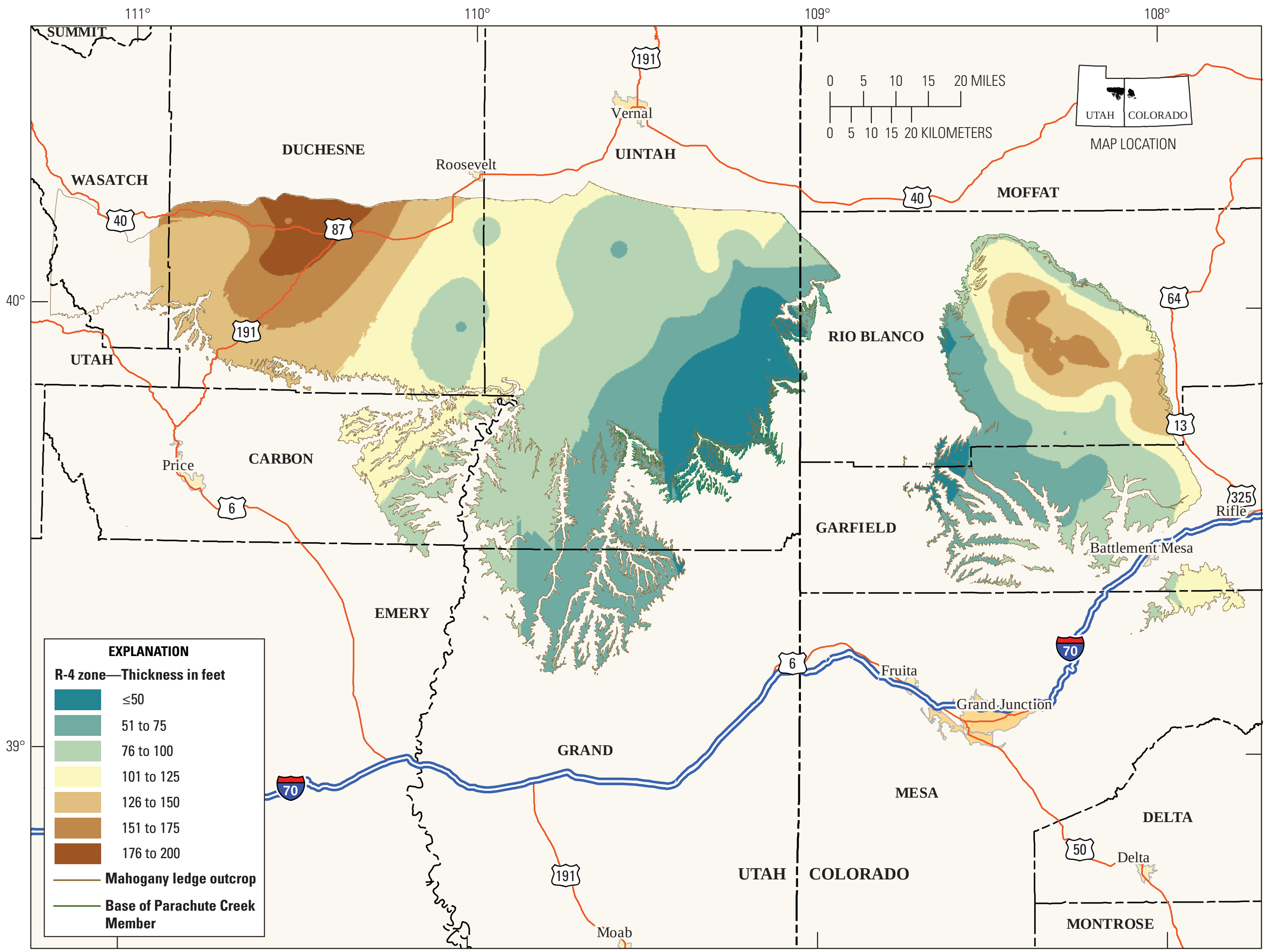


**Figure 37.** Isopach map of R-4 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

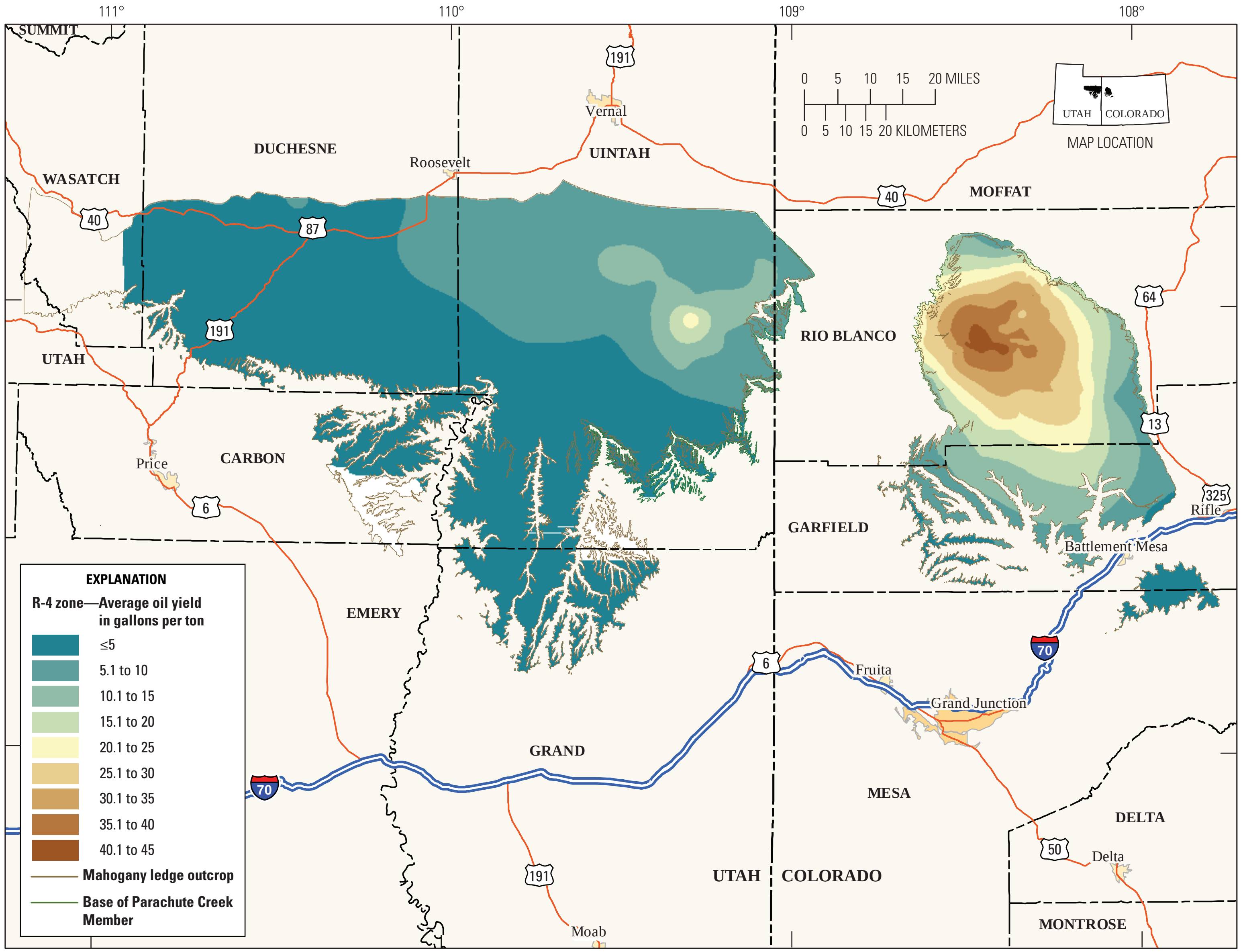


**Figure 38.** Isoresource map of R-4 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

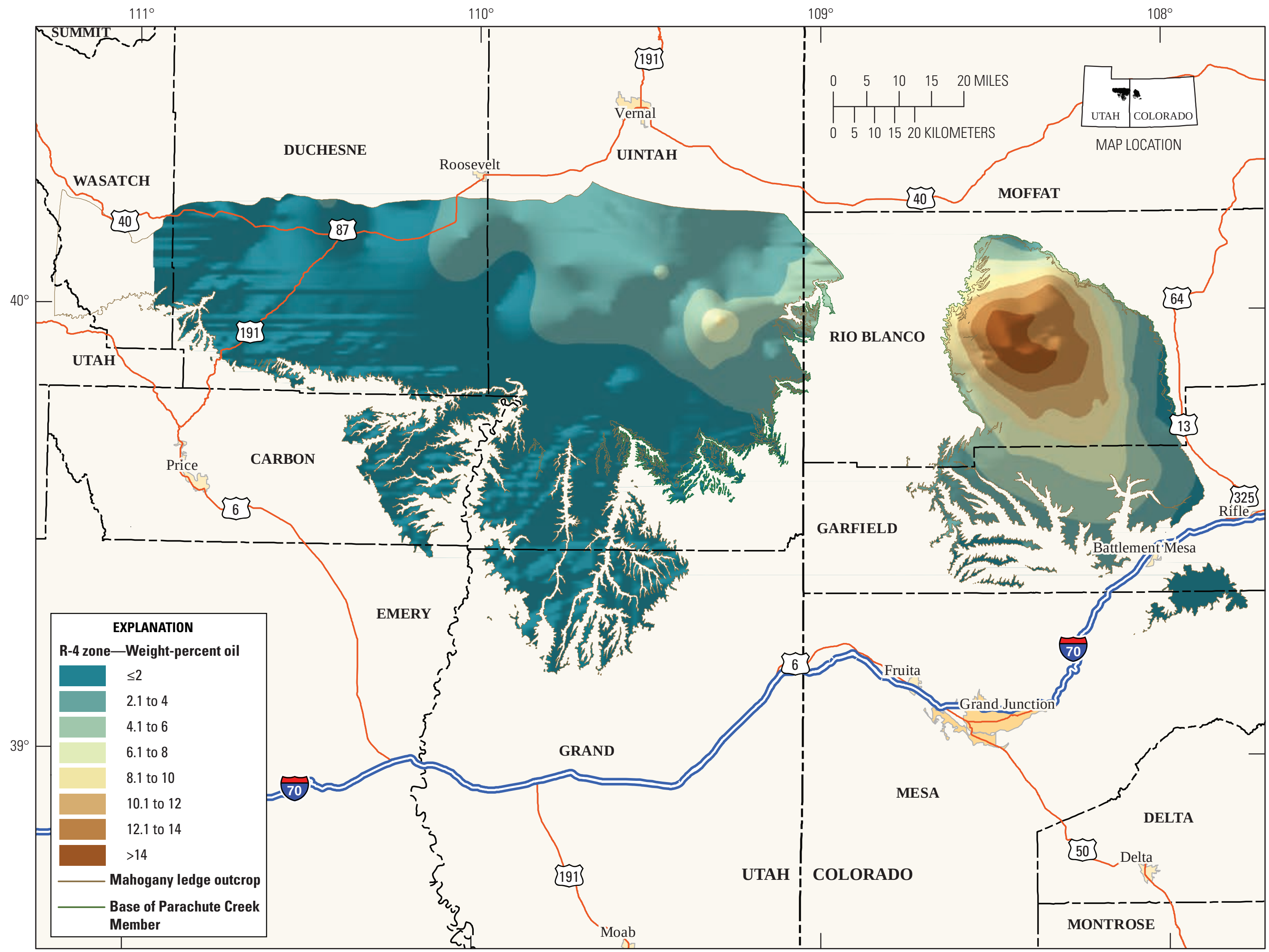


**Figure 39.** Isoresource map of R-4 zone in Uinta and Piceance Basins showing oil yield in weight percent.

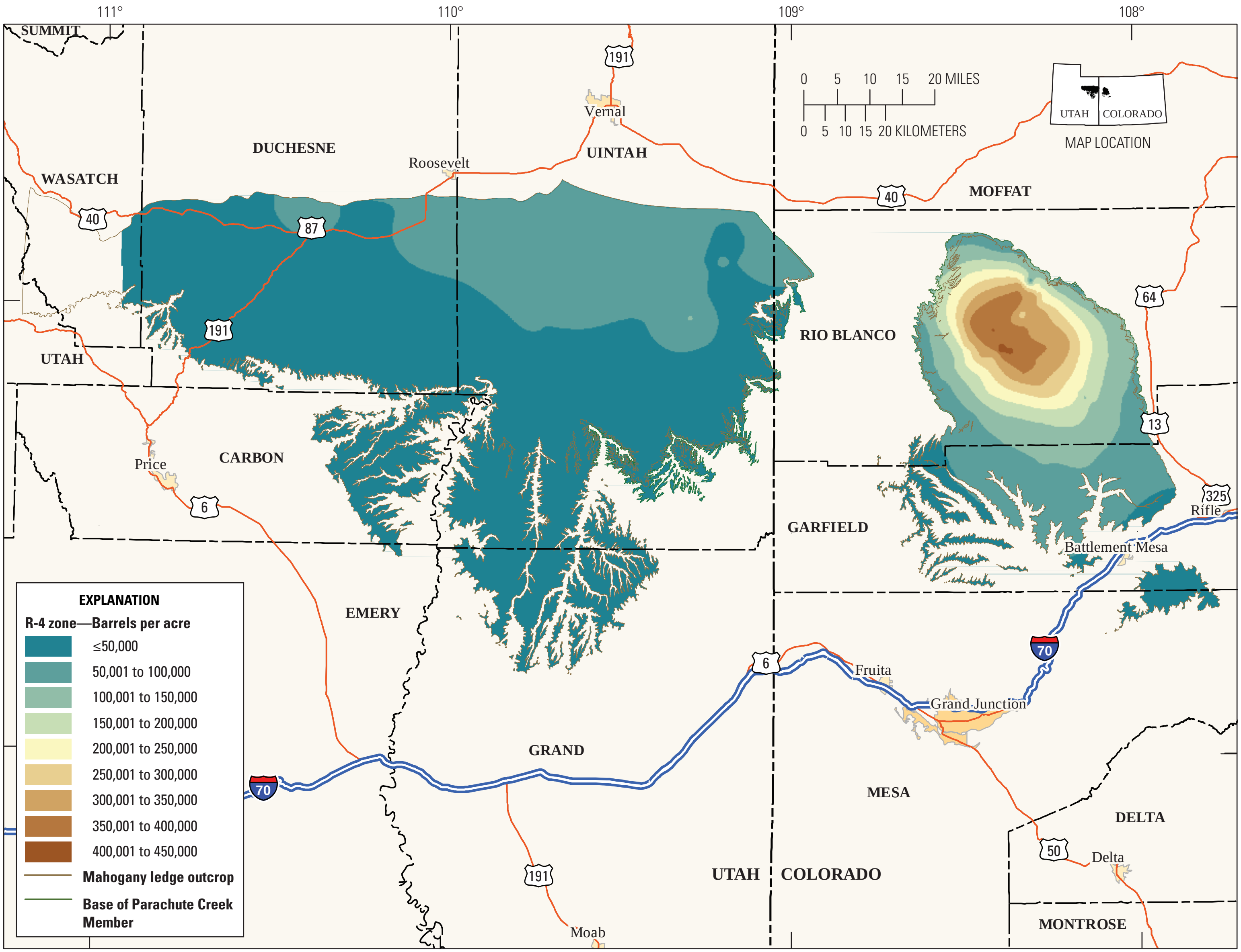


**Figure 40.** Isoresource map of R-4 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

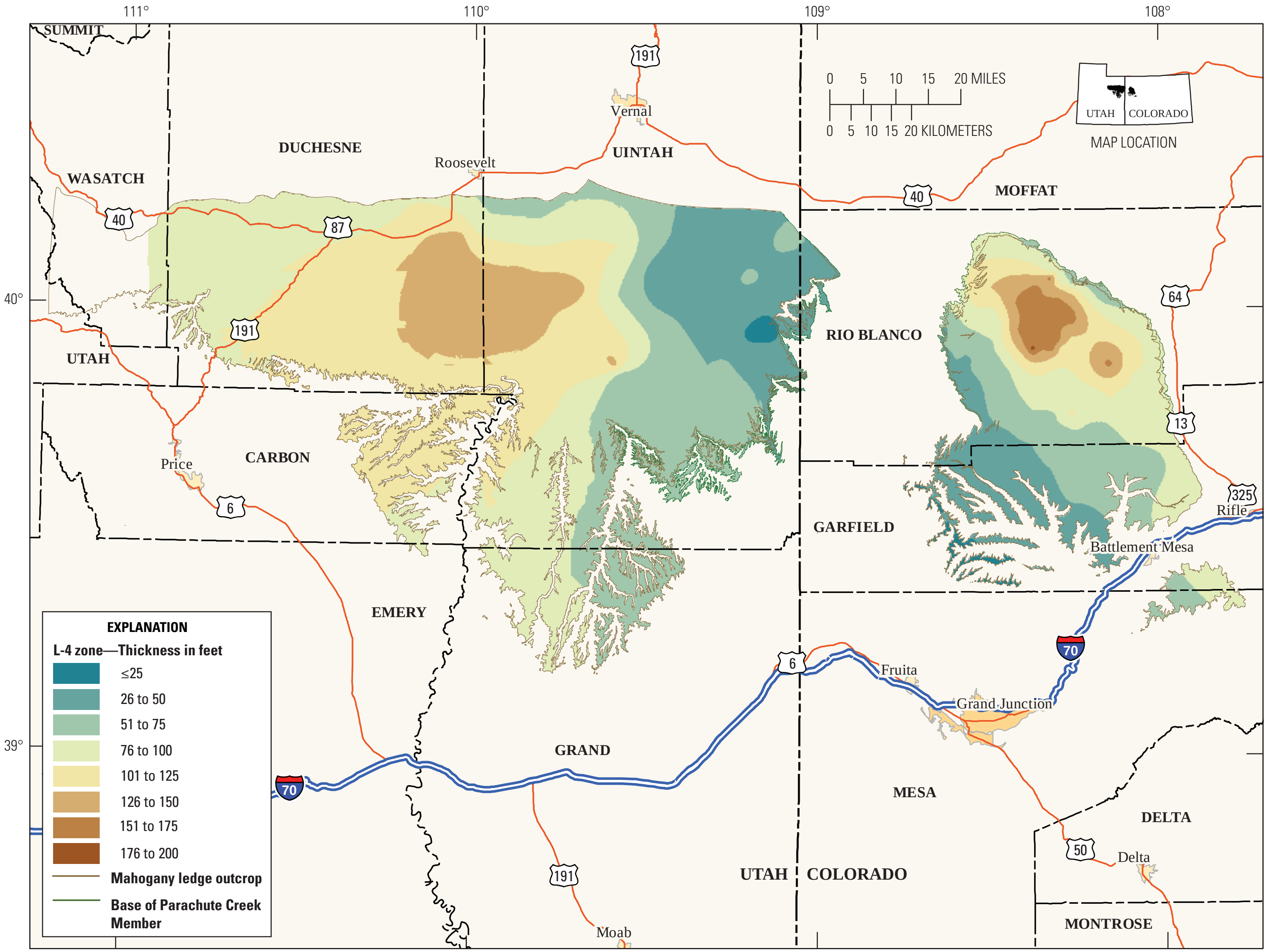


**Figure 41.** Isopach map of L-4 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

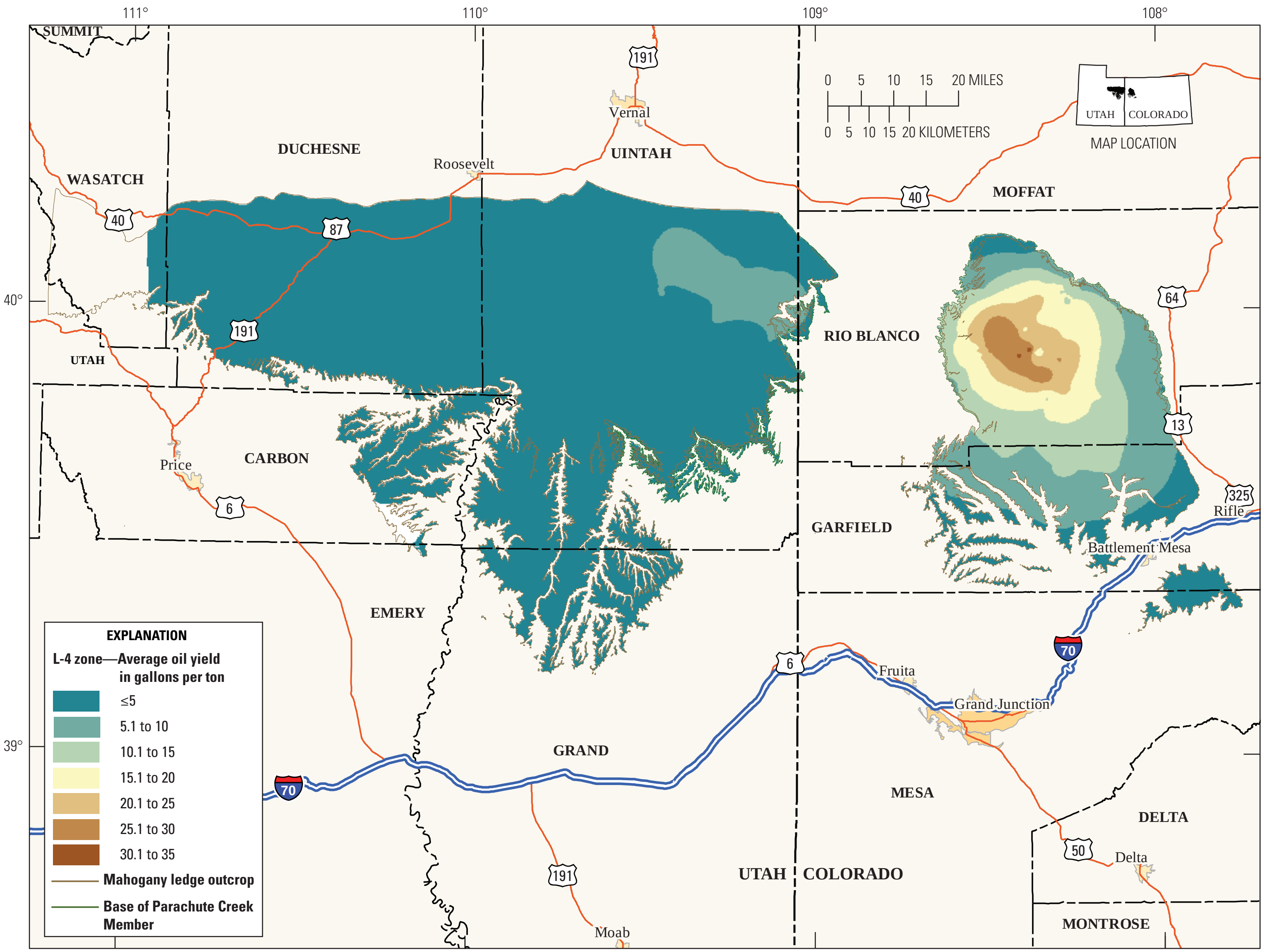


**Figure 42.** Isoresource map of L-4 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

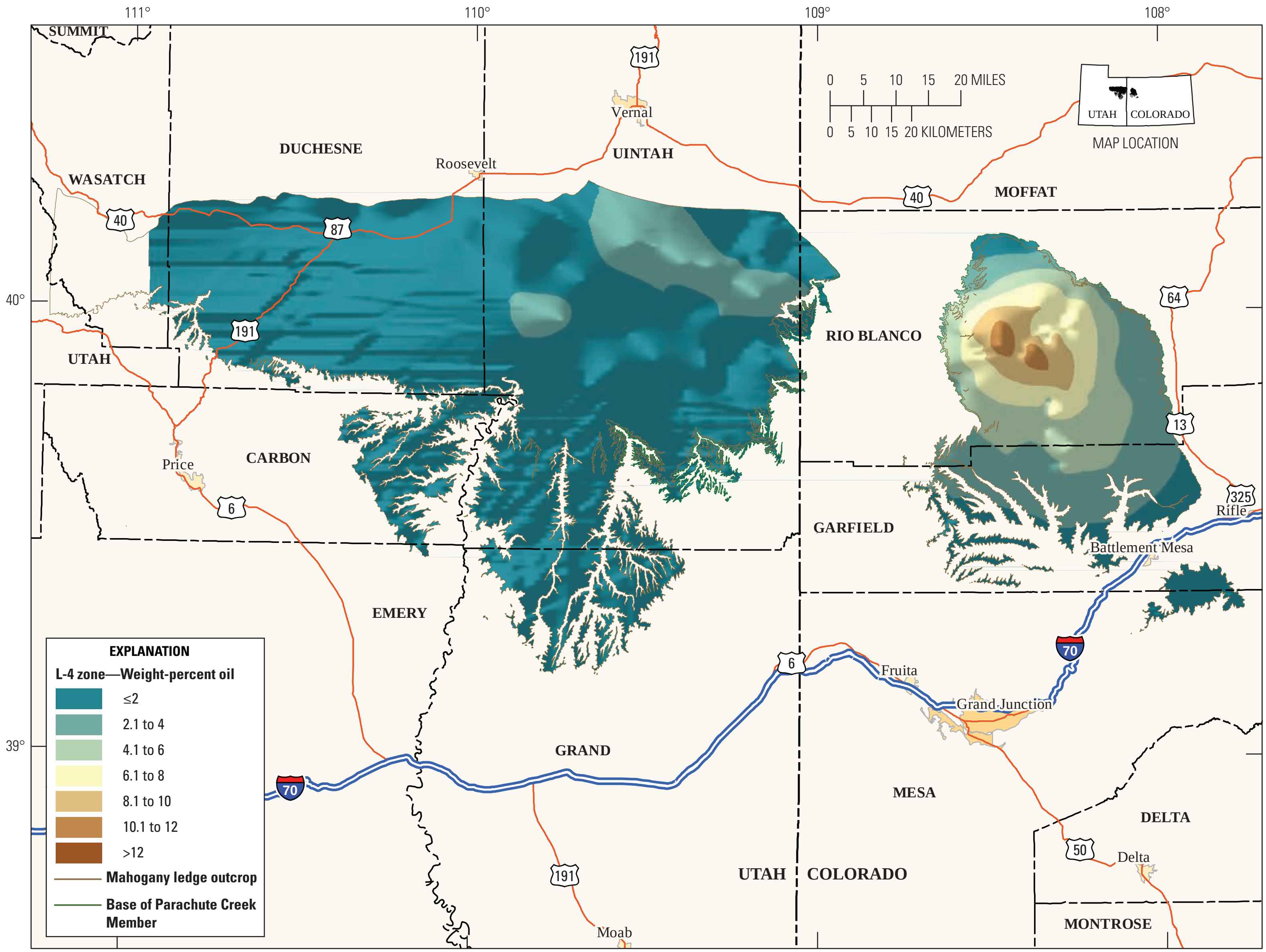


**Figure 43.** Isoresource map of L-4 zone in Uinta and Piceance Basins showing oil yield in weight percent.

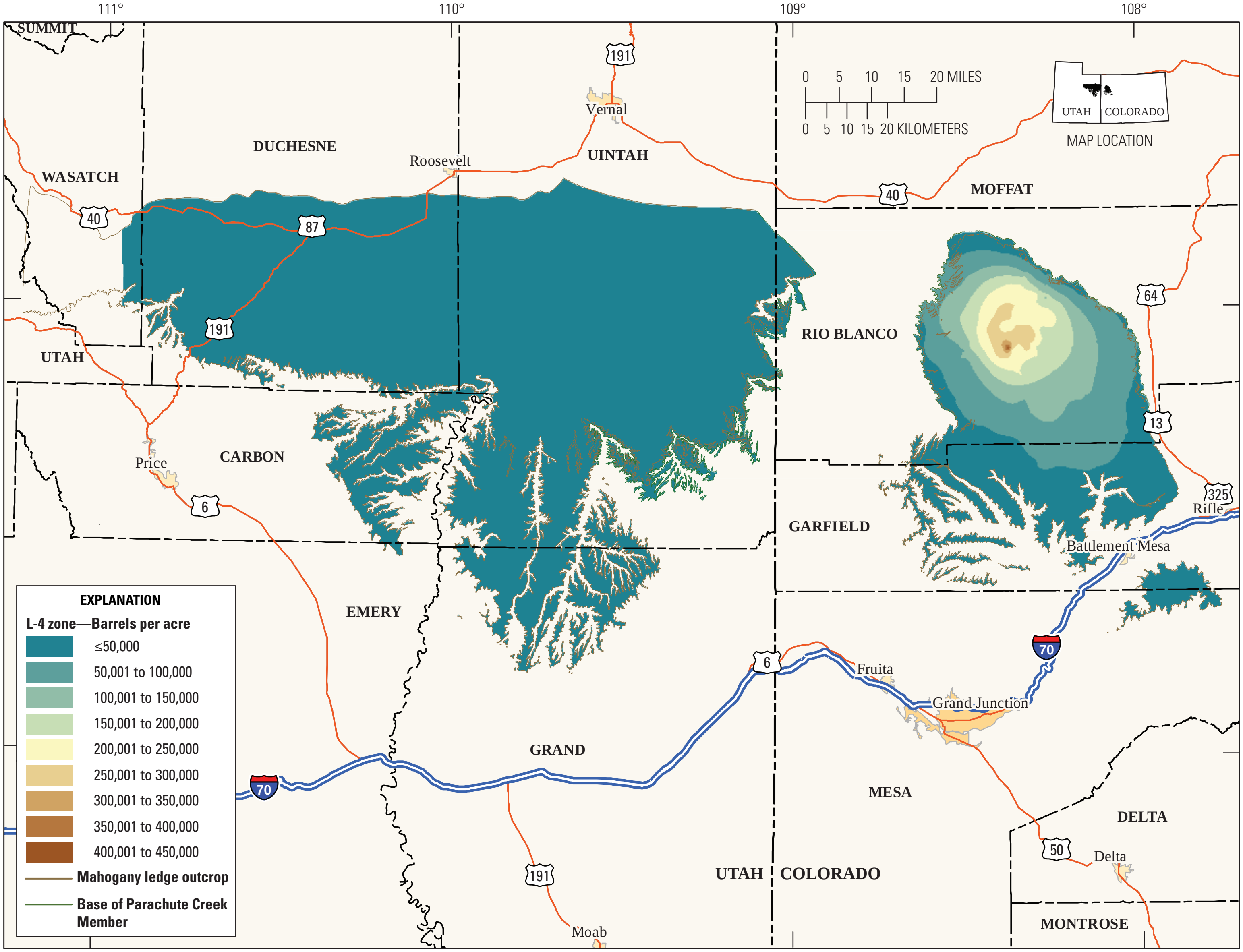


**Figure 44.** Isoresource map of L-4 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

## R-5 Zone

A significant increase in oil yield marks the base of the R-5 zone (fig. 3). In the Piceance Basin, the basal bed of the R-5 zone contains abundant nahcolite in the oil shale depocenter, and thick beds of halite and nahcolite exist throughout the lower part of the R-5 zone starting about 15–20 ft above the base (Dyni 1974, 1981). Thinner beds of halite and nahcolite exist in the upper part of the R-5 zone, and nahcolite levels, in general, are comparatively high in the R-5 zone when compared to older oil shale zones. In the Piceance Basin, the R-5 zone is thickest through a broad band that extends from the oil shale depocenter southeastward to near the basin margin (fig. 45). Maximum thickness for the zone is in the oil shale and saline-mineral depocenter where thickness ranges from 225 to 380 ft. In the Uinta Basin, the R-5 zone thickens from about 58 to 120 ft along the west flank of the Douglas Creek arch to a maximum of about 220 ft in the western part of the Uinta Basin (fig. 45).

The R-5 zone contains as much as 41.4 GPT or 15.5 weight-percent oil in the oil shale and saline depocenter in the north-central part of the Piceance Basin with oil yields generally decreasing in a radial pattern outward (figs. 46 and 47). Maximum BPA varies from about 400,000 to 870,000 in the oil shale and saline depocenter (fig. 48). In the Uinta Basin, estimated oil yields range to as much as 16.8 GPT (fig. 46) or to about 10 weight percent (fig. 47), and estimated in-place oil ranges to as much as 155,000 BPA (fig. 48).

## L-5 Zone

In the Piceance Basin, the lower part of the L-5 zone contains large deposits of halite and nahcolite in two beds about 20 ft apart with each bed reaching a maximum thickness of 60–65 ft (Dyni 1974, 1981). These two beds are the highest preserved saline beds in the section, but there is a persistent collapse breccia near the top of the L-5 zone indicating that an additional thick saline bed was probably once present. The two thick nahcolite and halite beds have been leached out over much of their original extent and were replaced by collapse breccias. The isopach map for the L-5 zone in the Piceance Basin (fig. 49) shows complex thickening trends that are significantly different from underlying oil shale zones because the L-5 zone has been highly modified by relatively recent leaching of the thick nahcolite and halite beds. Throughout much of the Piceance Basin, the L-5 zone thickens in a fairly regular pattern to