Spatial and Stratigraphic Distribution of Water in Oil Shale of the Green River Formation Using Fischer Assay, Piceance Basin, Northwestern Colorado

Open-File Report 2014–1059

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

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

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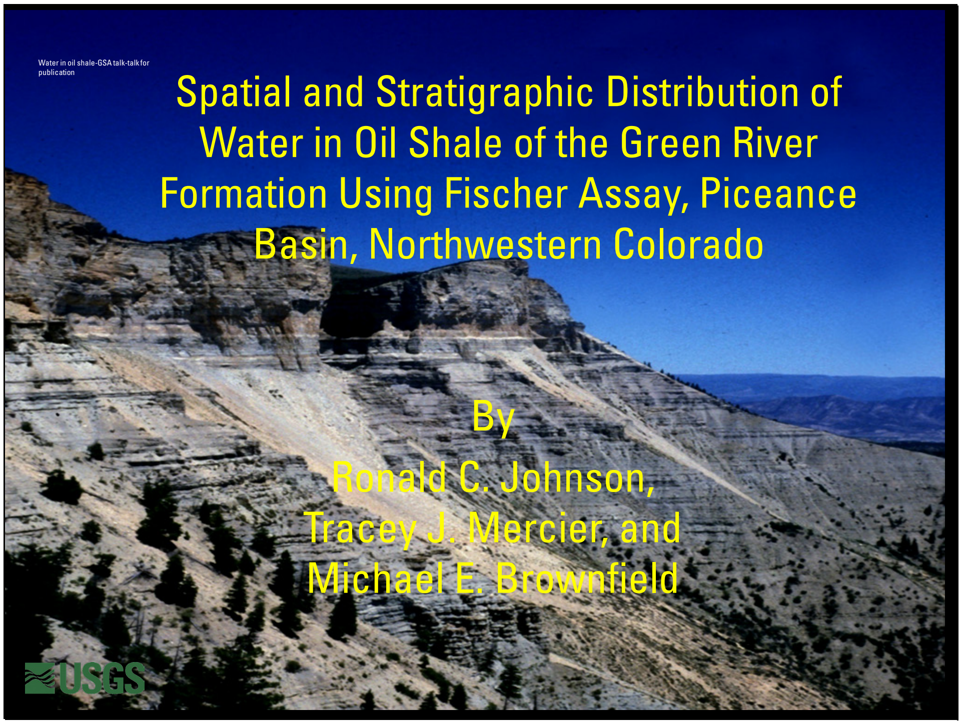
Water in oil shale-GSA talk-talk for publication
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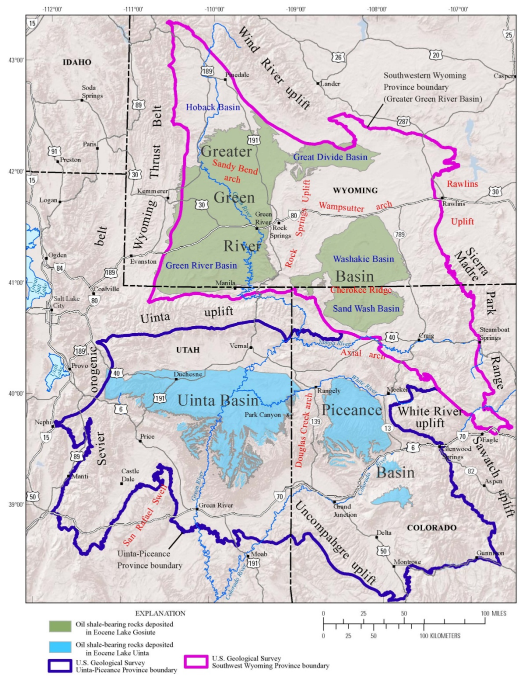
The Eocene Green River Formation was deposited in two large lakes, Lake Gosiute in the Greater Green River Basin southwest Wyoming and northwest Colorado and Lake Uinta in the Uinta Basin northeast Utah and northwest Colorado and the Piceance Basin northwest Colorado



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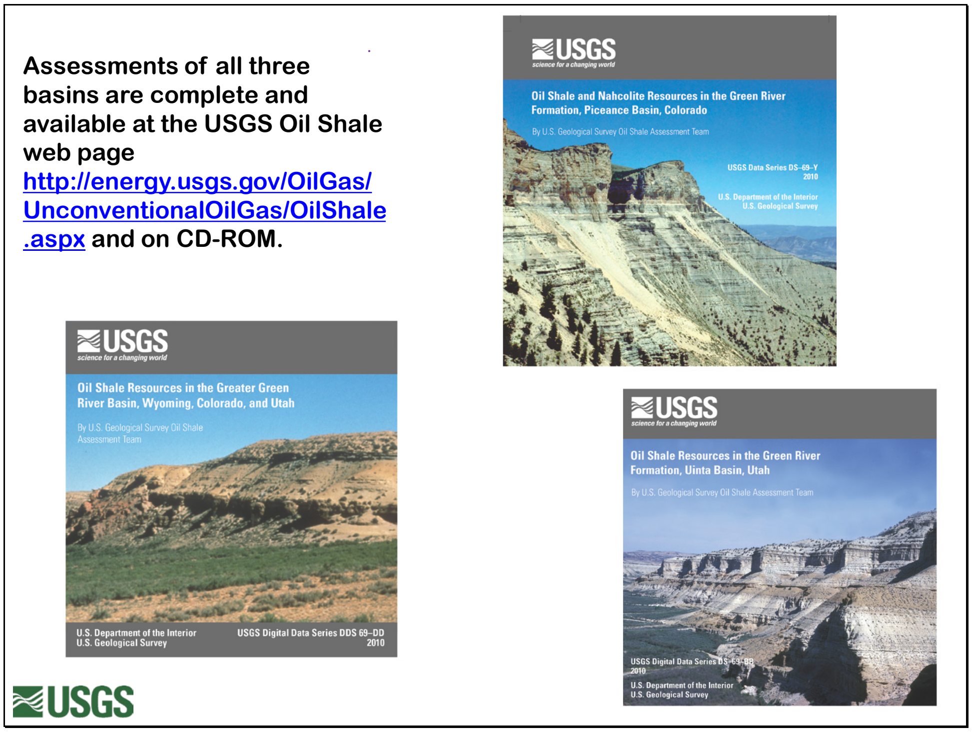

The U.S Geological Survey has now completed and published assessments of in-place oil in the Eocene Green River Formation in the Piceance Basin of western Colorado, the Uinta Basin of eastern Utah and western Colorado, and the Greater Green River Basin of southwest Wyoming.

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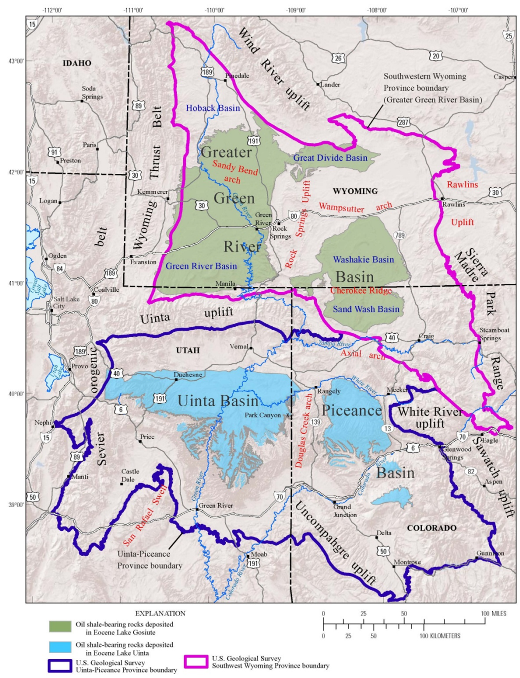
Piceance Basin: 1,335 square miles (3,458 square kilometers). In-place resource: 1.52 trillion barrels (Johnson and others, 2010a).

Uinta Basin: 3,834 square miles (9,930 square kilometers). In-place resource: 1.32 trillion barrels (Johnson and others, 2010b).

Greater Green River Basin: 5,500 square miles (14,244 square kilometers). In-place resource: 1.44 trillion barrels (Johnson and others, 2011).

The Piceance Basin has the smallest area and largest resource.