the east-northeast. In the depocenter, however, the L-5 zone thickens from about 80 to 100 ft where the two saline beds have been leached, to nearly 230 ft where they are still preserved. In addition, the L-5 zone thickens markedly toward the northern part of the basin (fig. 49). This thickening is due to an influx of clastics from the north that Johnson (1985, 2007) suggested was related to outflow from Lake Gosiute to the north. In the Uinta Basin, the L-5 zone thickens from about 60 to 100 ft along the west flank of the Douglas Creek arch to a maximum of about 230 ft in the northeast corner of the basin (fig. 49).

In the Piceance Basin, estimated oil yield for the L-5 zone ranges to more than 22 GPT or 8.1 weight percent in the oil shale and saline depocenter in the north-central part with values decreasing outward in a general radial pattern (figs. 50 and 51). In-place oil ranges to as much as 274,000 BPA in the Piceance Basin depocenter with values decreasing rapidly toward the southwest and northeast and more slowly toward the southeast (fig. 52). In the Uinta Basin, estimated oil yields for the L-5 zone range to as much as 10.8 GPT or as much as 6 weight percent (figs. 50 and 51) with estimated in-place oil as much as 88,000 BPA (fig. 52).

## R-6 Zone

The R-6 zone contains no preserved nahcolite or halite in the Piceance Basin depocenter, but some solution cavities that may once have been filled with nahcolite were described in the upper part of the R-6 zone in outcrop near the mouth of Piceance Creek in the north-central part of the basin by Pipiringos and Johnson (1976). There are no breccia zones in the R-6 zone (Dyni, 1974); thus, it is doubtful that thick beds of halite and nahcolite, like those in the underlying L-5 zone, ever existed in the R-6 zone. According to Dyni (1974, p. 119), the highest solution breccia is in the middle of his zone 12 (the L-5 zone) and "No unleached saline beds equivalent to this breccia, or younger solution breccias, are known to exist in the Piceance Creek basin."

In the Piceance Basin, the R-6 zone thickens generally toward the east-northeast across the basin to a maximum of about 250 ft in the eastern part of the basin, then thins abruptly to 106 ft along the northeast margin (fig. 53). There is no thickening toward the saline depocenter in the north-central part of the basin as in previous oil shale zones that contain abundant saline minerals. There is a pronounced thickening to 537 ft toward the north-central part of the basin, in the vicinity of where the underlying L-5 zone thickened, suggesting again a source of sediment from the north. In the Uinta Basin, the R-6 zone thickens from about 166 to 200 ft along the west flank of the Douglas Creek arch to a maximum of more than 450 ft in the western part of the Uinta Basin (fig. 53).

Maximum oil yields for the R-6 zone in the Piceance Basin range from about 21 to 33 GPT or 11.9 weight percent through an elongated south- to southeast-trending area that extends for a considerable distance to the southeast from the former oil shale and saline mineral depocenter (figs. 54 and 55). This expansion of the oil shale depocenter toward the southeast, which was apparent but less pronounced in the underlying L-5 zone, is especially conspicuous on the map showing estimated BPA for the R-6 zone (fig. 56). The area of maximum in-place oil, from about 300,000 to 425,000 BPA, extends to the upper reaches of the Parachute Creek drainage north of the Colorado River. In the Uinta Basin, the R-6 zone thickens from about 166 to 200 ft along the west flank