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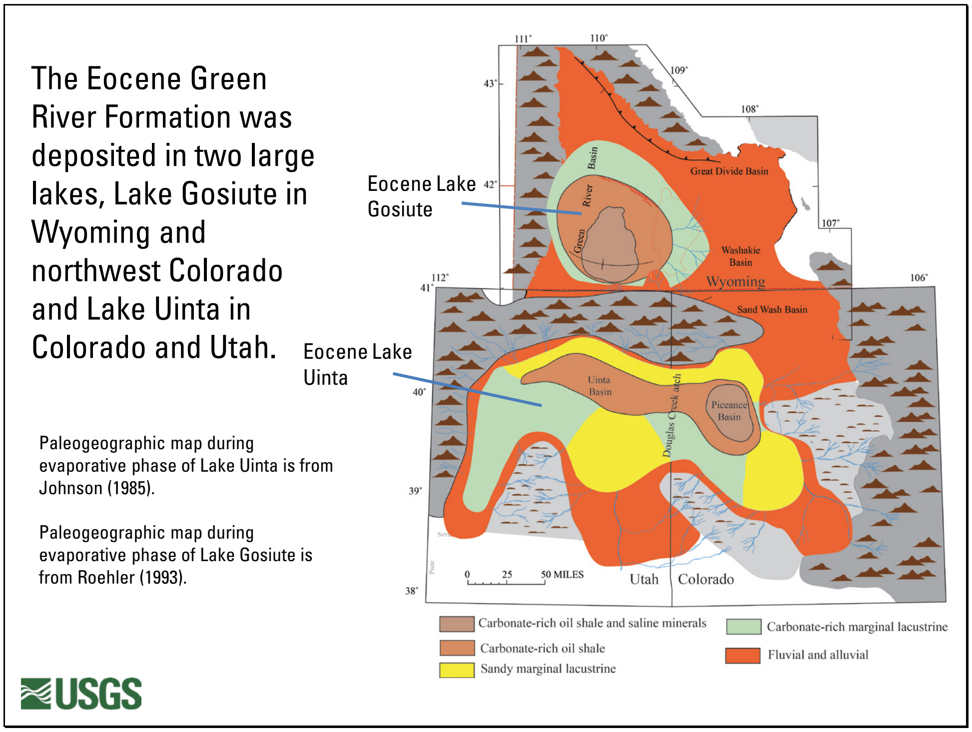

The Eocene Green River Formation was deposited in two large lakes: (1) Lake Gosiute in the Greater Green River Basin, and (2) Lake Uinta in the Uinta and Piceance Basins. Lake Uinta extended across the Douglas Creek arch throughout most, if not all, of its history.

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All data used for each of the three assessments were put into a single Access table

- The ability to create custom forms in Access was a crucial element in the assessment methodology as it allowed staff to write Visual Basic scripts and Structured Query Language (SQL) statements to filter subsets of the data and perform the necessary calculations using Access form controls.
- After resources were calculated for each core hole, the resultant Access tables were linked seamlessly with ESRI's ArcGIS software to model, extrapolate, and quantify the data spatially.
- The end product is a database of tables (spreadsheets), forms to view the data and a series of GIS maps quantifying the results of those calculations.

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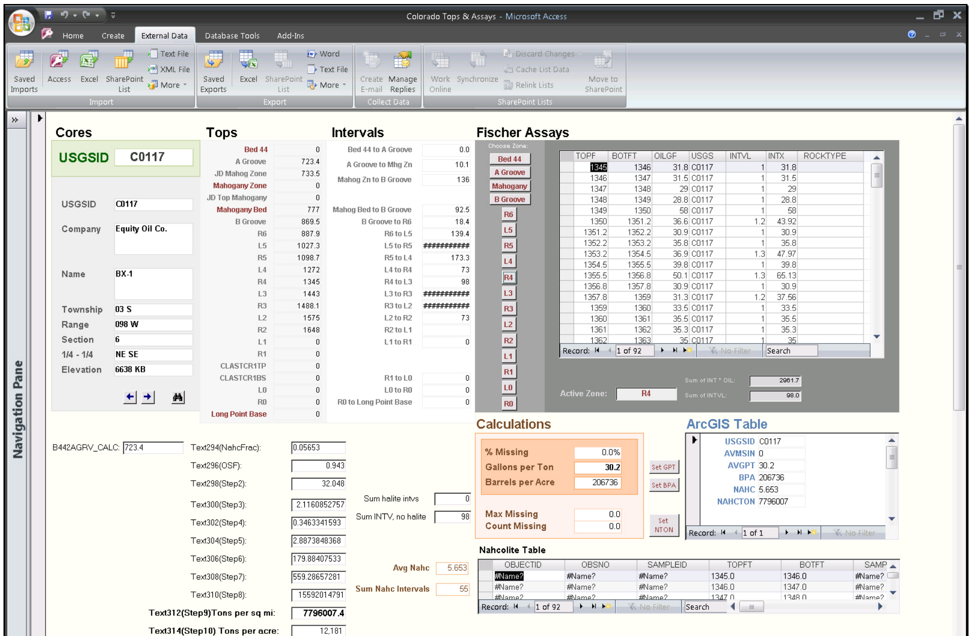

Microsoft Access interface used in the oil shale assessments

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The published database with the in-place assessment of oil shale resources in the Piceance Basin is used here to generate maps showing variations in water content.

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Data included in Access table for Piceance Basin oil shales

- Tops, 1,049 records
- Fischer Assay analyses, 321,410 records
- Nahcolite measurements, 37,716
- Resultant ArcGIS table to store calculations, 2,615 records (points for all 3 states)

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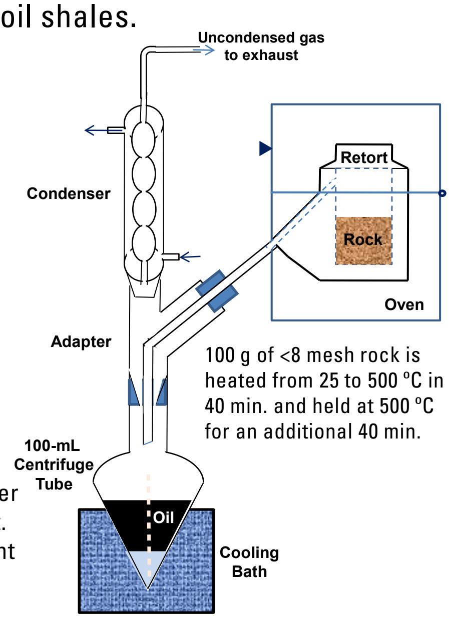
The Fischer assay method is the standardized method used to estimate oil content in oil shales.

Fischer Assay

ASTM: D 3904-90

Products Collected
condensed oil
condensed water
spent rock

Reported Values
wt% oil
wt% water
wt% Loss (gases)
oil density



100 g of <8 mesh rock is heated from 25 to 500 °C in 40 min. and held at 500 °C for an additional 40 min.

The Fischer assay method measures water content of oil shale as well as oil content. Percent water was substituted for percent oil in the equations used to generate oil yield maps thus generating water yield maps.

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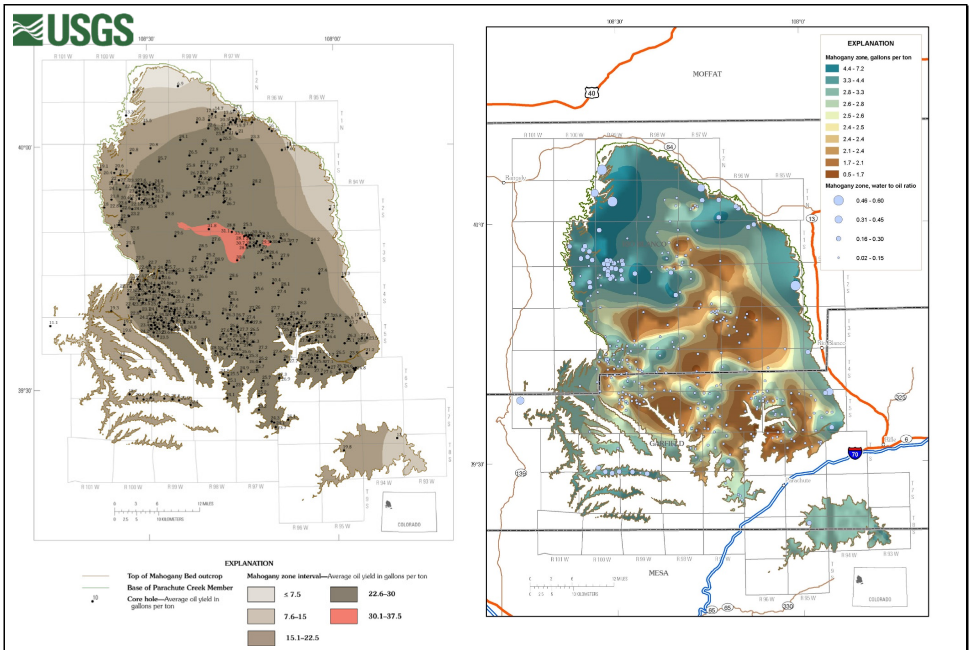

Variations in gallons per ton oil (left) and gallons per ton water (right) for the Mahogany oil shale zone. A hillside shading feature was used on the gallons per ton water map.