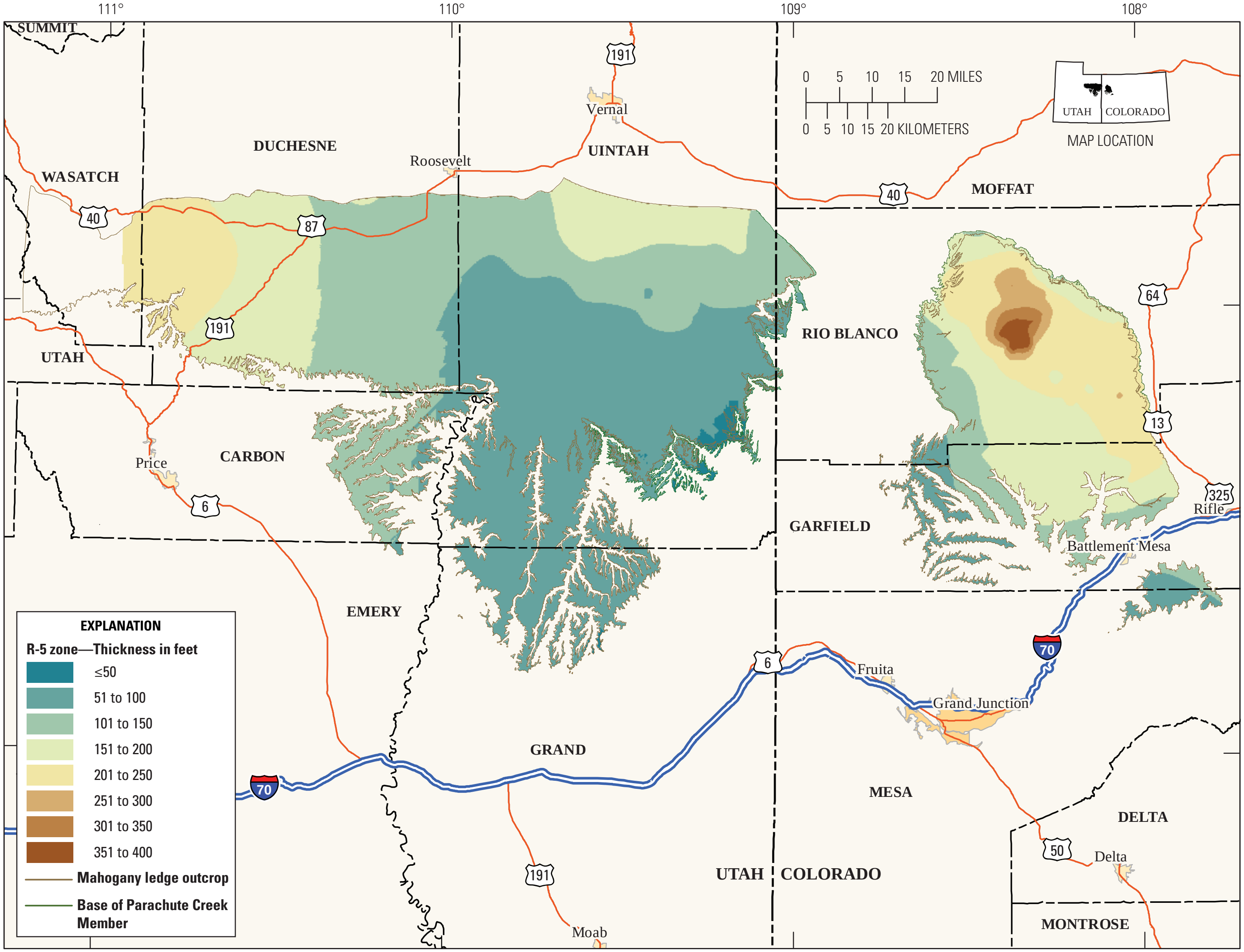


**Figure 45.** Isopach map of R-5 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

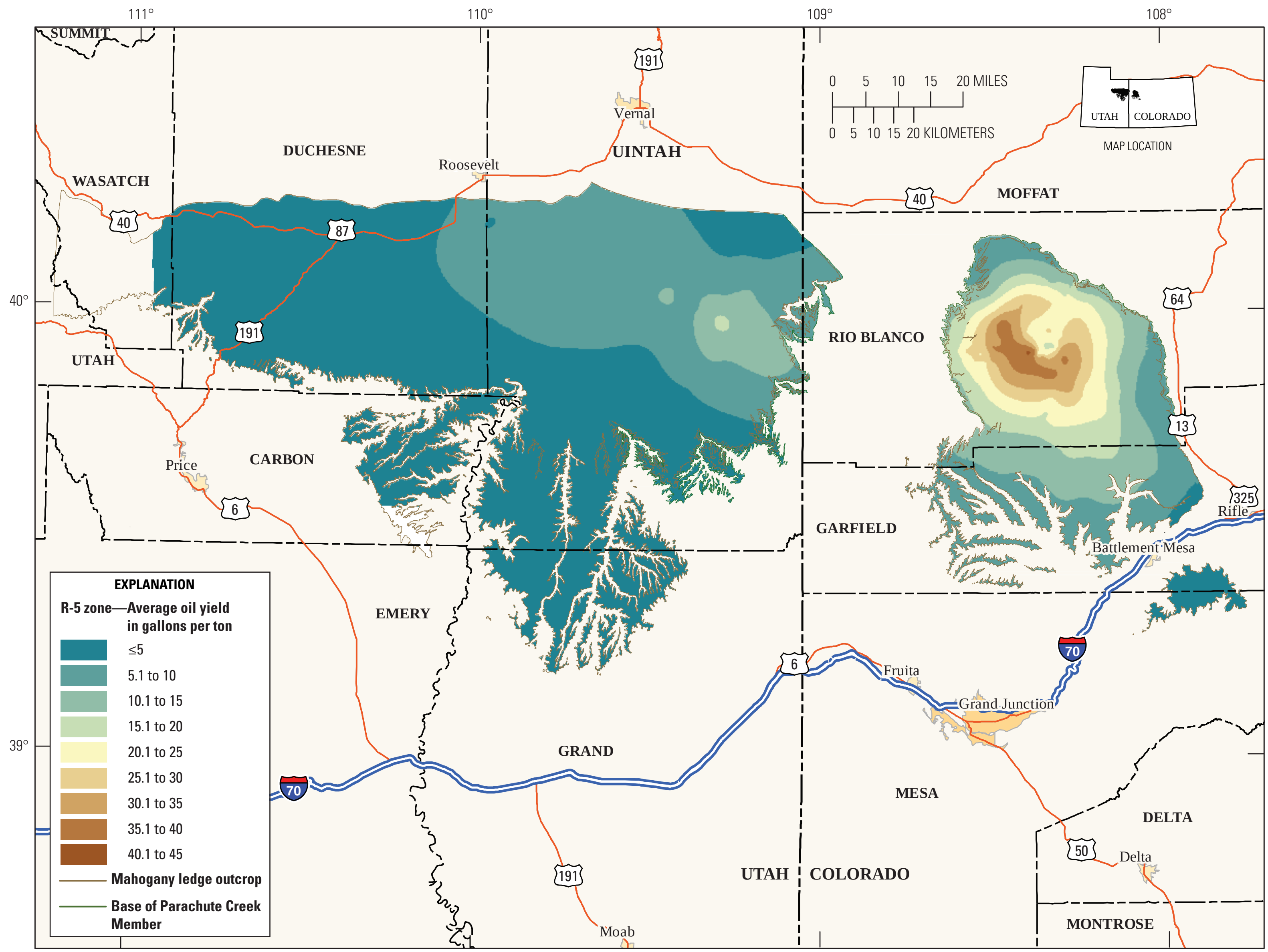


**Figure 46.** Isoresource map of R-5 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

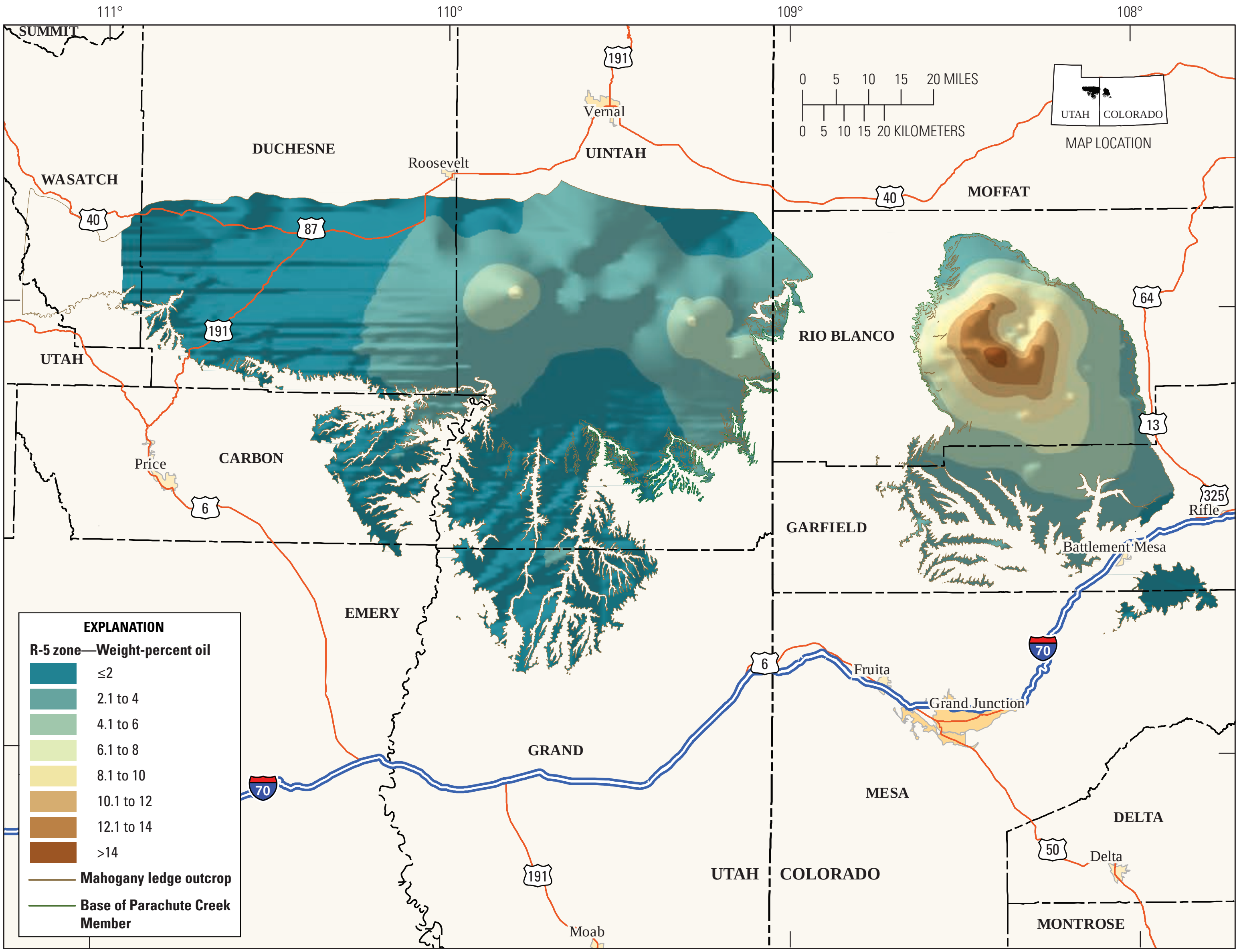


**Figure 47.** Isoresource map of R-5 zone in Uinta and Piceance Basins showing oil yield in weight percent.

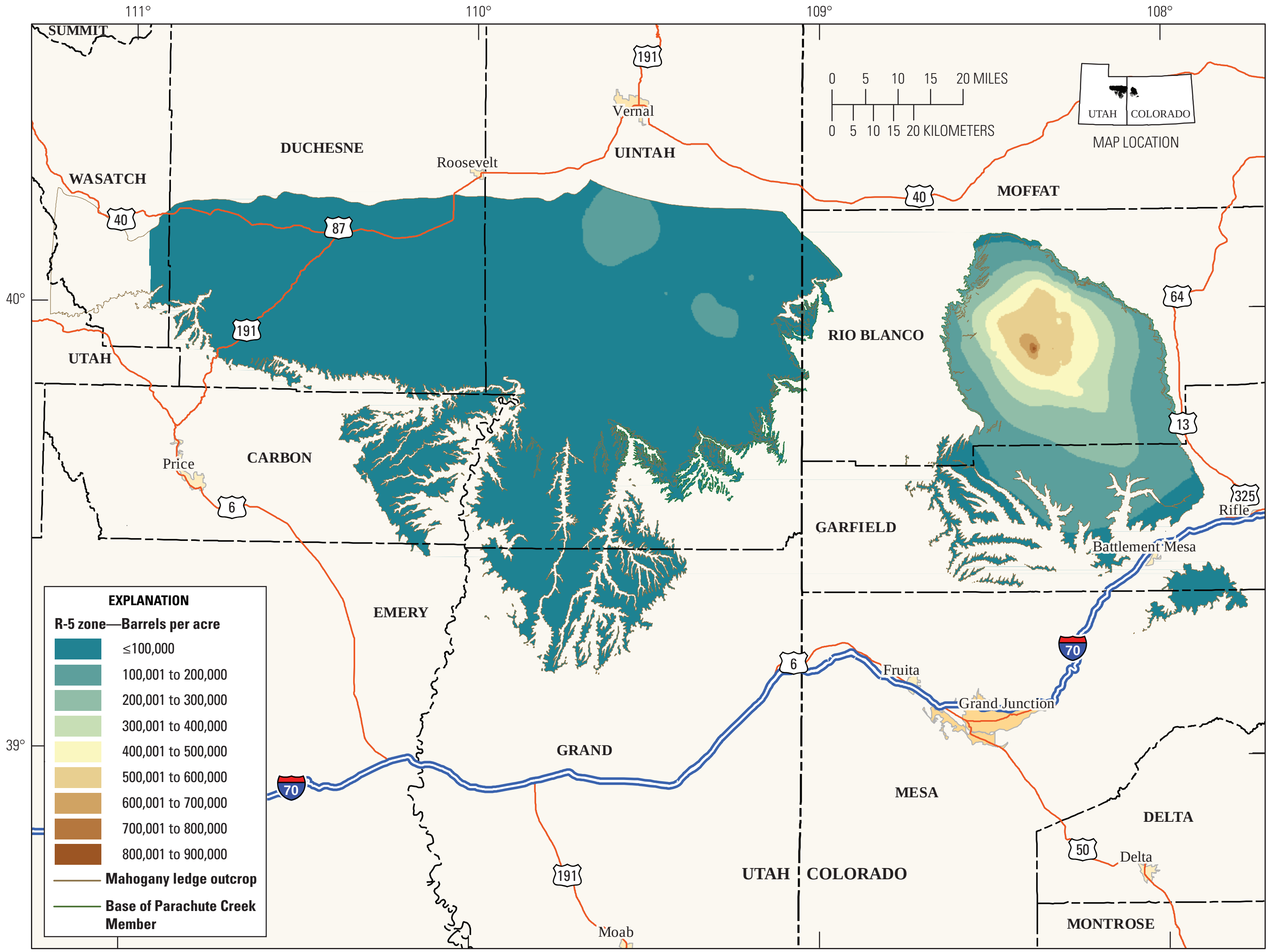


**Figure 48.** Isoresource map of R-5 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

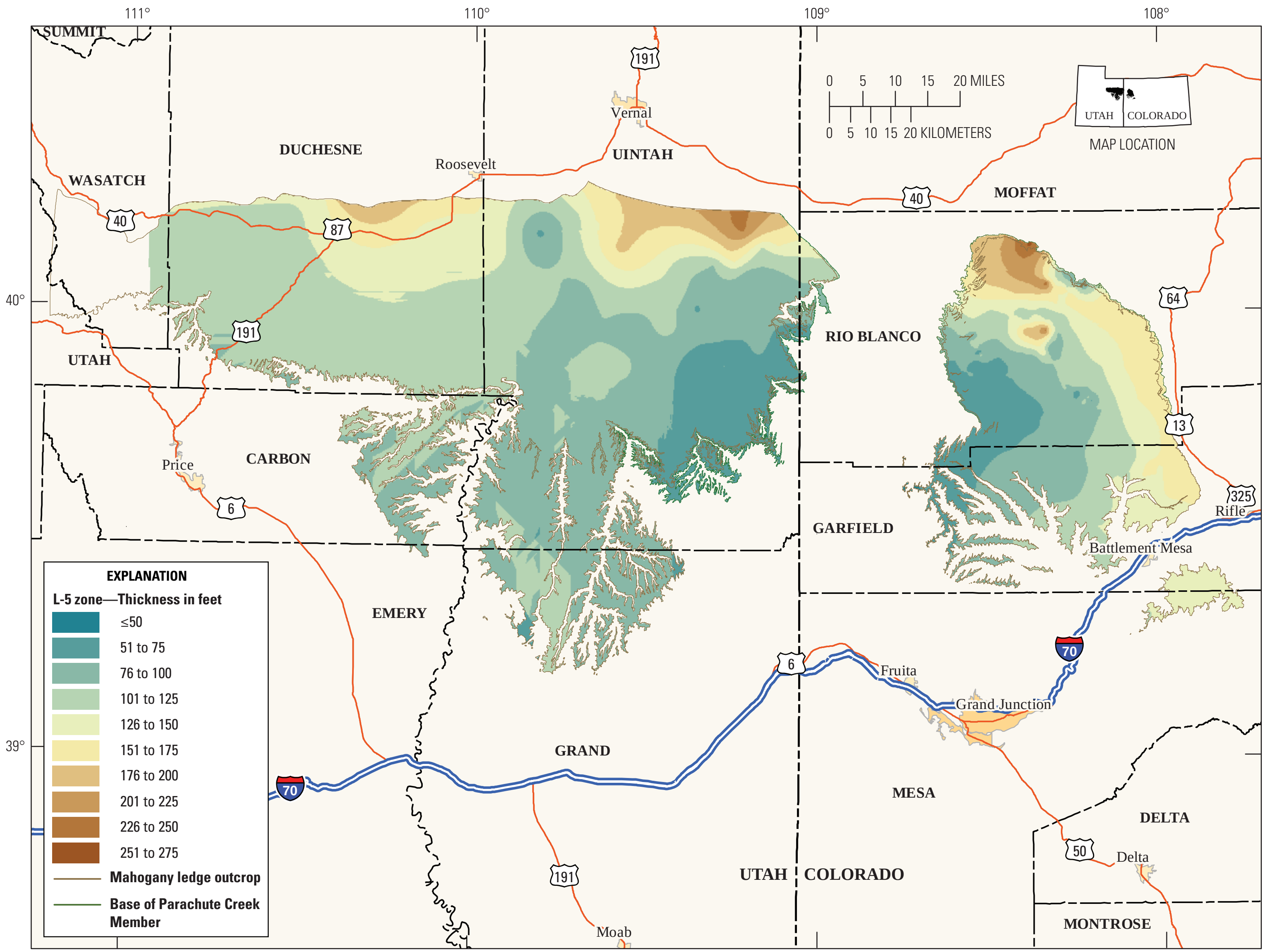


**Figure 49.** Isopach map of L-5 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

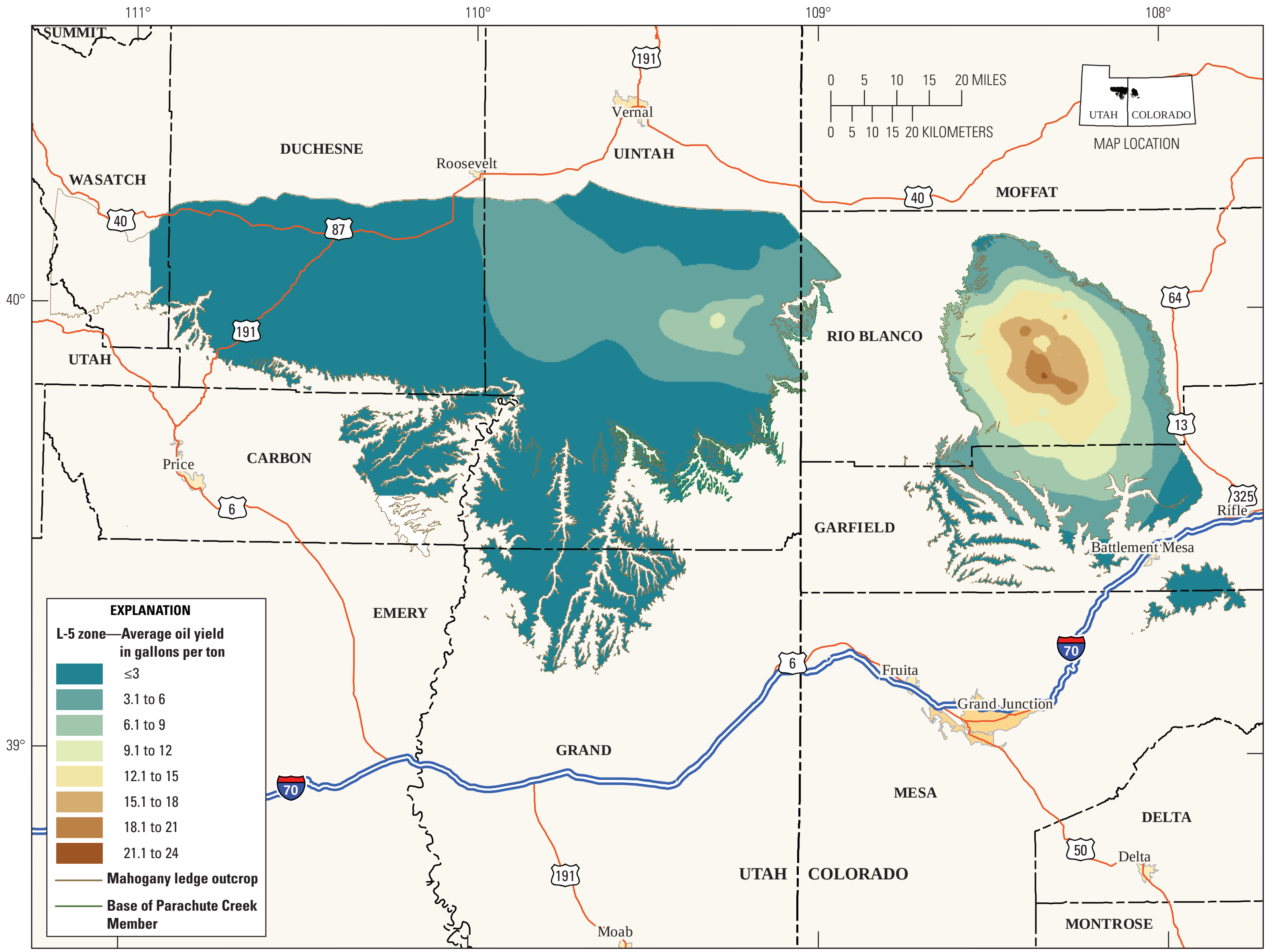


**Figure 50.** Isoresource map of L-5 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

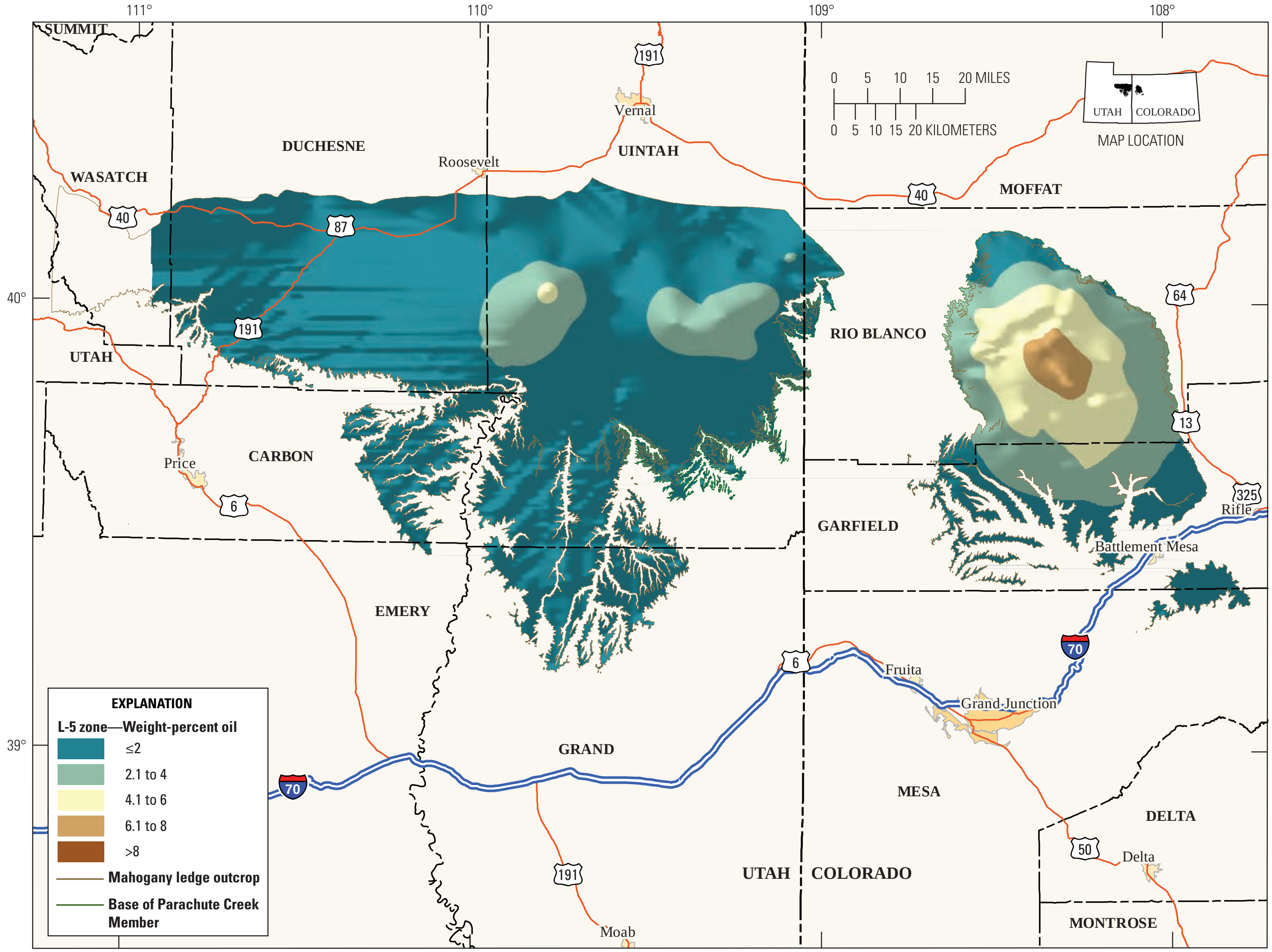


**Figure 51.** Isoresource map of L-5 zone in Uinta and Piceance Basins showing oil yield in weight percent.

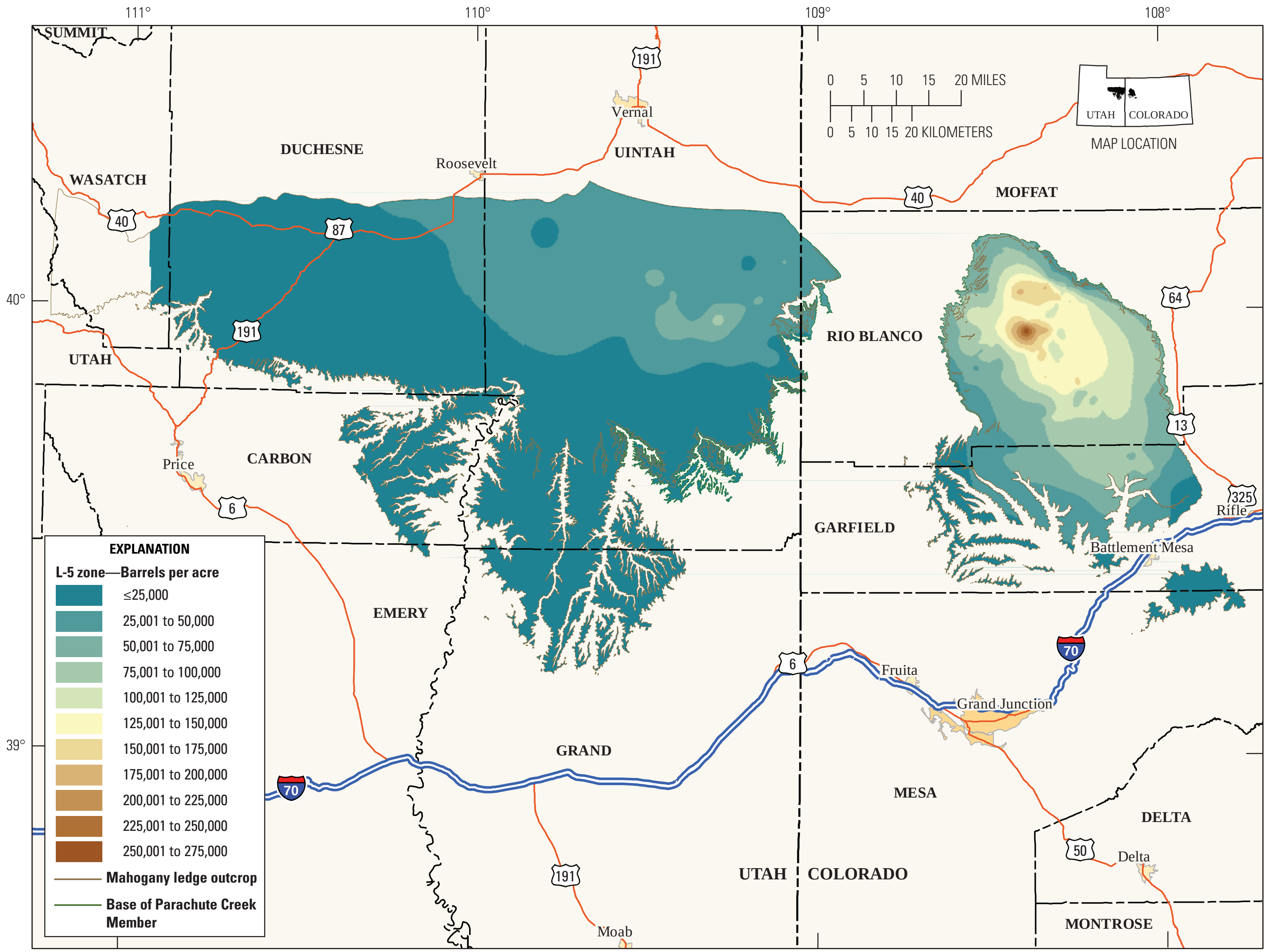