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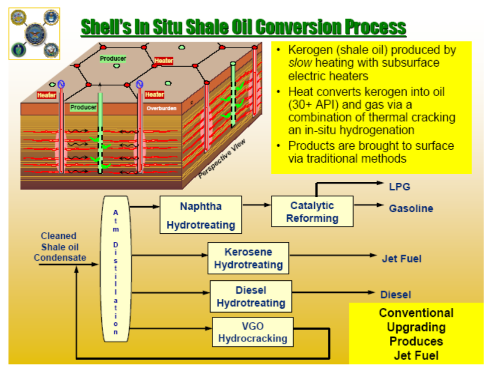
Recent estimates suggest that from one to three barrels of water is required for each barrel of oil produced, depending on the type of retort process used (Boak, 2012).

Here, we investigate whether water locked in minerals that is released during retorting could supply a significant part of that water.

ATP surface retort



Shell's in situ retort

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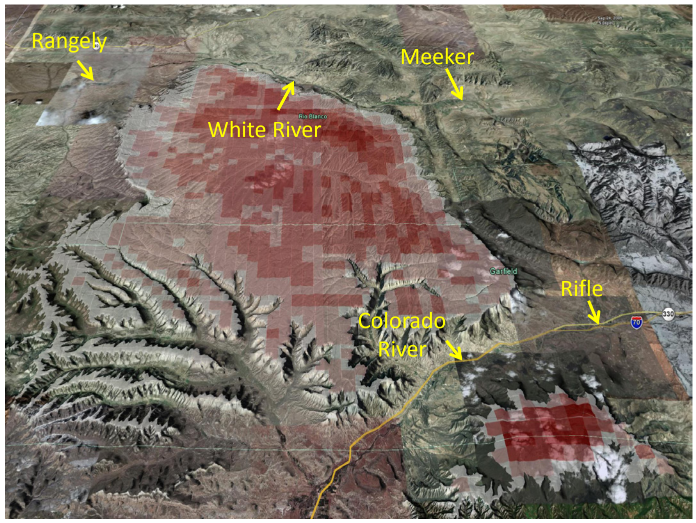
The Piceance Basin is a high semiarid plateau with limited water resources. Water in the major rivers in the areas is largely allocated for states, municipalities, and irrigation.



Oblique photograph of the oil shale deposits of the Piceance Basin with a overburden map showing cubic miles of surficial deposits (in red) per square mile; the darker the shade, the thicker the overburden deposits.

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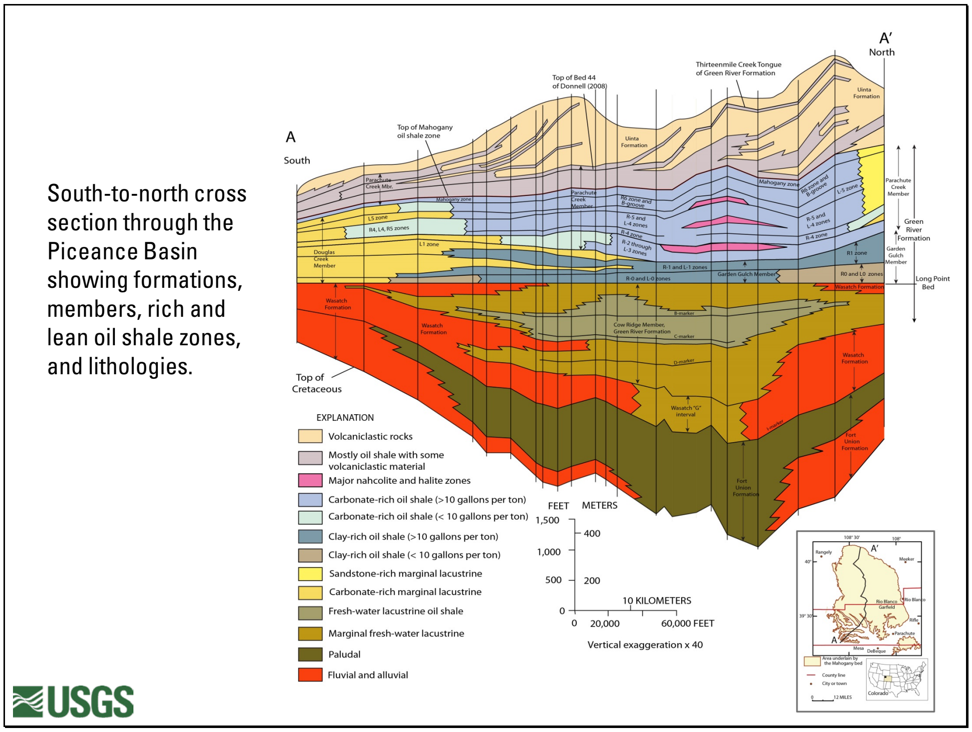

This south-to-north general cross section of the Piceance Basin shows: (1) members of the Green River Formation, (2) the rich and lean zone stratigraphy defined by Cashion and Donnell (1972), and (3) environments of deposition. Major nahcolite and halite zones in the north-central part of the basin are shown. Note that the oil shale interval grades toward the basin margins into marginal lacustrine rock. Note also the infilling of Lake Uinta in the Piceance Basin by volcaniclastic sediments from the north after deposition of the Mahogany oil shale zone.