**Figure 52.** Isoresource map of L-5 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

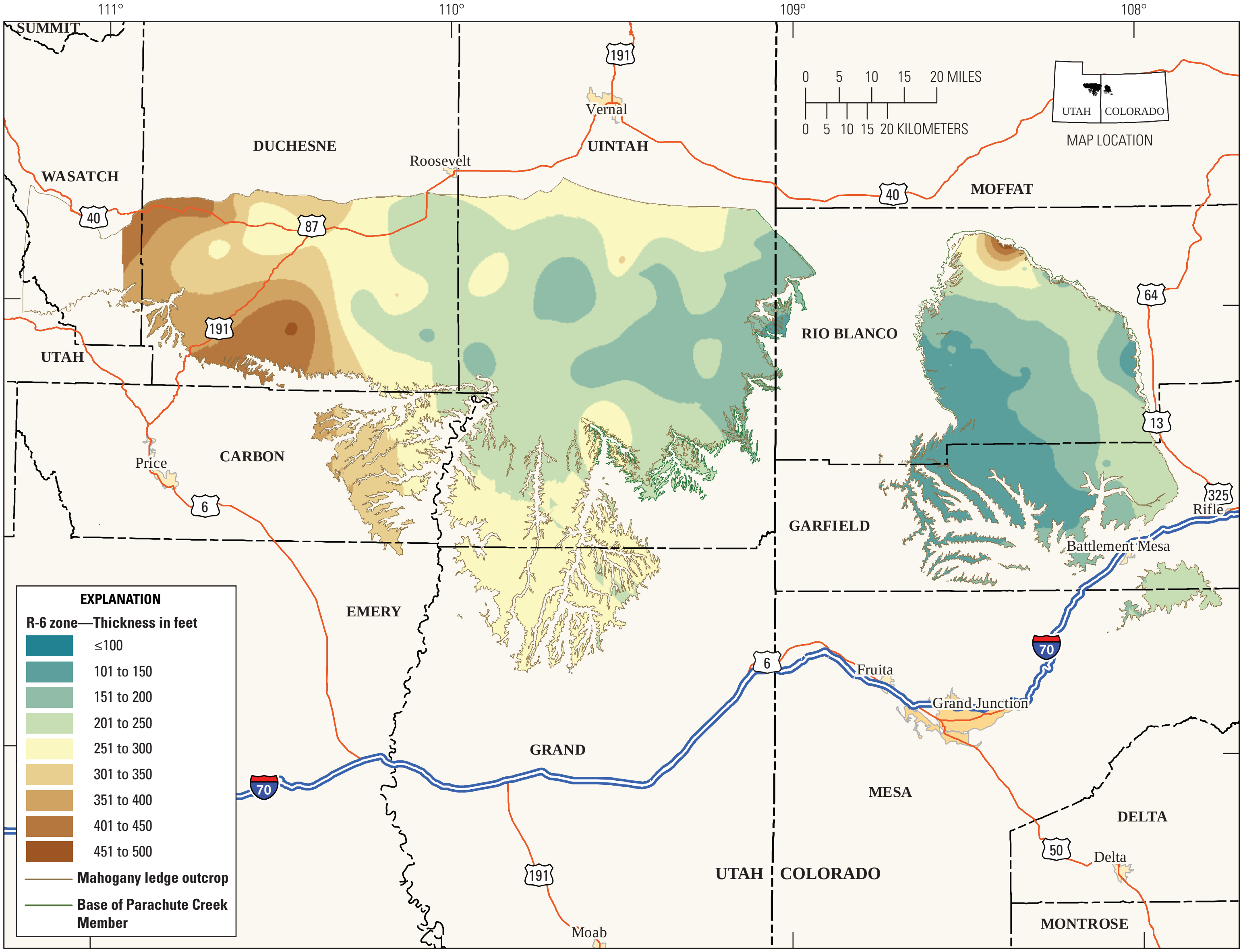


**Figure 53.** Isopach map of R-6 zone in Uinta and Piceance Basins using the Radial Basis Function method of contouring.

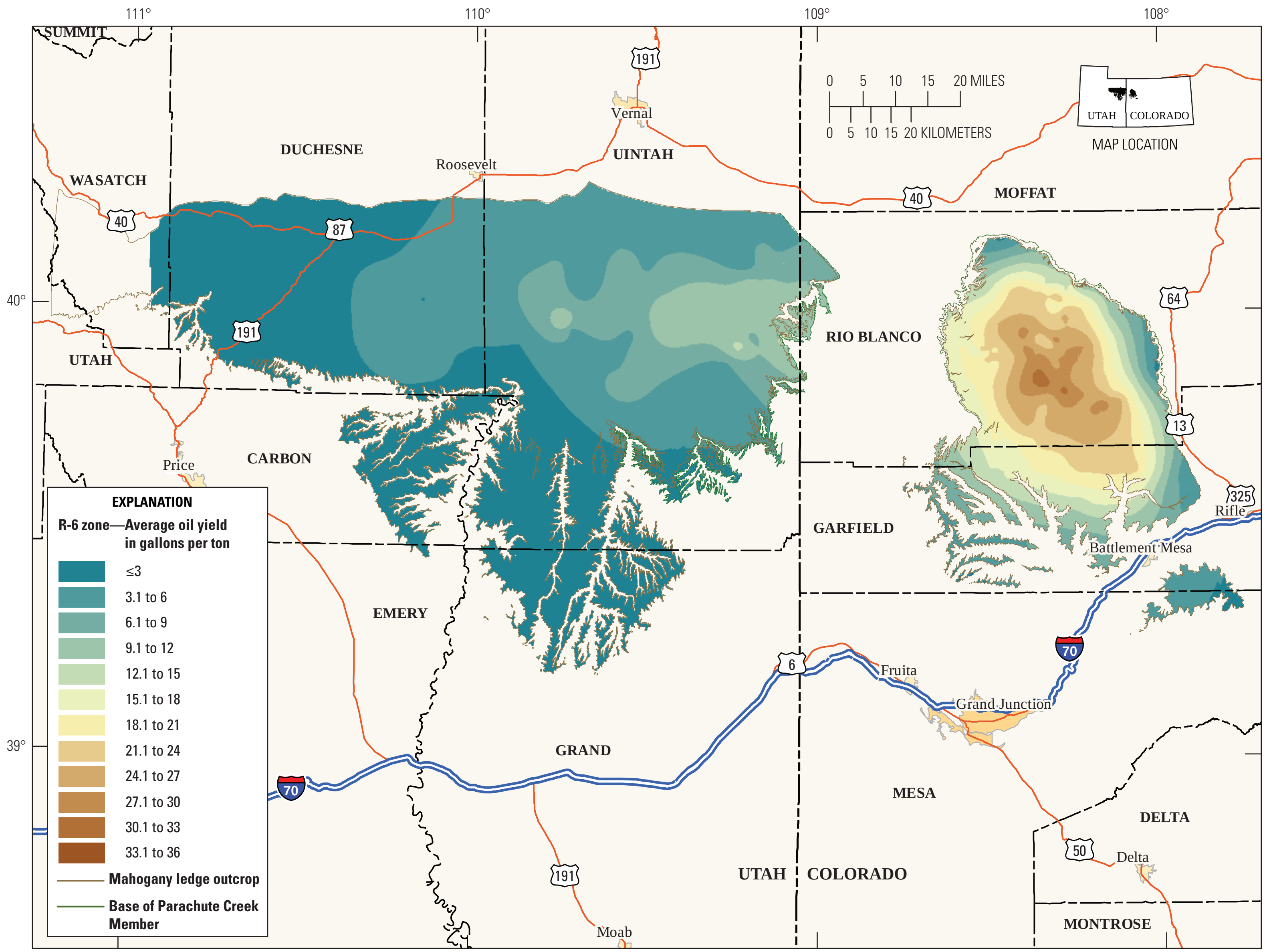


**Figure 54.** Isoresource map of R-6 zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

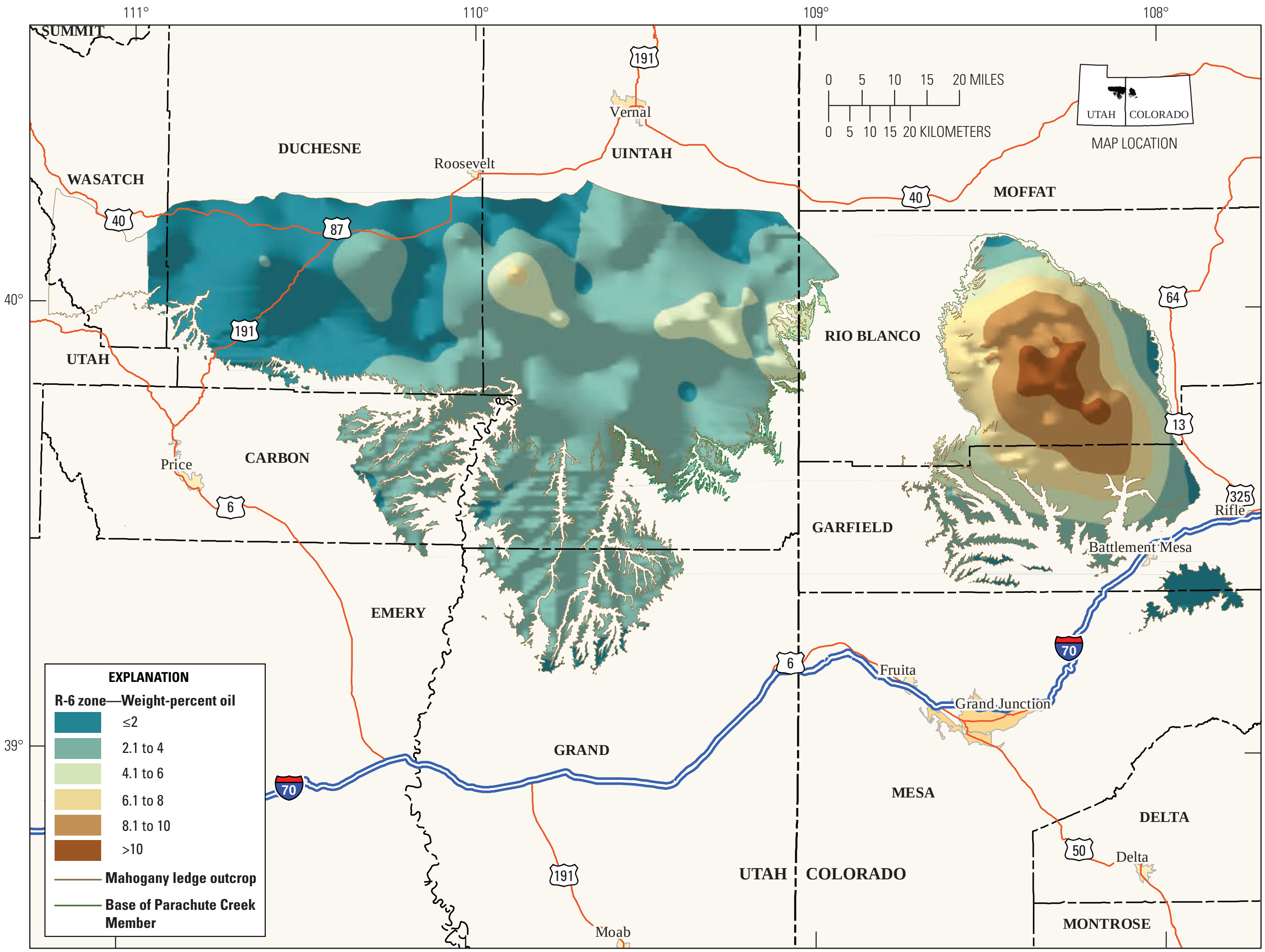


**Figure 55.** Isoresource map of R-6 zone in Uinta and Piceance Basins showing oil yield in weight percent.

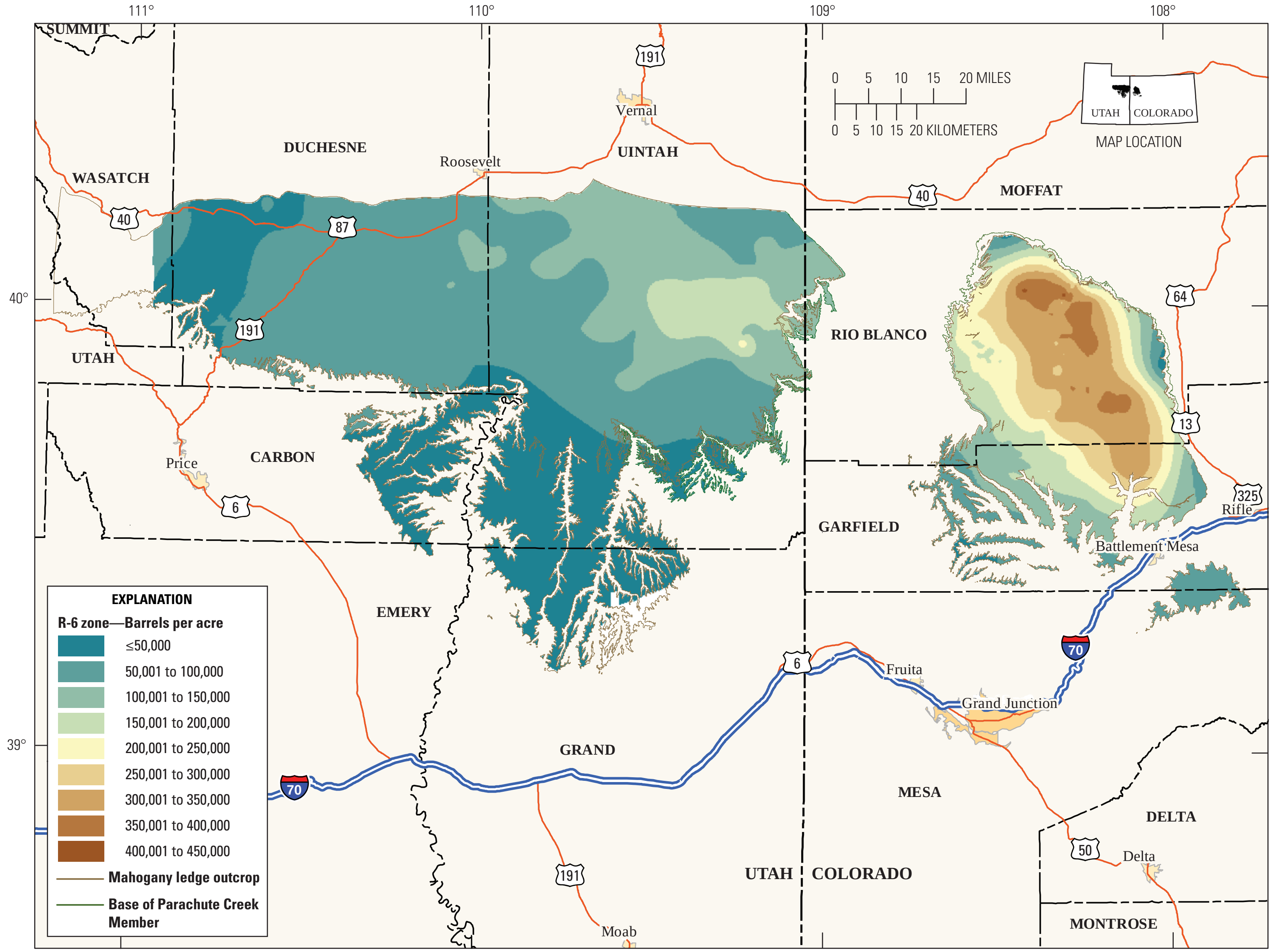


**Figure 56.** Isoresource map of R-6 zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

of the Douglas Creek arch to a maximum of over 450 ft in the western part of the basin (fig. 53). Estimated oil yields are as high as 13.9 GPT (fig. 54) or 8 weight percent (fig. 55), and estimated in-place oil ranges to as much as 195,000 BPA (fig. 56).

## B-Groove

B-groove is a comparatively thin interval that represents a major decrease in oil yields that is evident throughout the oil shale areas of the Piceance and Uinta Basins. It is one of the most distinctive and easily recognizable units on geophysical logs and oil-yield histograms in the entire oil shale interval (fig. 3). In the Piceance Basin, B-groove ranges from 5 to 40 ft thick throughout most of the basin (fig. 57) but thickens markedly toward both the north, where it reaches a thickness of almost 100 ft, and toward the east, where it reaches a maximum thickness of 90 ft (fig. 57). B-groove is very sandy in these marginal areas of the Piceance Basin where it is thickest (R.C. Johnson, unpub. sections; Donnell, 1961, his plate 49). In the Uinta Basin, B-groove thickens from about 5 to 50 ft along the west flank of the Douglas Creek arch to a maximum of about 160 ft in the north-central part of the basin just south of the Uinta Mountains (fig. 57). B-groove appears to represent a major contraction of the lake that brought sandy sediments much farther into the lake than during the previous R-6 interval or the Mahogany interval that followed. It is unclear why organic productivity was so much lower during this contraction of the lake than during previous contractions.

B-groove is organically poor overall with oil yields generally less than 10 GPT (4 weight percent) throughout most of the Piceance Basin, but oil yields are locally as much as 25 GPT (12.6 weight percent) in the central part of the basin (figs. 58 and 59). The overall pattern is a general increase in oil yield toward about the same southeast-trending oil shale depocenter as for the underlying R-6 zone but with a high degree of scatter. In-place oil is also higher in this depocenter (fig. 60) with values ranging to more than 40,000 BPA, but again, there is a high degree of scatter. Estimated oil yields in the Uinta Basin are as high as 14.5 GPT, but most values are less than 5 GPT (fig. 58). Estimated weight-percent oil is generally less than 4 (fig. 59). Estimated in-place oil in the Uinta Basin ranges to as much as 70,000 BPA (fig. 60).

## Mahogany Zone

The Mahogany zone and the strata above it compose the fifth stage of Lake Uinta as defined by Johnson (1985). The Mahogany zone has been the target of most oil shale extraction projects in both basins thus far because of its richness and because it crops out around the margins of the basins where it can be easily reached by underground mining. The base of the Mahogany zone is marked by a significant increase in oil yields (fig. 3). Oil yields generally increase upward in the Mahogany zone to a maximum in the Mahogany bed, one of the richest and probably the most widespread oil shale beds in both the Piceance and Uinta Basins (fig. 3). The Mahogany bed is the only significant oil shale bed remaining in the Green River Formation throughout much of the southern part of the Uinta Basin where most of the Green River Formation has graded into marginal lacustrine and fluvial rocks (Cashion, 1967, his pl. 3). It represents the culmination of a major transgression of Lake Uinta that began at the base of the Mahogany zone.

The Mahogany bed can be recognized throughout most, if not all, of the area where the Green River Formation is preserved in both the Uinta and Piceance Basins. However, near the mouth of Yellow Creek (fig. 1) in the north-central part of the Piceance Basin, it grades into organically lean marlstone, siltstone, and sandstone. Johnson (1985, 2007) believed that (1) the Mahogany zone graded into clastics in this area due to outflow from Lake Gosiute to the north, and (2) the expansion of the lake during deposition of the Mahogany was caused by the increase in water supplied to Lake Uinta due to this outflow. The Mahogany bed represents the maximum extent of Lake Uinta when oil shale was deposited across nearly all the areas that had previously been marginal lacustrine. Oil yields gradually decline in the Mahogany zone above the Mahogany bed. In the Piceance Basin, the expansion of the oil shale depocenter toward the southeast that began during deposition of the L-5 zone continued with deposition of the rich oil shale of the Mahogany zone across much of the southeastern part of the basin.

The Mahogany zone in the Piceance Basin ranges from 150 to 250 ft thick through a broad northwest-trending belt in the middle of the Piceance Basin (fig. 61). It thins toward the west, south, and east but thickens and grades into marlstone, siltstone, and sandstone near the mouth of Yellow Creek. In the Uinta Basin, thickness of the Mahogany zone is variable and complex (fig. 61). In about the northeastern one-third of the Uinta Basin, the Mahogany zone generally increases in thickness to the north-northeast from about 65 to 160 ft (fig. 61). In the western one-third of the basin, it generally thickens to the north from 106 to more than 300 ft. In the southern part of the basin, where the Mahogany zone is only partially preserved, the remaining unit varies widely ranging from 9 ft thick to as much as 185 ft thick, depending on the thickness of clastic wedges within it (fig. 61). The insertion of these clastic wedges toward the south is marked by a distinct thickening of the Mahogany zone just north of the area where it is only partially preserved (fig. 61).

Oil yield for the Mahogany zone in the Piceance Basin ranges from about 21 to 33 GPT (8 to 12.7 weight percent) throughout the oil shale depocenter (figs. 62 and 63). In-place oil ranges from 200,000 to 427,000 BPA in the richest part of the depocenter with values decreasing in a regular fashion outward (fig. 64). In the Uinta Basin, oil yield reaches a maximum of about 25 GPT (12 weight percent) in the eastern one-third of the basin (figs. 62 and 63). Oil yields gradually decrease to the west-northwest, away from this area, to as little as 3 to 5 GPT (less than 2 weight percent) in the westernmost