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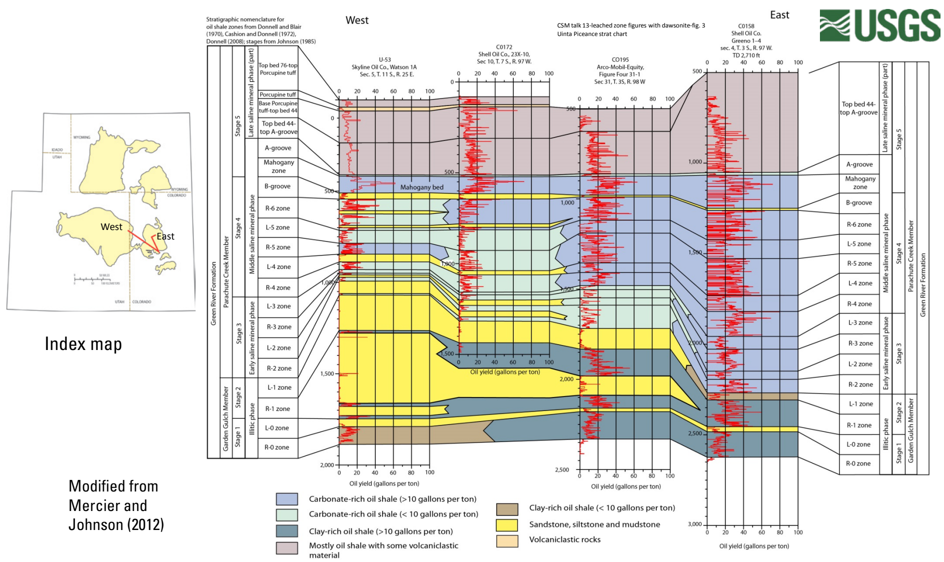

Modified from Mercier and Johnson (2012)

The oil shale interval in the Piceance and Uinta Basins is subdivided into rich and lean zones by Cashion and Donnell (1972). Oil and water content of each zone in the Piceance Basin were assessed separately.

Cashion and Donnell (1972) were the first to subdivide the oil shale interval into roughly time stratigraphic rich and lean zones that represent alternating periods of high and low organic productivity and preservation in Lake Uinta.

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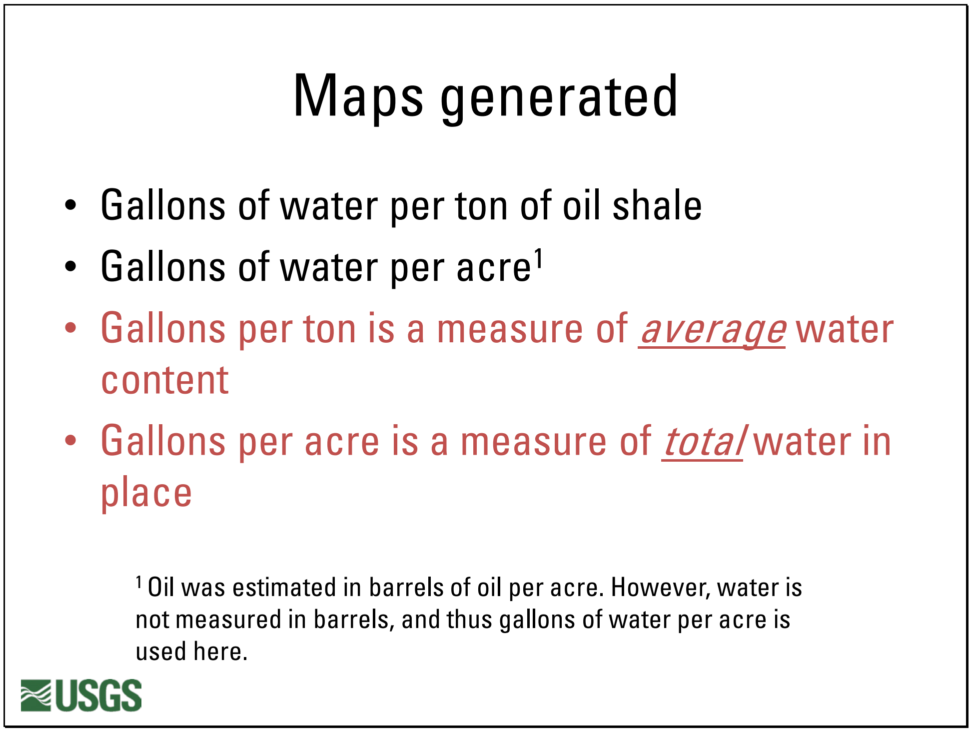