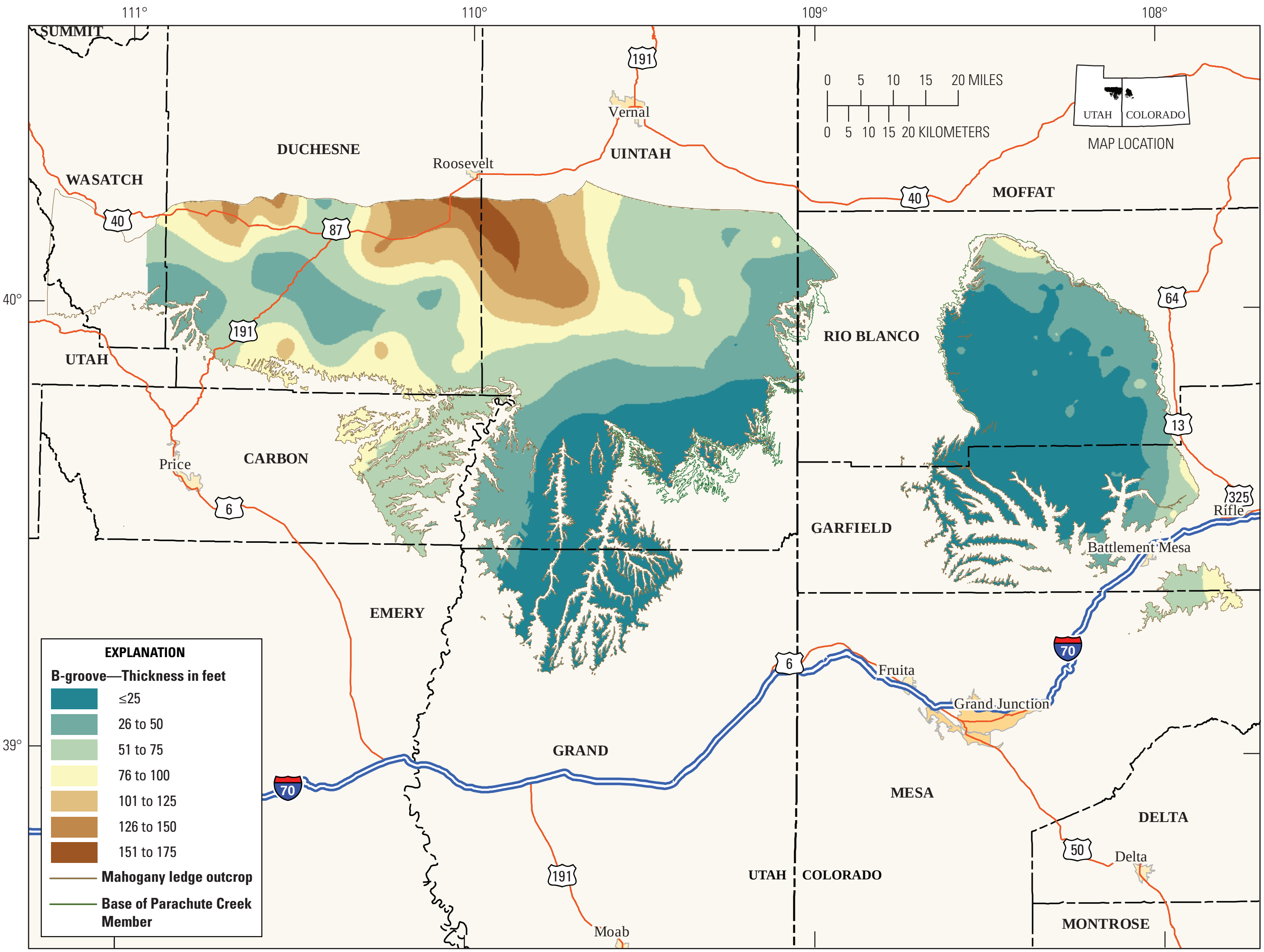


**Figure 57.** Isopach map of B-groove in Uinta and Piceance Basins.

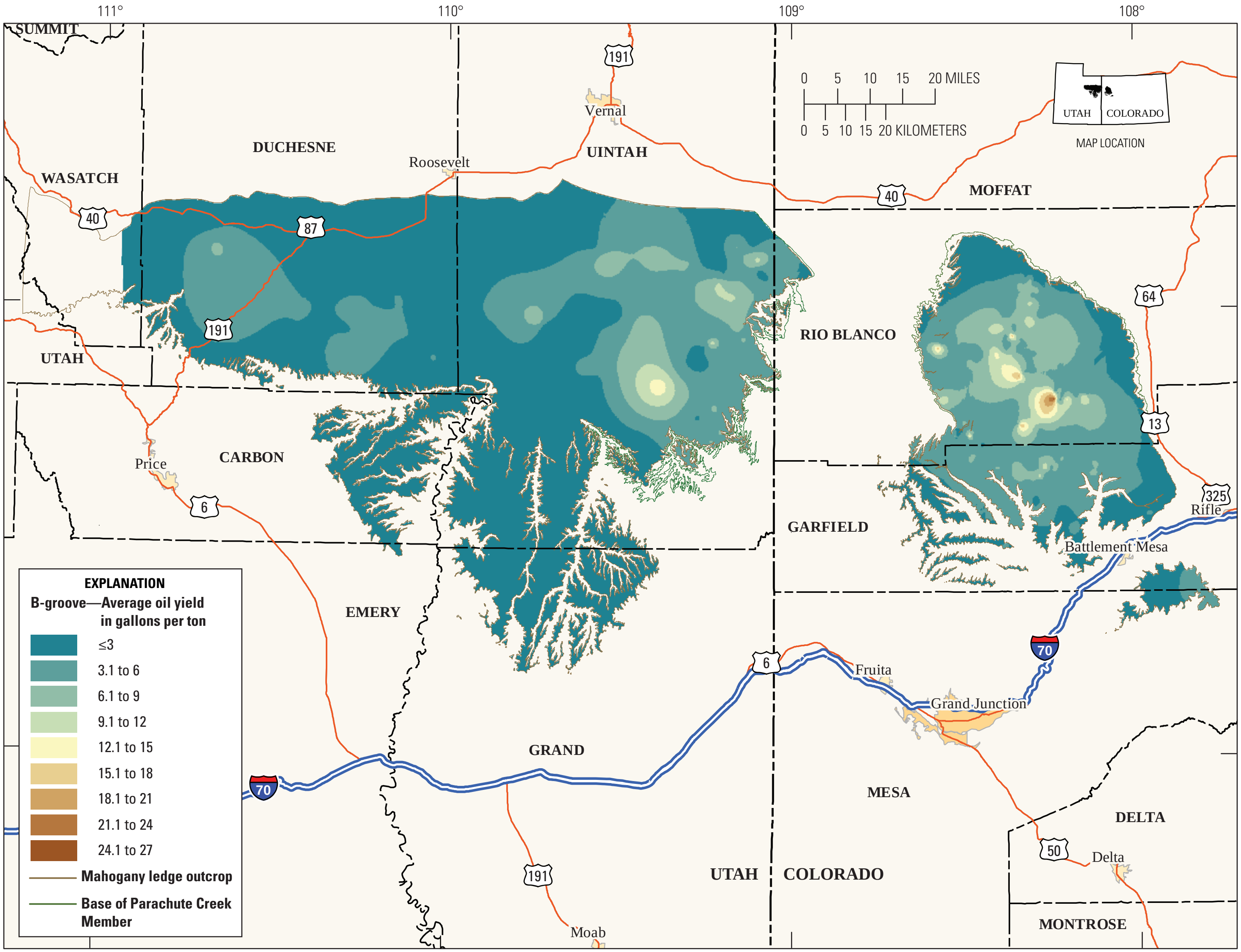


**Figure 58.** Isoresource map of B-groove in Uinta and Piceance Basins showing oil yield in gallons per ton.

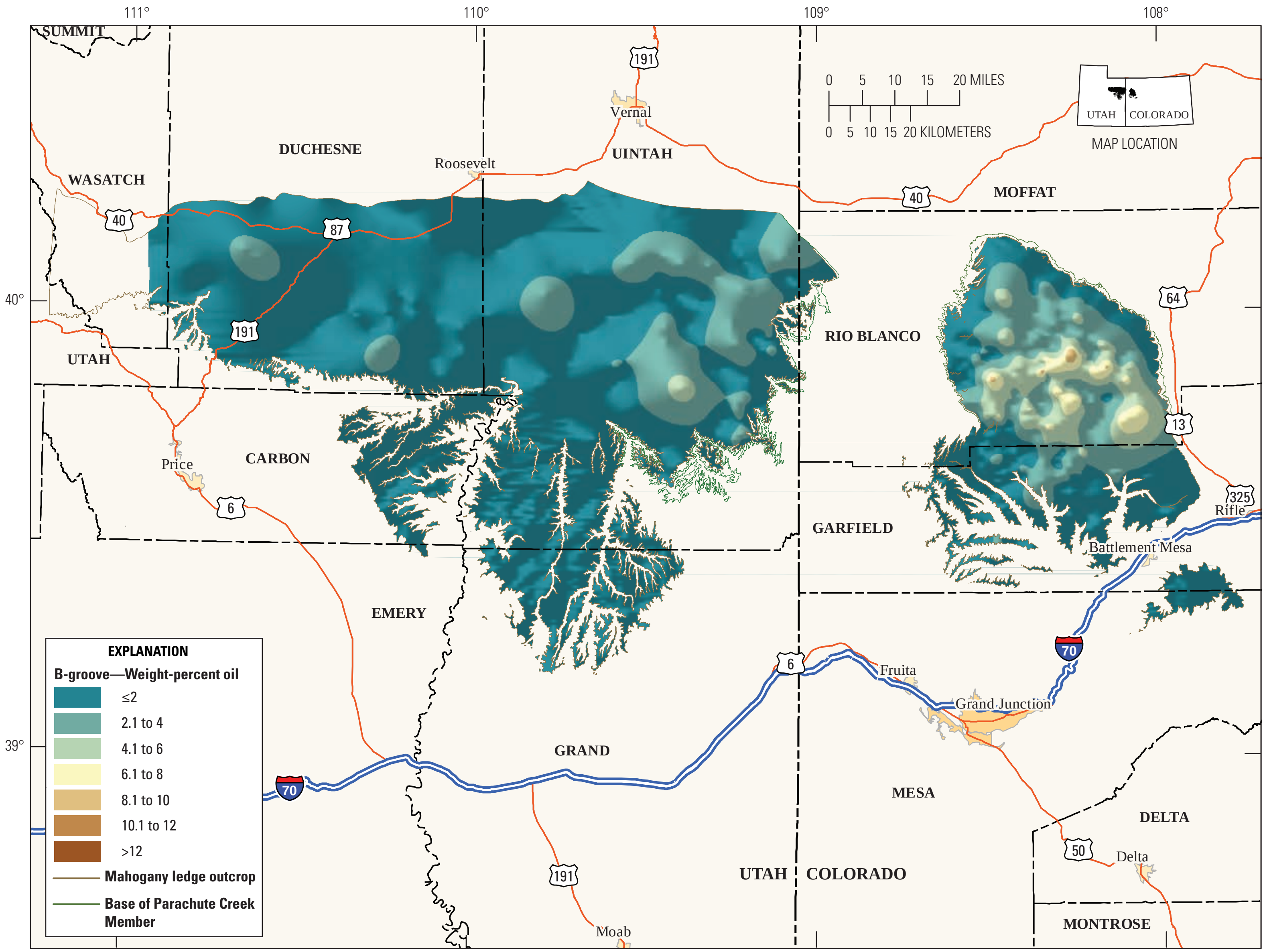


**Figure 59.** Isoresource map of B-groove in Uinta and Piceance Basins showing oil yield in weight percent.

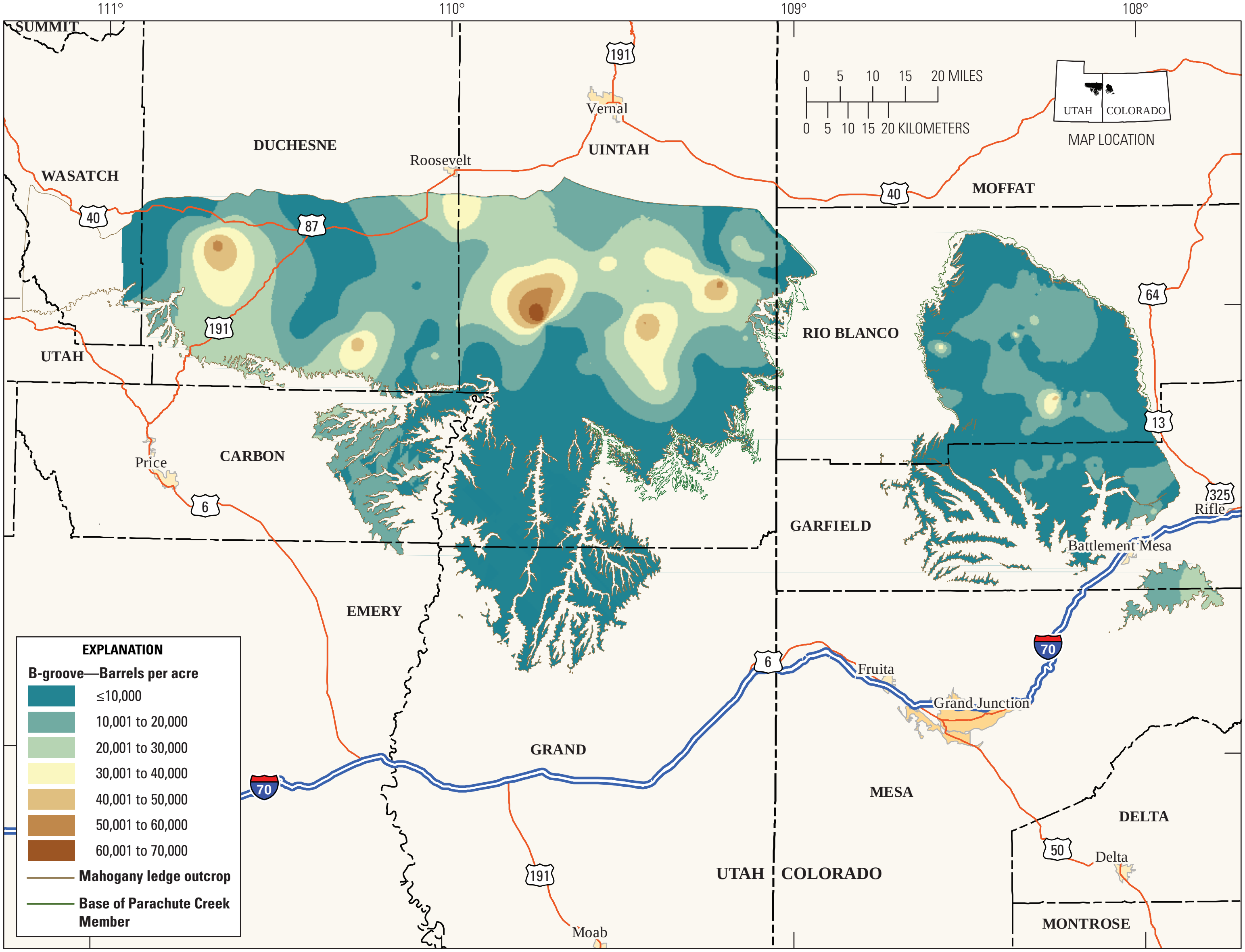


**Figure 60.** Isoresource map of B-groove in Uinta and Piceance Basins showing oil yield in barrels per acre.

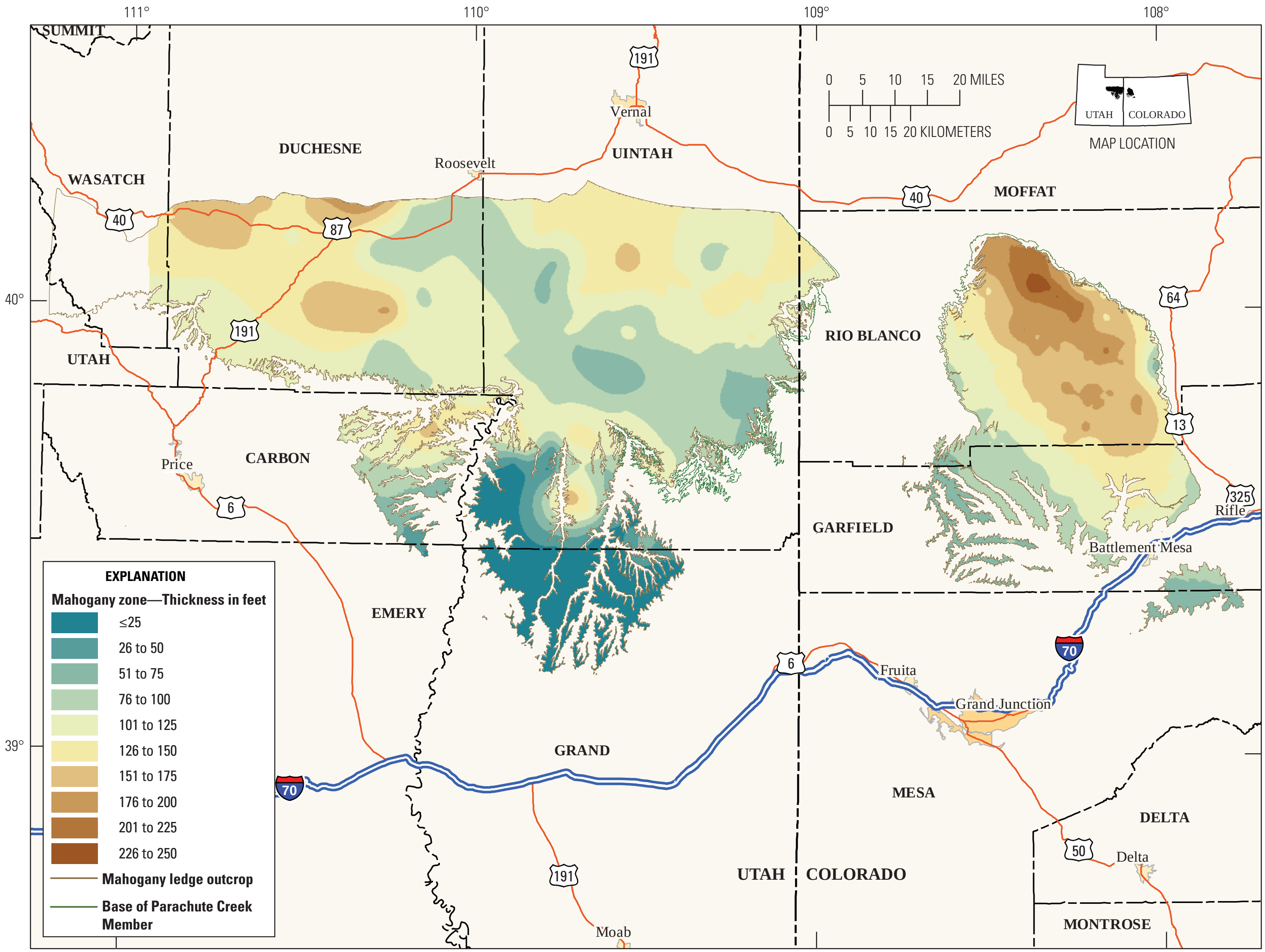


**Figure 61.** Isopach map of Mahogany oil shale zone in Uinta and Piceance Basins.

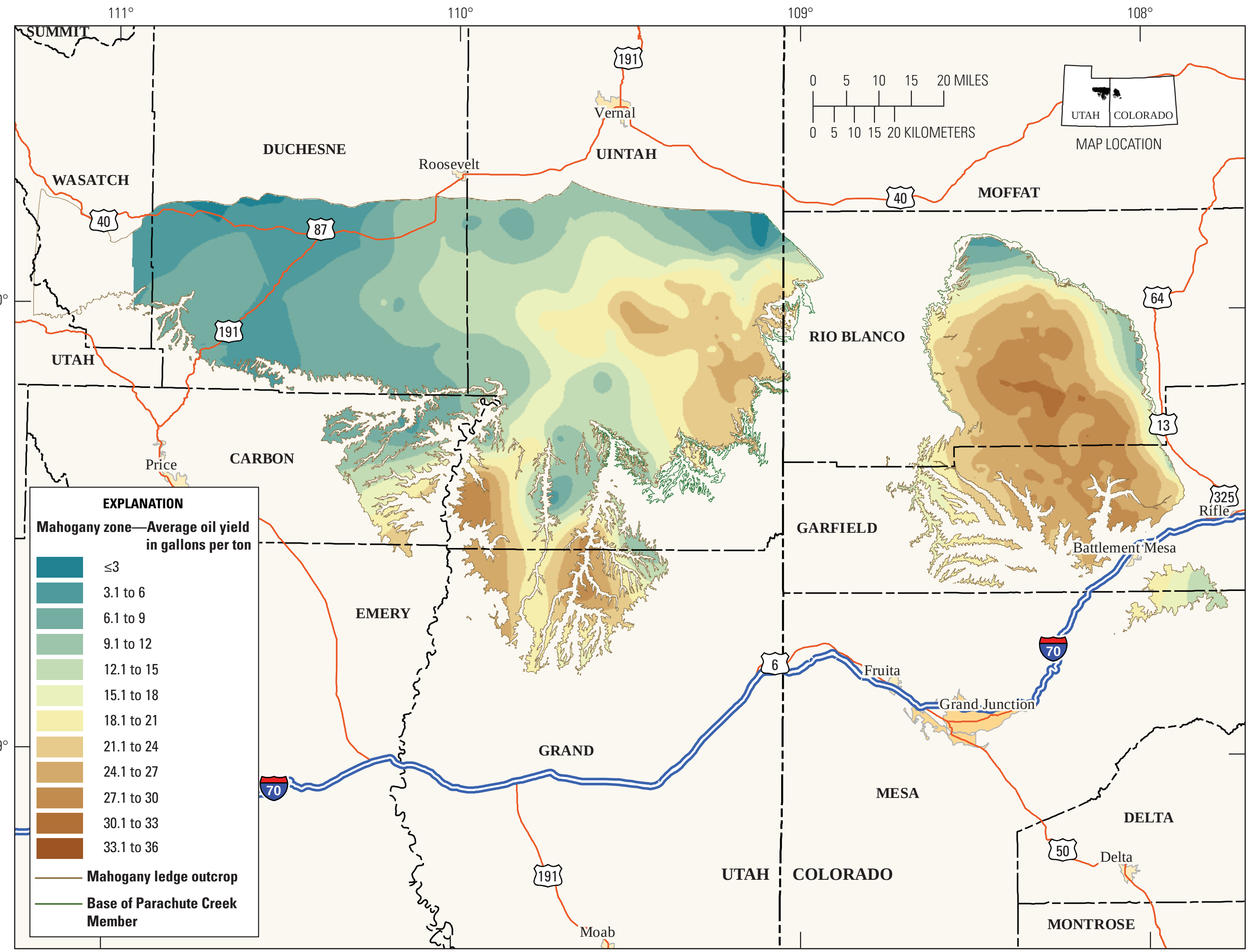


**Figure 62.** Isoresource map of Mahogany oil shale zone in Uinta and Piceance Basins showing oil yield in gallons per ton.

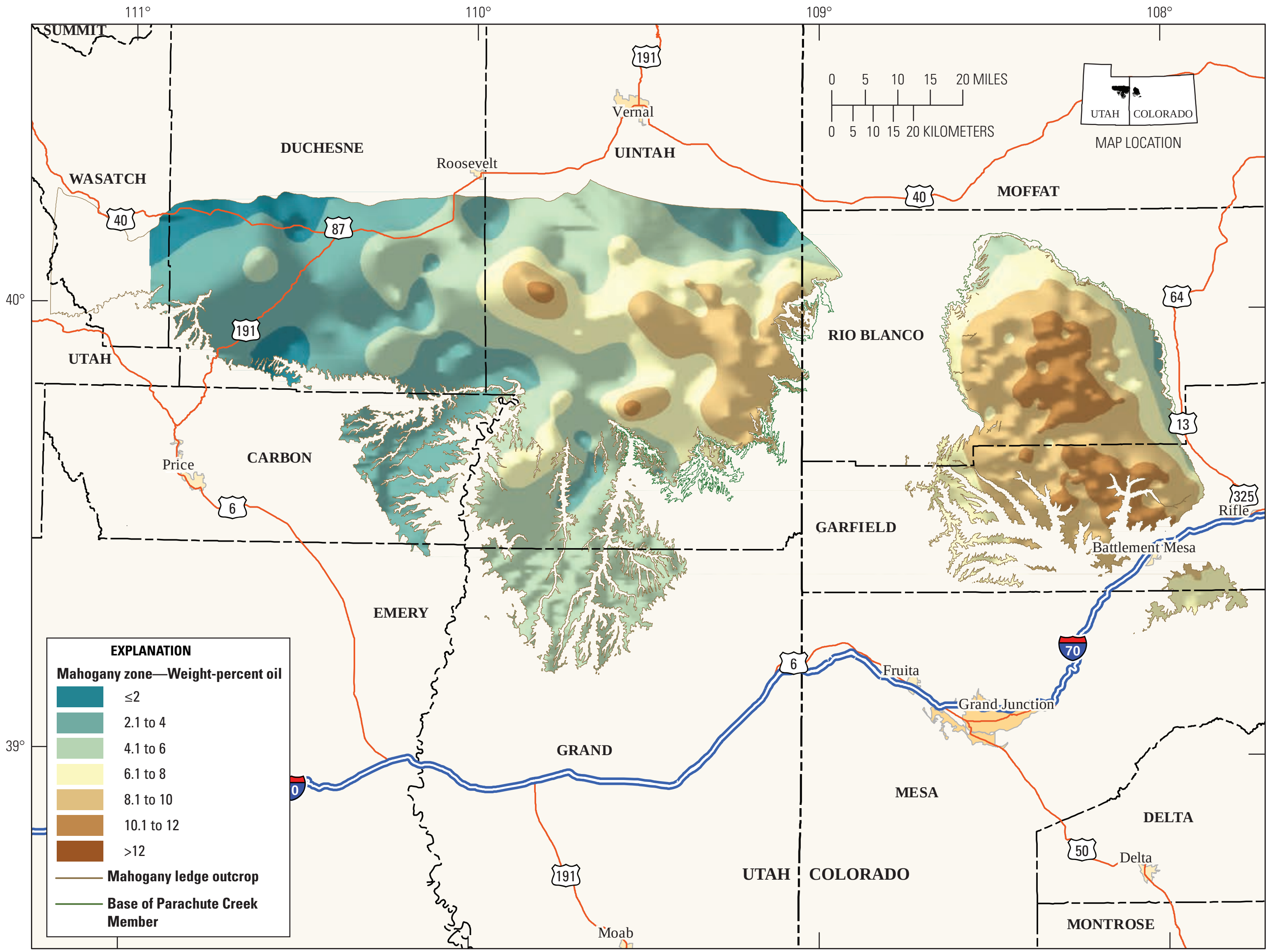


**Figure 63.** Isoresource map of Mahogany oil shale zone in Uinta and Piceance Basins showing oil yield in weight percent.

part of the basin. In the southern part of the Uinta Basin, where the Mahogany zone is split by clastic wedges and only partially preserved, average oil yields vary markedly with lower GPT values in areas where thick clastic wedges are present in the zone. In-place oil ranges from about 120,000 to 230,000 BPA in the depocenter to minimum values of about 25,000 BPA in some areas in the western part of the basin and 3,000 BPA along the south margin (fig. 64).

## A-Groove

A-groove represents another comparatively thin interval, similar to B-groove, that contains low oil yields. A-grove ranges in thickness from 5 to 25 ft throughout most of the Piceance Basin (fig. 65). In the Uinta Basin, A-groove is thickest in a north- to south-trending area in the central part of the basin where it reaches a maximum of 100 ft thick (fig. 65). Oil yields for A-groove in the Piceance Basin range from less than 1 GPT to about 22 GPT (less than 1 to 13.1 weight percent) in a highly irregular fashion (figs. 66 and 67). Total in-place oil also shows a high degree of irregularity, but in general, in-place oil is greatest along approximately the same southeast-trending area where in-place oil was highest for the underlying Mahogany zone (fig. 68). In the Uinta Basin, estimated oil yields range to as much as 14.3 GPT (6 weight percent) in the northeast part of the basin (figs. 66 and 67). In-place oil is as much as 200,000 BPA in the northeast part of the basin (fig. 68).

## The Interval above A-Groove

The interval above A-groove represents the infilling stage of Lake Uinta when the Piceance Basin part of the lake was largely, if not completely, filled in. Thick wedges of volcaniclastic sediments derived from the Absaroka volcanic field in northwestern Wyoming prograded from north to south across the Piceance Basin starting from a point source near the mouth of Yellow Creek in the north-central part of the basin (Johnson, 1981, 1985). The southward progradation of these volcaniclastics occurred over a significant period of time with intervals of oil shale deposited during periods when the rate of volcaniclastics supplied to the basin from the north diminished or ceased entirely. These oil shale intervals coalesce toward the south end of the Piceance Basin as the intervening clastic wedges pinch out resulting in a nearly continuous interval of oil shale several hundred feet thick in the southern part of the basin.

Only the interval from the top of A-groove to the top of bed 44 of Donnell (2008) is presented here because it is the highest oil shale zone assessed by Johnson, Mercier, Brownfield, and others (2010) and Johnson, Mercier, Brownfield, and Self (2010) in both the Uinta and Piceance Basins. A higher interval from the top of bed 44 to the top of bed 76 was assessed in the Uinta Basin but not in the Piceance, because it is present in only a limited area in the southern part of that basin. In the Piceance Basin, the interval from the top of A-groove to the top of bed 44 thickens from about 150 ft along the southwest margin of the basin to over 1,500 ft in the north-central part of the basin (fig. 69) where it consists of predominantly volcaniclastic sandstone with a few thin zones of marlstone. In the Uinta Basin, the interval from the top of A-groove to top of bed 44 thickens to the west-northwest from about 135 to 170 ft along the west flank of the Douglas Creek arch, to 270 ft thick in the northeastern part of the basin, and to 500 ft in the northwestern part (fig. 69).

Estimated oil yield for the interval from the top of A-groove to the top of bed 44 in the Piceance Basin ranges from about 16 GPT to 22 GPT (4 to 6.9 weight percent) throughout much of the south-central part of the basin. Oil yields drop off rapidly to the north as the interval becomes intertongued with the Uinta Formation but more gradually to the east, south, and west, due to an overall decrease in oil yields (figs. 70 and 71). In-place oil in the Piceance Basin ranges from 375,000 to 475,000 BPA in this area and diminishes in a more or less radial pattern outward (fig. 72). In the Uinta Basin, estimated oil yield throughout much of the northeastern part of the basin ranges from about 10 to 14.3 GPT (4 to 6 weight-percent oil) and decreases to the northeast, south, and west (figs. 70 and 71). In the Uinta Basin, in-place oil for the interval from the top of A-groove to the top of bed 44 ranges from about 120,000 to 200,000 BPA in the depocenter with values decreasing markedly away from that area (fig. 72).

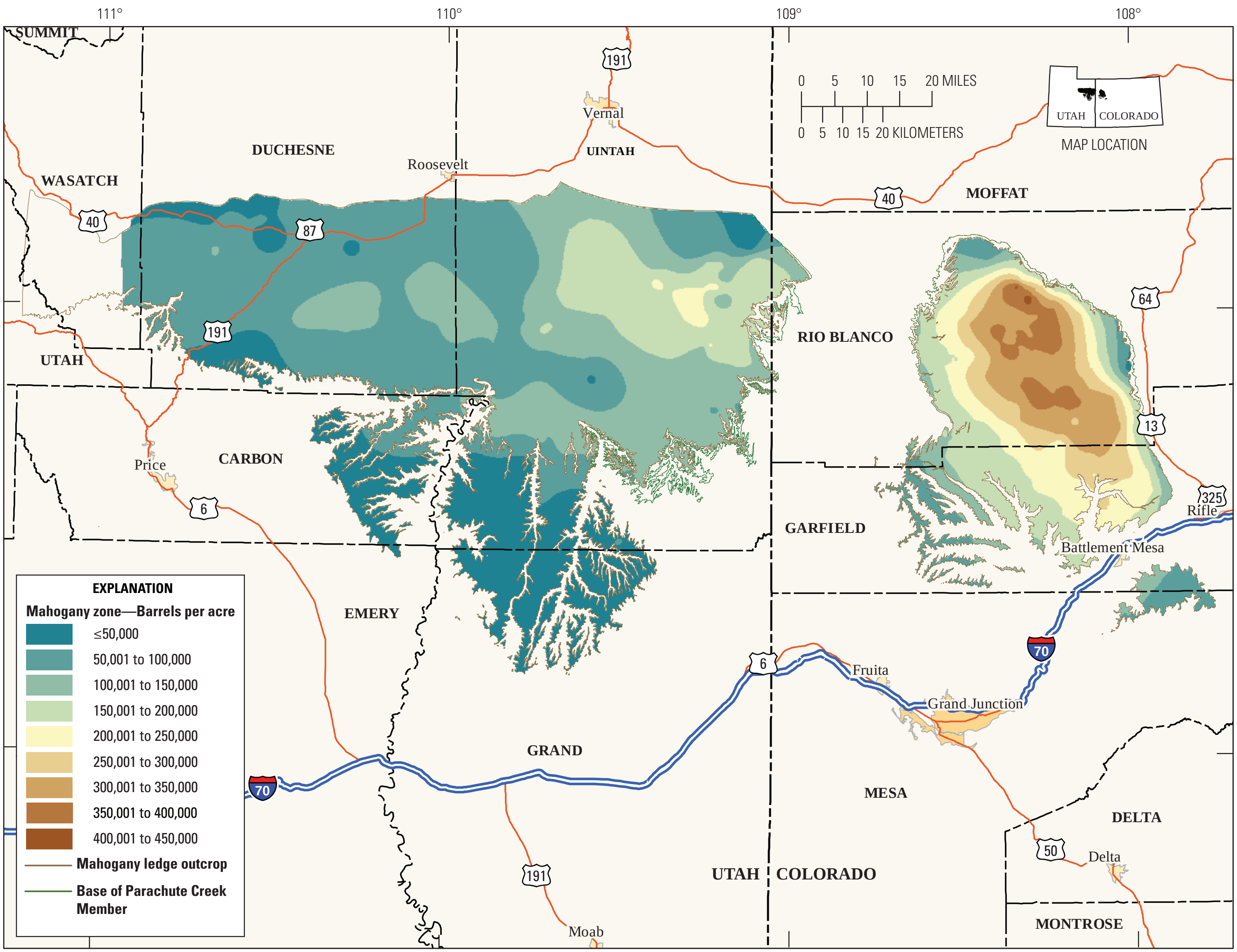


**Figure 64.** Isoresource map of Mahogany oil shale zone in Uinta and Piceance Basins showing oil yield in barrels per acre.