The gallons per ton water and gallons per acre water maps presented here were generated from the same database using the same formulas as the gallons per ton oil and barrels per acre oil maps presented in the assessment of in-place oil shale resources (Johnson and others, 2010a). Gallons of water per acre was used instead of barrels of water per acre, because water content is generally not measured in barrels.

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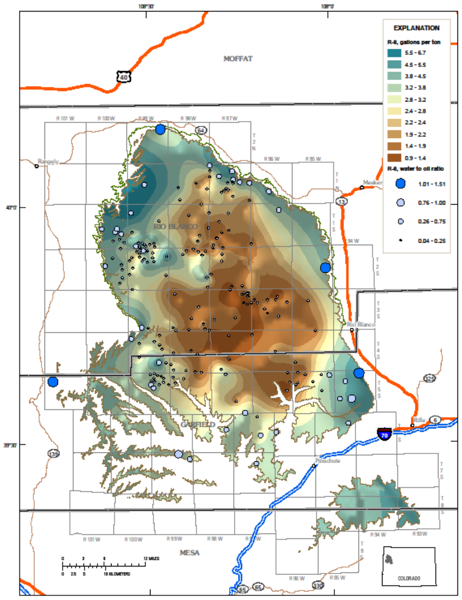
Representative map showing gallons per ton of water

The water to oil ratio is usually less than one except in basin-margin areas where oil yields are very low.

Bubbles represent the water-to-oil ratio at each control point.



Gallons per ton of water in the R-6 zone

USGS

The in-place water maps presented here resemble the in-place oil maps generated by Johnson and others (2010a) except a hillside shading feature is used on the in-place water maps to enhance the visualization of variations in water content.

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The breakdown of water-bearing mineral phases is the largest source of water generated during retorting.

Major water-bearing mineral phases:
Nahcolite ($NaHCO_3$)
Dawsonite ($NaAl(OH)_2CO_3$)
Analcime ($NaAlSi_2O_6 \cdot H_20$)
Clay, mainly illite

Photograph was taken in 1979 by Robert Bolhmar (U.S. Bureau of Mines).

Horse Draw Mine, third level. Channel sample analyses of face from roof to floor: nahcolite, 63 weight percent; dawsonite, 3.5 weight percent; oil yield, 12.3 gallons per ton; water, 16.3 gallons per ton

USGS

Most of the water generated during retorting probably comes from water-bearing mineral phases, such as nahcolite, dawsonite, analcime, and clay. All of these minerals lose most if not all of their water at retort temperatures.

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- Nahcolite and dawsonite are present in the richest part of the oil shale deposit in the north-central part of the basin.
- Nahcolite decomposes to natrite (Na_2CO_3) or soda ash, carbon dioxide, and water at temperatures near 100 °C during the recovery processes.
- Dawsonite decomposes to soda ash, Al_2O_3, water, and carbon dioxide at temperatures of 200 to 370 °C.
- In addition, nahcolite is considered a leasable mineral and, thus, must not be destroyed during processes used to recover oil from oil shale.