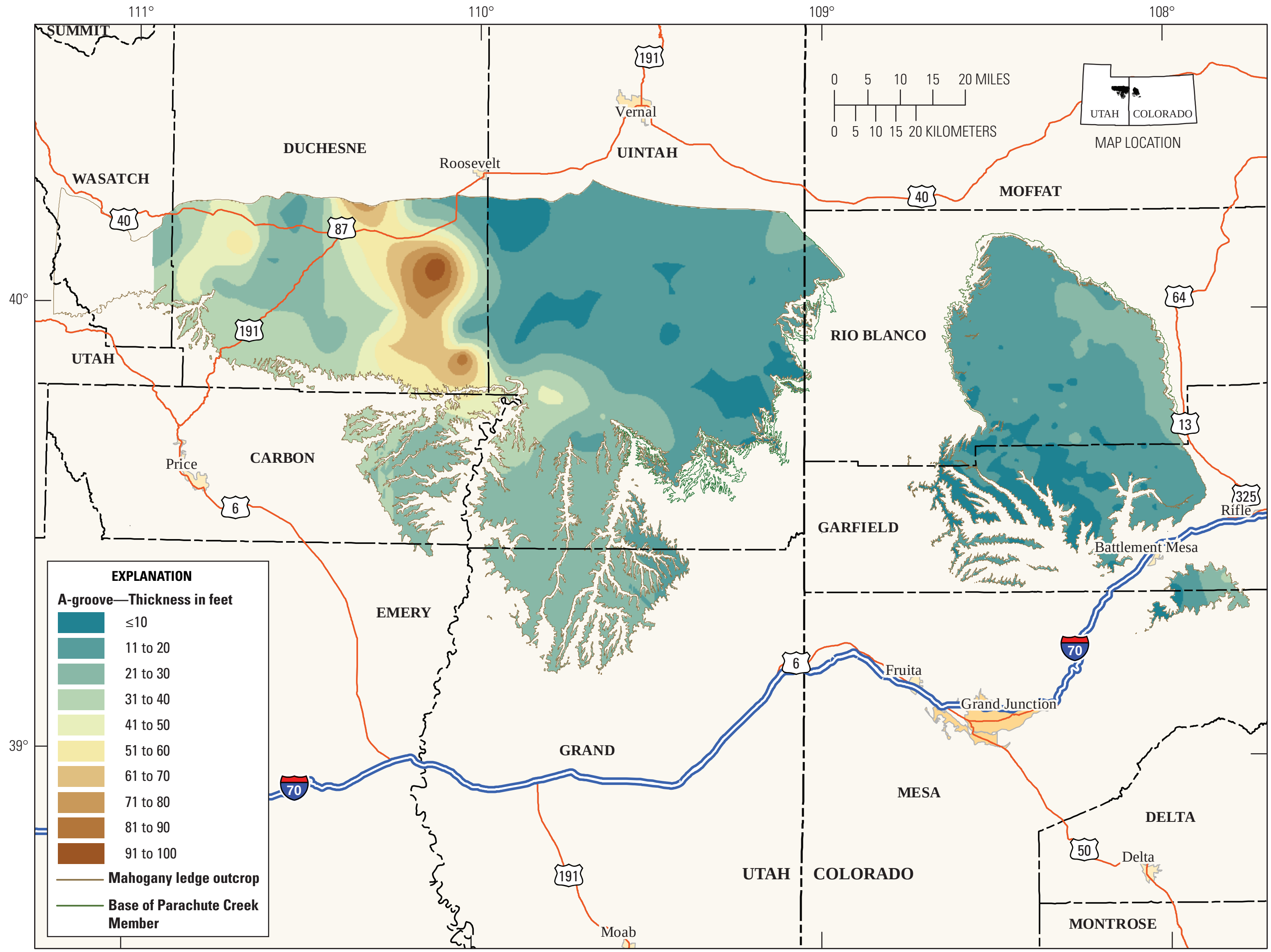


**Figure 65.** Isopach map of A-groove in Uinta and Piceance Basins.

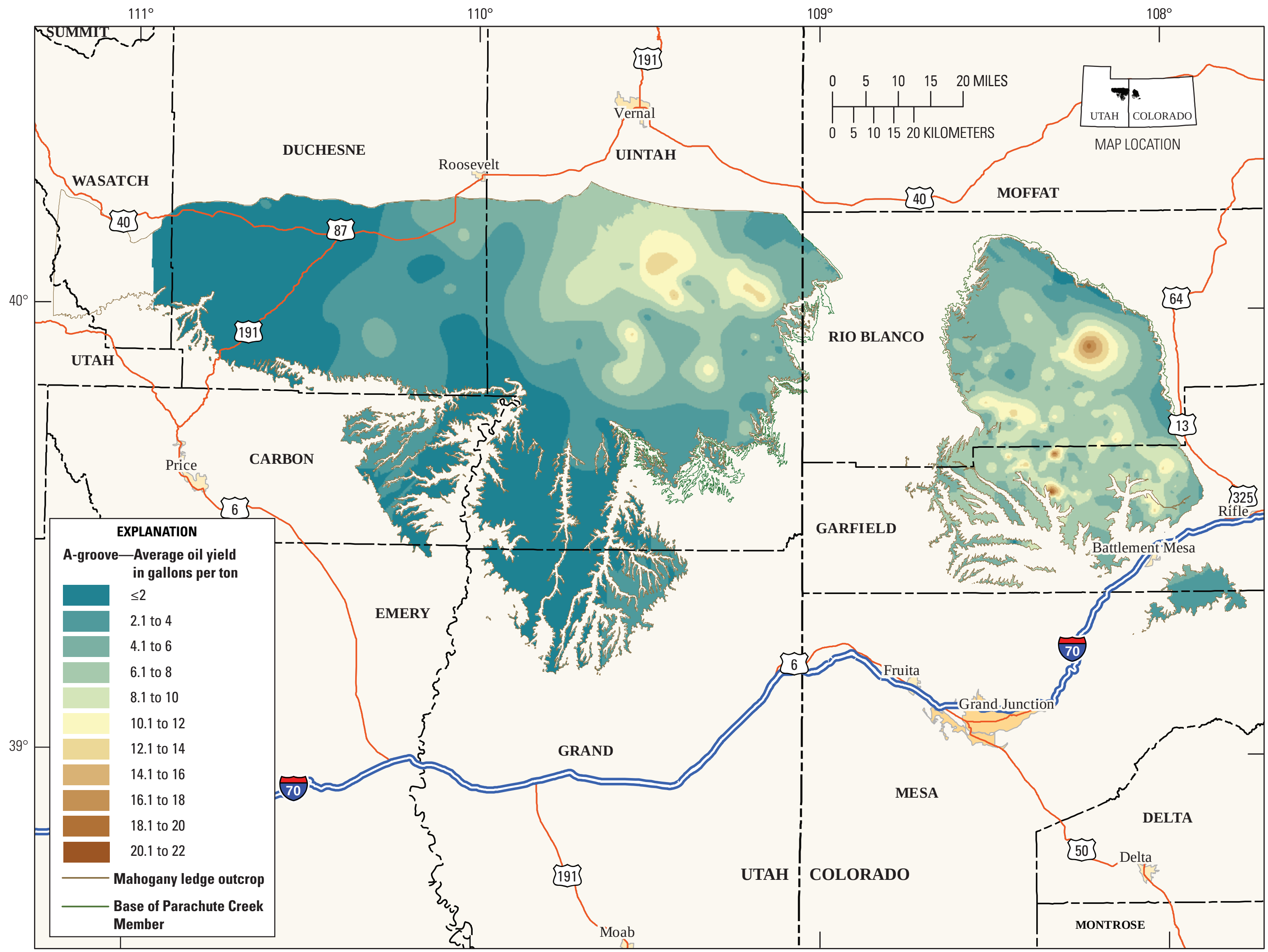


**Figure 66.** Isoresource map of A-groove in Uinta and Piceance Basins showing oil yield in gallons per ton.

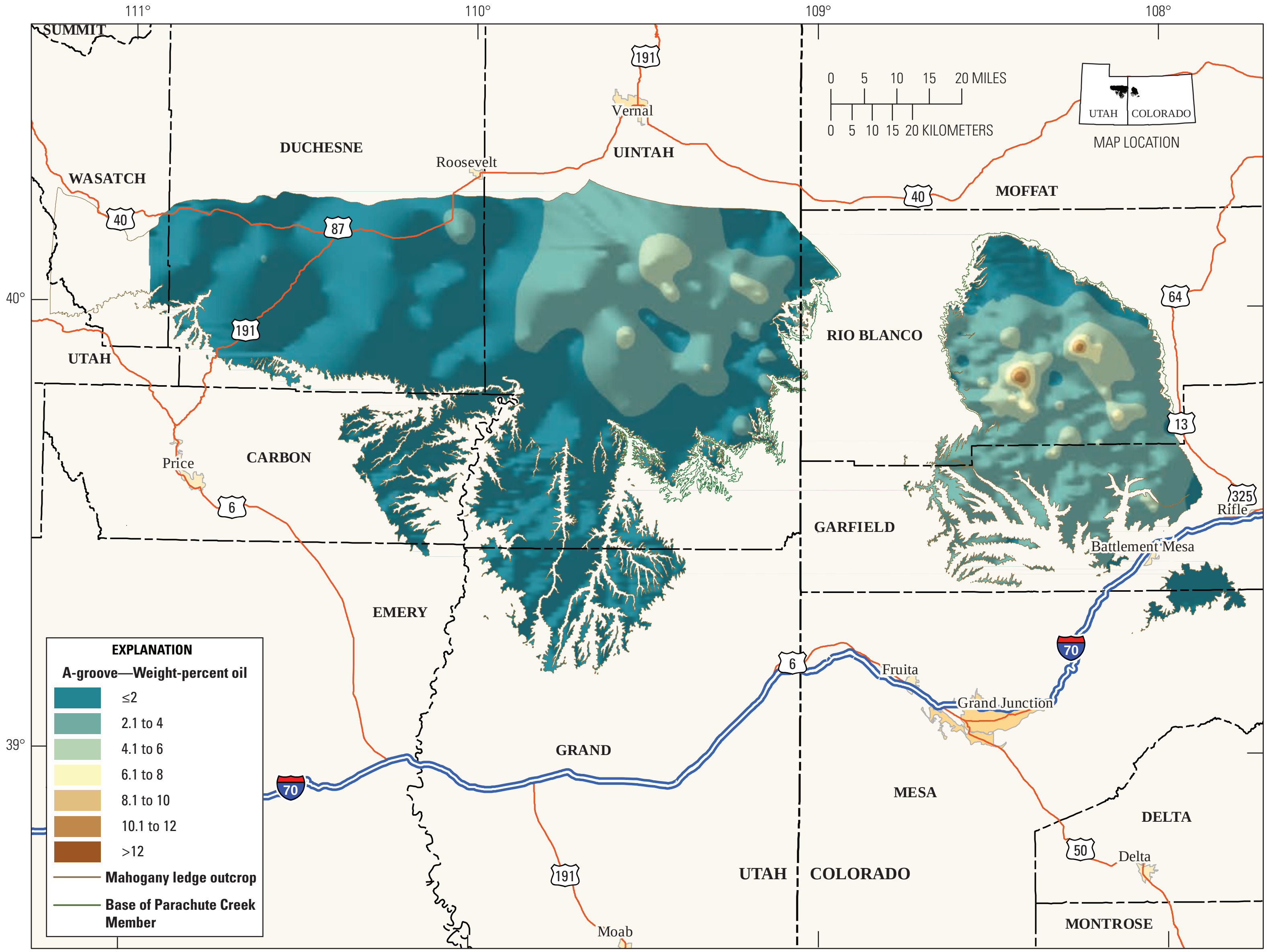


**Figure 67.** Isoresource map of A-groove in the Uinta and Piceance Basins showing oil yield in weight percent.

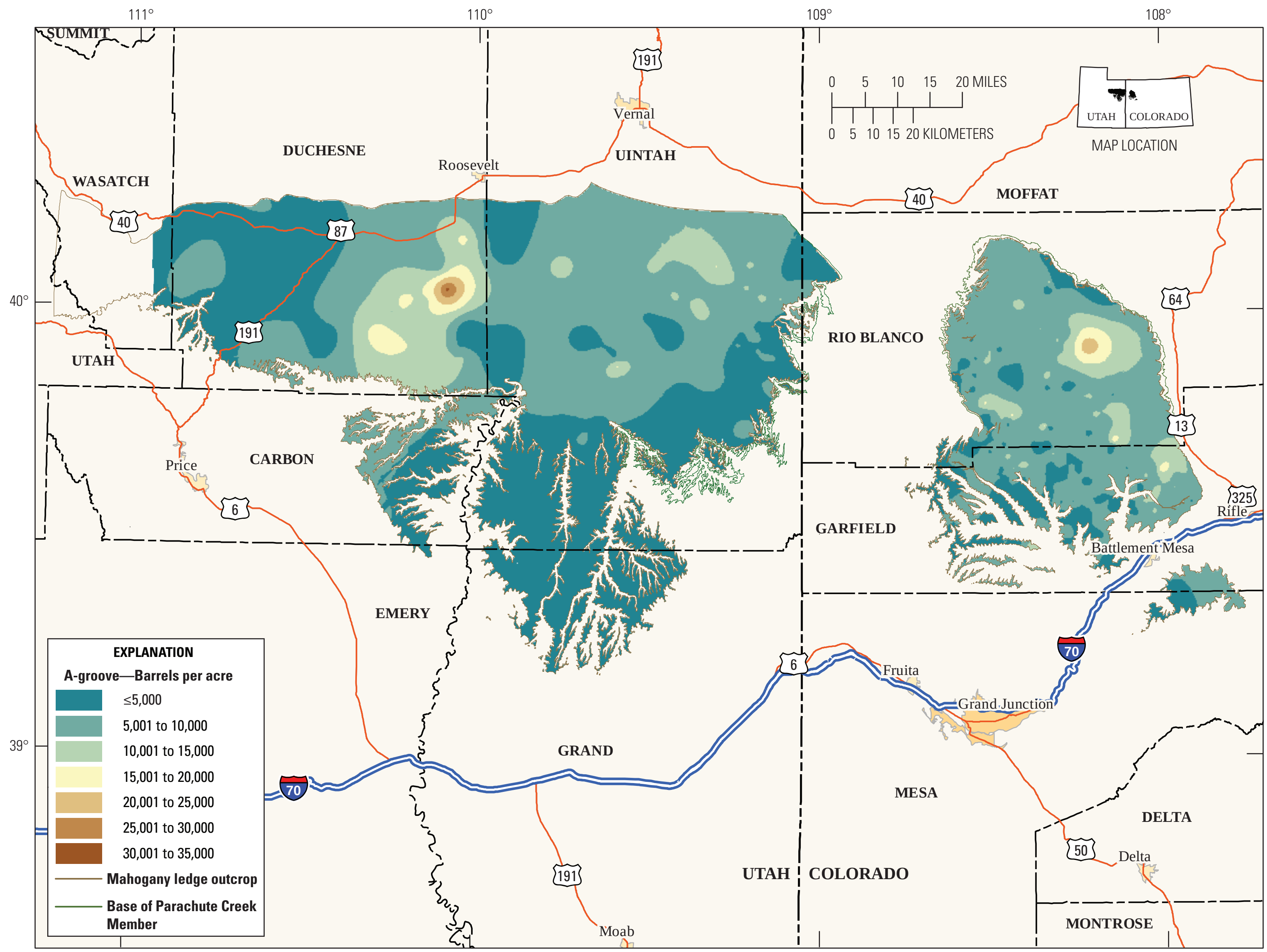


**Figure 68.** Isoresource map of A-groove in Uinta and Piceance Basins showing oil yield in barrels per acre.

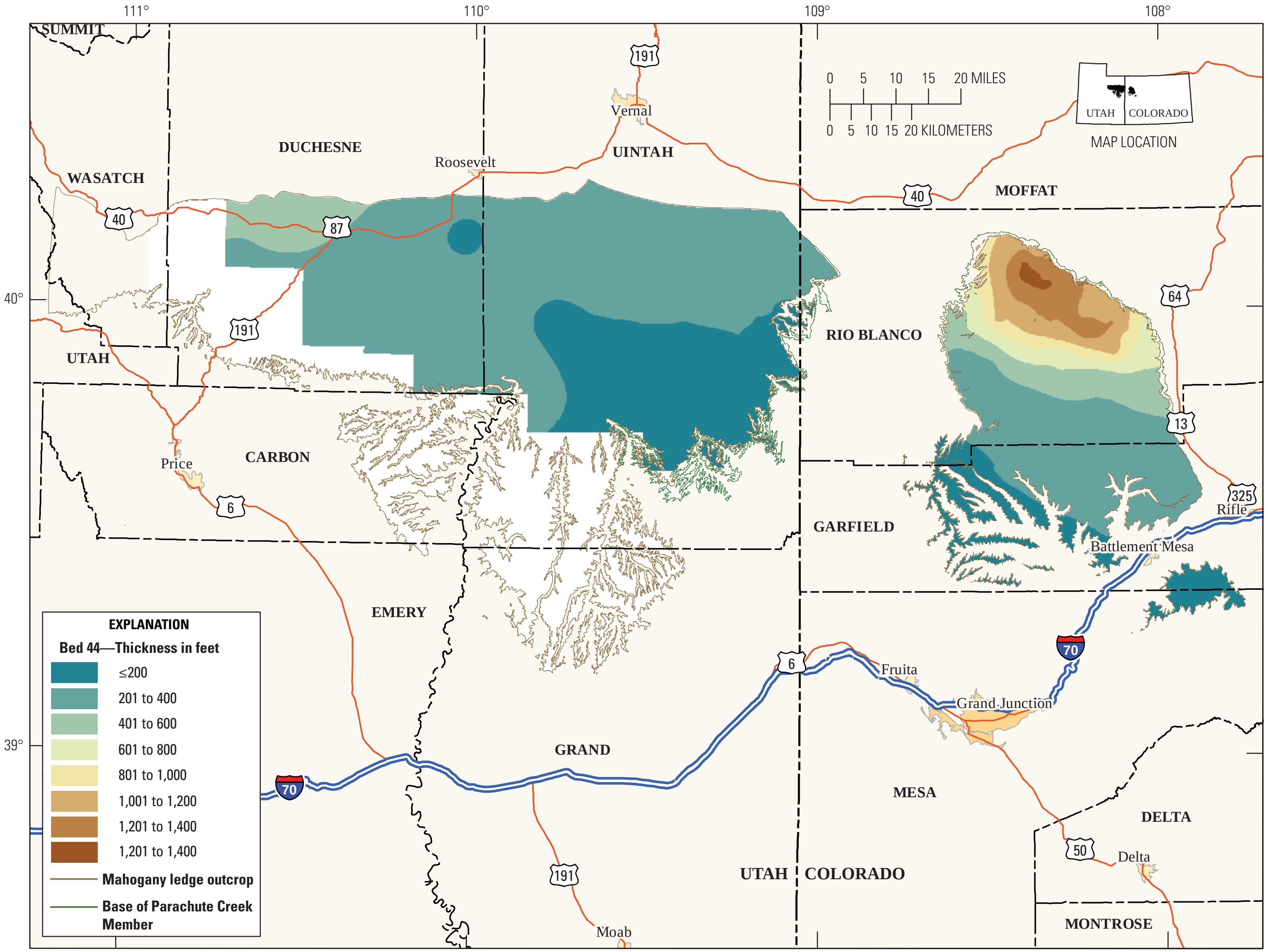


**Figure 69.** Isopach map of bed 44 to A-groove in Uinta and Piceance Basins.

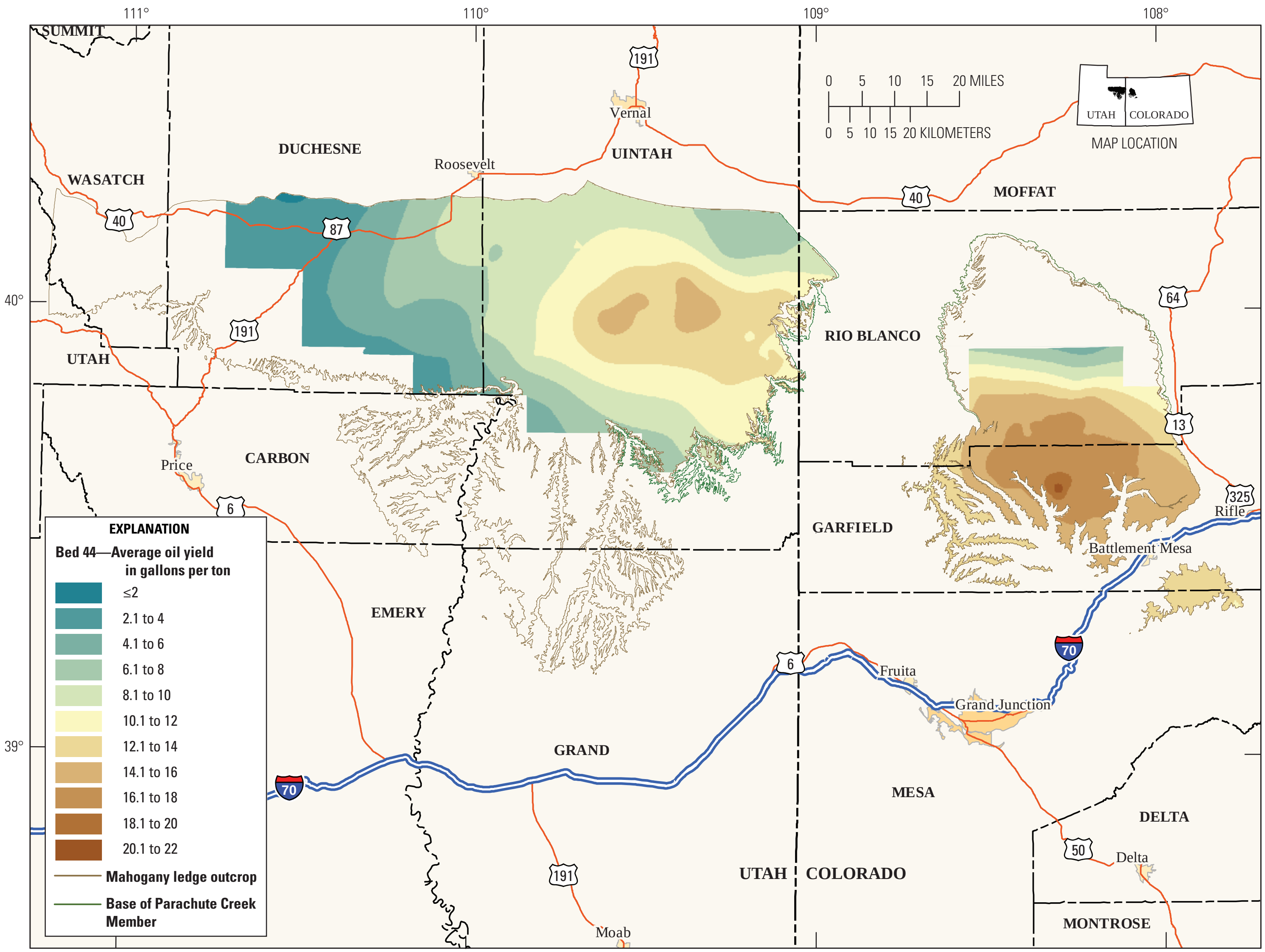


**Figure 70.** Isoresource map of bed 44 to A-groove in Uinta and Piceance Basins showing oil yield in gallons per ton.

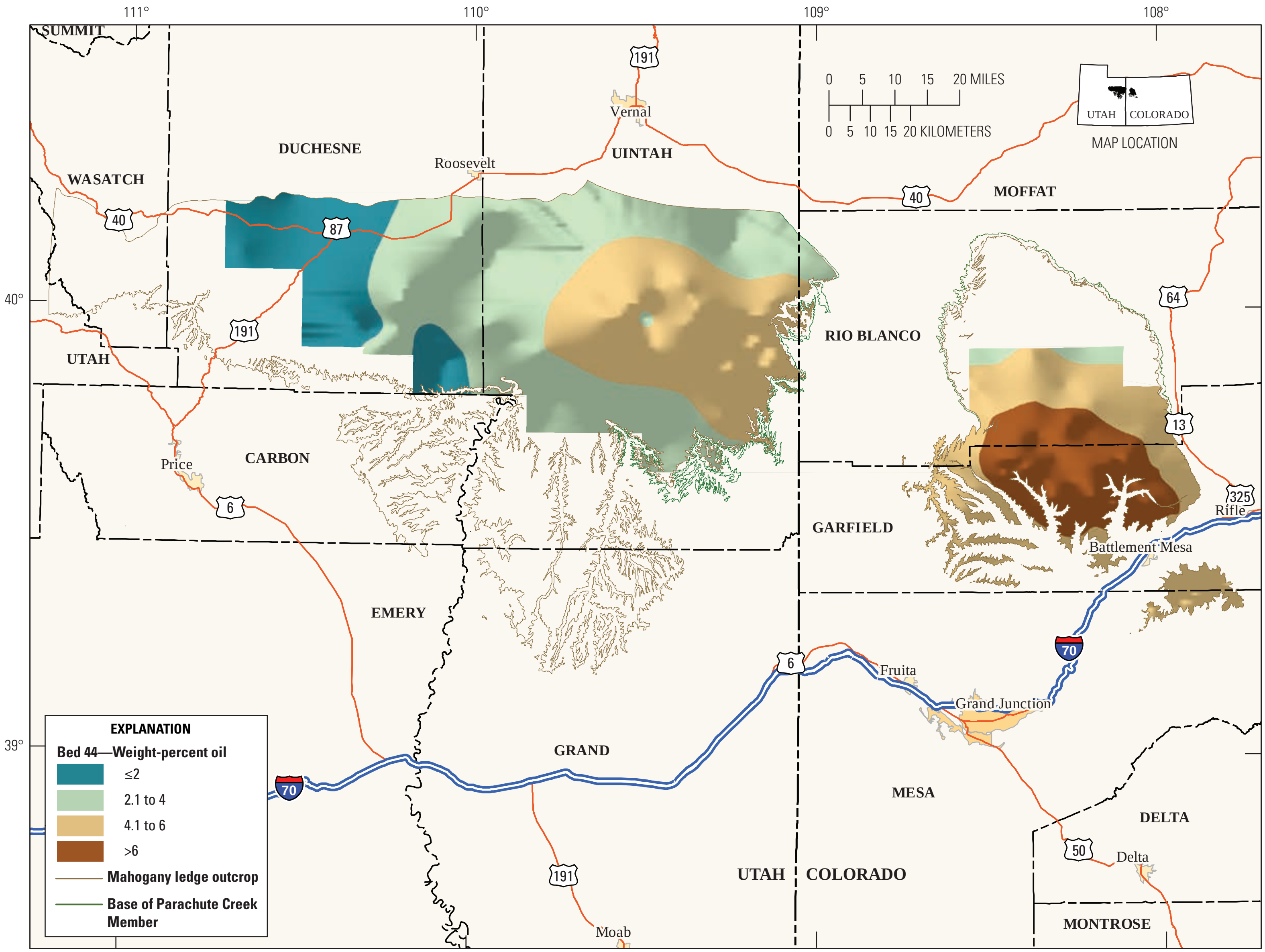


**Figure 71.** Isoresource map of bed 44 to A-groove in Uinta and Piceance Basins showing oil yield in weight percent.

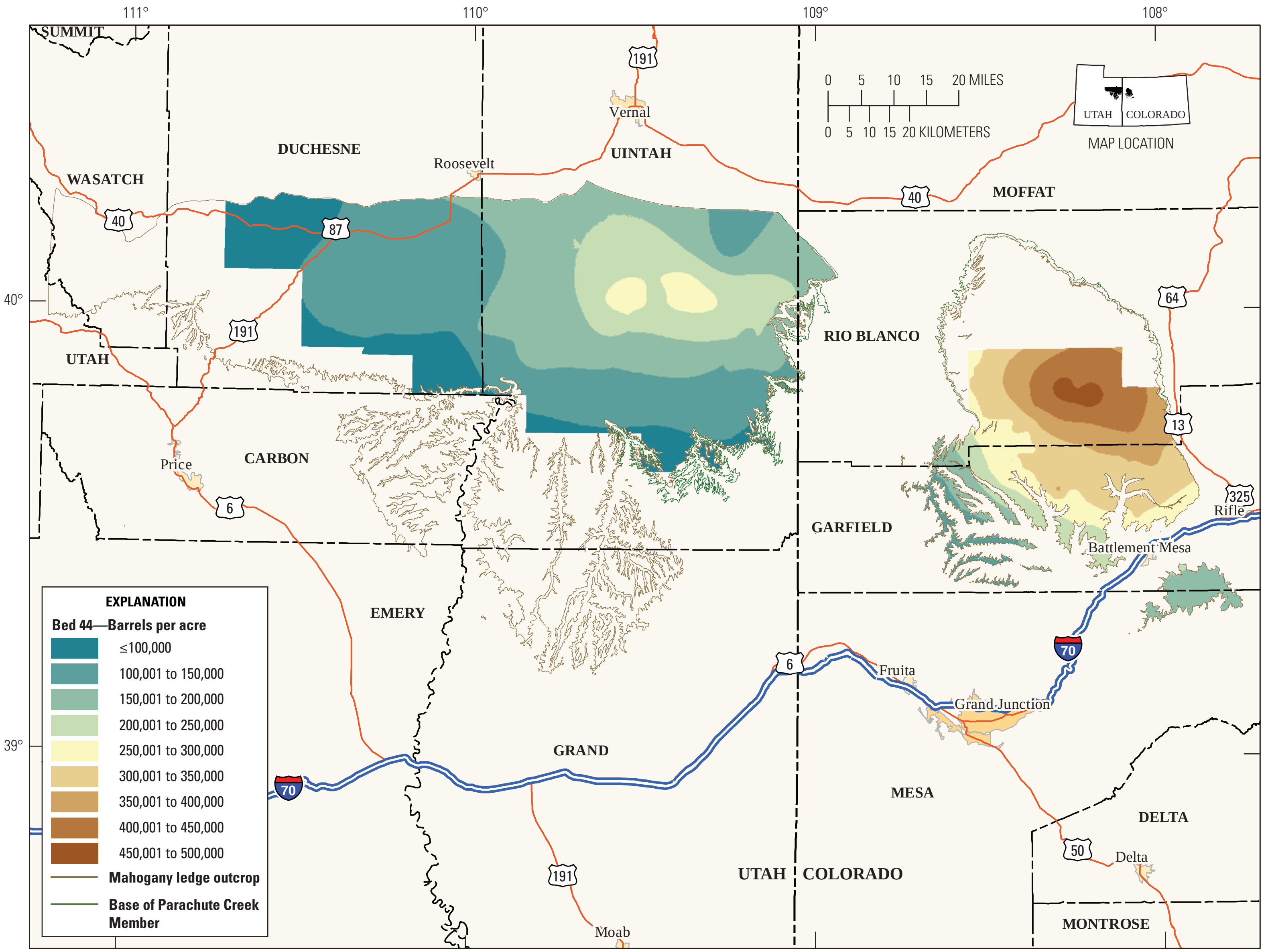


**Figure 72.** Isoresource map of bed 44 to A-groove in Uinta and Piceance Basins showing oil yield in barrels per acre.

# Discussion

The total in-place resource for the Uinta Basin of 1.32 trillion barrels of oil is only slightly lower than the total of 1.53 trillion barrels of in-place resource for the Piceance Basin, which is thought to contain the richest oil shale deposit in the world. However, the area underlain by oil shale in the Uinta Basin is much larger than that of the Piceance Basin, with the Mahogany zone underlying 3,834 $mi^2$ of the Uinta Basin as compared to 1,335 $mi^2$ in the Piceance Basin. Average GPT and BPA values for each oil shale zone assessed are significantly lower in the Uinta Basin than in the Piceance Basin.

The oil shale and saline mineral depocenter throughout much of the history of Lake Uinta was in the north-central part of the Piceance Basin, and this depocenter is clearly defined on all GPT, weight percent, and BPA maps, including the R-0 zone, the first zone deposited after Lake Uinta formed (figs. 6 to 8). The depocenter is considerably west of the rapidly subsiding trough of the basin (pl. 1), and Johnson (1985) hypothesized that sediment eroded off the rising White River uplift east of the basin pushed the lake west of the basin trough. The area of richest oil shale in the Uinta Basin, as measured by GPT, weight percent, and BPA, is generally in the northeast part adjacent to the crest of the Douglas Creek arch, in a west- to northwest-trending area that is nearly perpendicular to subsidence trends at that time (fig. 4). This is the only area of the Uinta Basin where all of the rich and lean oil shale zones, originally defined in the Piceance Basin, can be identified. This area is also distant from sources of clastic influx, such as the Uinta Mountains to the north, the Sevier orogenic belt to the west, and a major river system that entered the lake from the south (fig. 4).

# References Cited


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

Bradley, W.H., 1931, Origin and microfossils of the oil shale of the Green River Formation of Colorado and Utah: U.S. Geological Survey Professional Paper 168, 58 p.

Brownfield, M.E., Mercier, T.J., Johnson, R.C., and Self, J.G., 2010, Nahcolite resources in the Green River Formation, Piceance Basin, Colorado, chap. 2 *of* U.S. Geological Survey Oil Shale Assessment Team, Oil shale and nahcolite resources of the Piceance Basin, Colorado: U.S. Geological Survey Digital Data Series DDS–69–Y, 51 p.

Brownfield, M.E., Johnson, R.C., and Dyni, J.R., 2010, Sodium carbonate resources of the Eocene Green River Formation, Uinta Basin, Utah and Colorado, chap. 2 *of* U.S. Geological Survey Oil Shale Assessment Team, Oil shale resources of the Uinta Basin, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–BB, 13 p.

Cashion, W.B., 1967, Geology and fuel resources of the Green River Formation, southeastern Uinta Basin, Utah and Colorado: U.S. Geological Survey Professional Paper 548, 48 p.

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

Cashion, W.B., 1977, Geologic map of the Weaver Ridge quadrangle, Utah and Colorado: U.S. Geological Survey Miscellaneous Field Investigations Map MF–824, scale 1:24,000.

Cashion, W.B., 1978, Geologic map of the Wash Knolls quadrangle, Uintah County, Utah, and Rio Blanco County, Colorado: U.S. Geological Survey Miscellaneous Field Investigations Map MF–1013, scale 1:24,000.

Cashion, W.B., 1986, Geologic map of the Bonanza quadrangle, Uintah County, Utah: U.S. Geological Survey Miscellaneous Field Investigations Map MF–1865, scale 1:24,000.

Cashion, W.B., and Donnell, J.R., 1972, Chart showing correlation of selected key units in the organic-rich sequence of the Green River Formation, Piceance Creek Basin, Colorado, and Uinta Basin, Utah: U.S. Geological Survey Oil and Gas Investigations Chart OC–65.

Cashion, W.B., and Donnell, J.R., 1974, Revision of nomenclature of the upper part of the Green River Formation, Piceance Creek Basin, Colorado, and Eastern Uinta Basin, Utah: U.S. Geological Survey Bulletin 1394–G, 9 p.

Chancellor, R.E., Barksdale, W.L., and Dolezal, George, Jr., 1974, Occurrence of oil and gas in the Tertiary System, Rio Blanco unit, Rio Blanco County, Colorado, *in* Murray, D.K., ed., Guidebook to the energy resources of the Piceance Creek Basin, Colorado: Rocky Mountain Association of Geologists, 25th Field Conference, p. 225–233.

Dane, C.H., 1954, Stratigraphic and facies relationships of upper part of Green River Formation and lower part of Uinta Formation in Duchesne, Uintah, and Wasatch Counties, Utah: American Association of Petroleum Geologists Bulletin v. 38, no. 3, p. 405–425.

Dane, C.H., 1955, Stratigraphic and facies relationships of upper part of Green River Formation and lower part of Uinta Formation in Duchesne, Uinta, and Wasatch Counties, Utah: U.S. Geological Survey Oil and Gas Chart OC–52.

Donnell, J.R., 1961, Tertiary geology and oil-shale resources of the Piceance Creek Basin between the Colorado and White Rivers, northwestern Colorado: U.S. Geological Survey Bulletin 1082–L, 56 p.

Donnell, J.R., 2008, Intertonguing of the lower part of the Uinta Formation with the upper part of the Green River Formation in the Piceance Creek Basin during the late stages of Lake Uinta: U.S. Geological Survey Scientific Investigation Report 2008–5237, 25 p.

Dyni, J.R., 1974, Stratigraphy and nahcolite resources of the saline facies of the Green River Formation in northwest Colorado, *in* Murray, D.K., ed., Guidebook to the energy resources of the Piceance Creek Basin, Colorado: Rocky Mountain Association of Geologists 25th Field Conference, p. 111–122.

Dyni, J.R., 1981, Geology of the nahcolite deposits and associated oil shales of the Green River Formation in the Piceance Creek Basin, Colorado: Boulder, University of Colorado, Ph.D. dissertation, 144 p.

Dyni, J.R., 1996, Sodium carbonate resources of the Green River Formation: U.S. Geological Survey Open-File Report 96–729, 39 p.

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

Fouch, T.D., 1975, Lithofacies and related hydrocarbon accumulations in Tertiary strata of the western and central Uinta Basin, Utah, *in* Bolyard, D.W., ed., Deep drilling frontiers of the central Rocky Mountains: Rocky Mountain Association of Geologists 1975 Symposium, p. 163–173.

Johnson, R.C., 1981, Stratigraphic evidence for a deep Eocene Lake Uinta, Piceance Creek Basin, Colorado: Geology, v. 9, p. 55–62.

Johnson, R.C., 1984, New names for units in the lower part of the Green River Formation, Piceance Creek Basin, Colorado: U.S. Geological Survey Bulletin 1529–I, p. I1–I20.

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

Johnson, R.C., 1989, Detailed cross section correlating the Upper Cretaceous and lower Tertiary rocks between the Uinta Basin of eastern Utah and western Colorado and the Piceance Basin of western Colorado: U.S. Geological Survey Miscellaneous Investigations Map I–1974, 2 sheets.

Johnson, R.C., 2007, The outflow of Eocene Lake Gosiute into Lake Uinta and its effects on sedimentation in Lake Uinta in the Piceance Basin of western Colorado [abs.]: American Association of Petroleum Geologists Rocky Mountain Section Meeting, Snowbird, Utah, Oct. 7–9, 2007, Program, p. 43.

Johnson, R.C., and Finn, T.M., 1986, Cretaceous through Holocene history of the Douglas Creek arch, Colorado and Utah, *in* Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists Guidebook, p. 77–95.

Johnson, R.C., Mercier, T.J., Brownfield, M.E., and Self, J.G., 2011, Assessment of in-place oil shale resources of the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah, chap. 1 *of* U.S. Geological Survey Oil Shale Assessment Team, Oil Shale Resources of the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–DD, 63 p.

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

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

Johnson, R.C., Nichols, D.J., and Hanley, J.H., 1988, Stratigraphic sections of lower Tertiary strata and charts showing palynomorph and mollusk assemblages, Douglas Creek arch area, Colorado and Utah: U.S. Geological Survey Miscellaneous Field Investigations Map MF–1997.

Johnson, R.C., and Roberts, S.B., 2003, The Mesaverde Total Petroleum System, Uinta-Piceance Province, Utah and Colorado, chap.7 *of* USGS Uinta-Piceance Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, 63 p.

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

Mercier, T.J., Brownfield, M.E., and Johnson, R.C., 2010, Methodology for calculating oil shale and nahcolite resources for the Piceance Basin, chap. 3 *of* U.S. Geological Survey Oil Shale Assessment Team, Oil shale and nahcolite resources of the Piceance Basin, Colorado: U.S. Geological Survey Digital Data Series DDS–69–Y, 61 p.

Pipiringos, G.N., 1978, Preliminary geologic map of the Bates Knolls quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Investigations Map MF–1025, scale 1:24,000.

Pipiringos, G.N., and Johnson, R.C., 1976, Preliminary geologic map and correlation diagram of the White River City quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey Miscellaneous Field Investigations Map MF–736, scale 1:24,000.

Pitman, J.K., Pierce, F.W., and Grundy, W.D., 1989, Thickness, oil-yield, and kriged resource estimates for the Eocene Green River Formation, Piceance Creek Basin, Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC–132, scale 1:250,000.

Robb, W.A., and Smith, J.W., 1974, Mineral profile of oil shales in Colorado core hole no. 1, Piceance Creek Basin, Colorado, *in* Murray, D.K., ed., Guidebook to the energy resources of the Piceance Creek Basin, Colorado: Rocky Mountain Association of Geologists 25th Field Conference, p. 81–100.

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

Ryder, R.T., Fouch, T.D., and Elison, J.H., 1976, Early Tertiary sedimentation in the western Uinta Basin, Utah: Geological Society of America Bulletin, v. 87, p. 496–512.

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

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

Trudell, L.G., Beard, T.N., and Smith, J.W., 1970, Green River Formation lithology and oil shale correlations in the Piceance Creek Basin, Colorado: U.S. Bureau of Mines Report of Investigations 7357, 11 p., 212 tables.

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

USGS Uinta-Piceance Assessment Team, 2003, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, CD-ROM.

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005, Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series 69–D, CD-ROM.

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

Ziemba, E.A., 1974, Oil shale geology, Federal Tract C-a Rio Blanco County, Colorado, *in* Murray, D.K., ed., Guidebook to the energy resources of the Piceance Creek Basin, Colorado: Rocky Mountain Association of Geologists, 25th Field Conference, p. 123–129.

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