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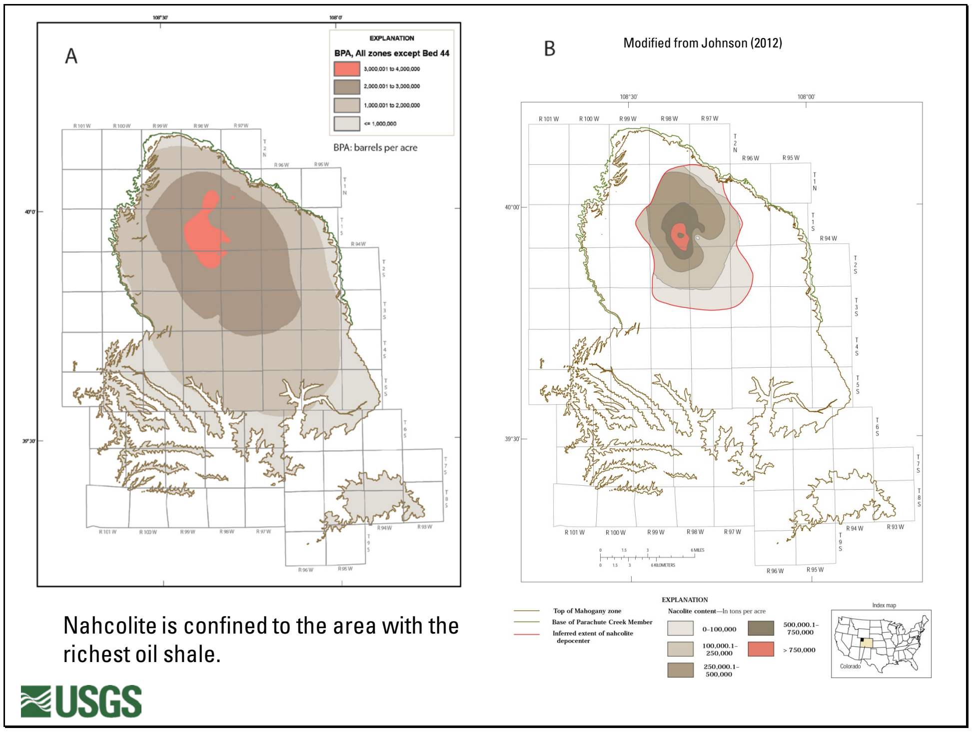

The map on the left shows total amount of oil in place in all seventeen oil shale zones in the Piceance Basin. The area containing nahcolite (outlined by brown line) is shown on the right. The area with the most oil in place is generally the same as the area containing nahcolite, thus extracting oil from the richest oil shale interval in the basin will also necessitate the extraction or preservation of nahcolite.

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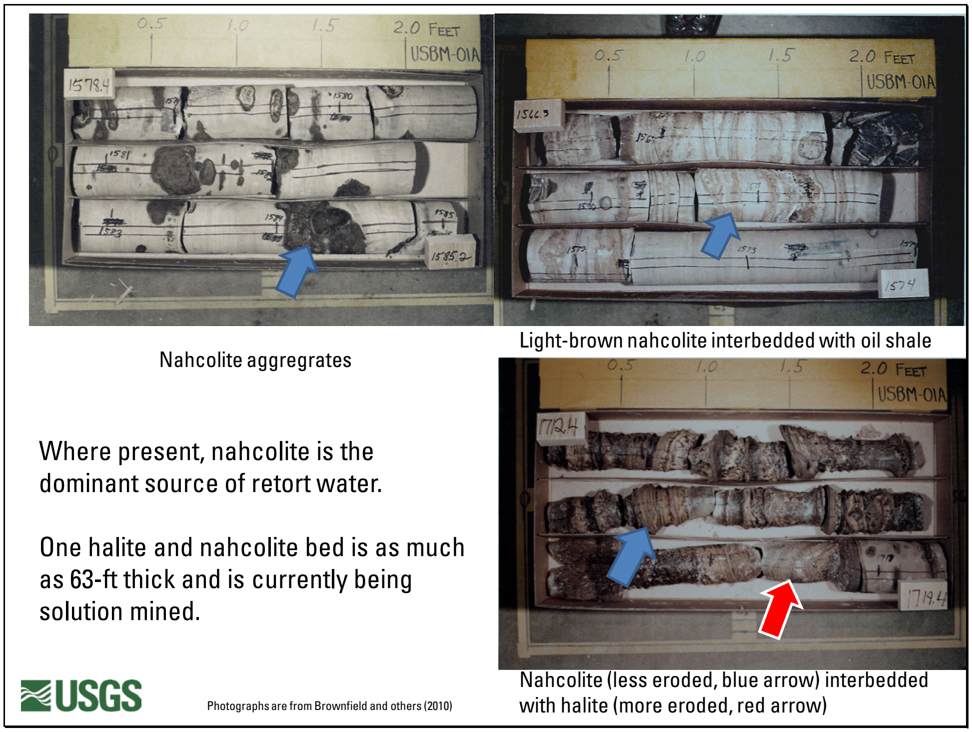

Nahcolite in the Piceance Basin occurs as: (1) nonbedded crystalline aggregates, (2) laterally continuous units of fine-grained crystals dissemintated in oil shale,(3) brown crystalline beds, and (4) white coarse-grained beds (Dyni, 1974). Some of these types of nahcolite occurrences are shown here.

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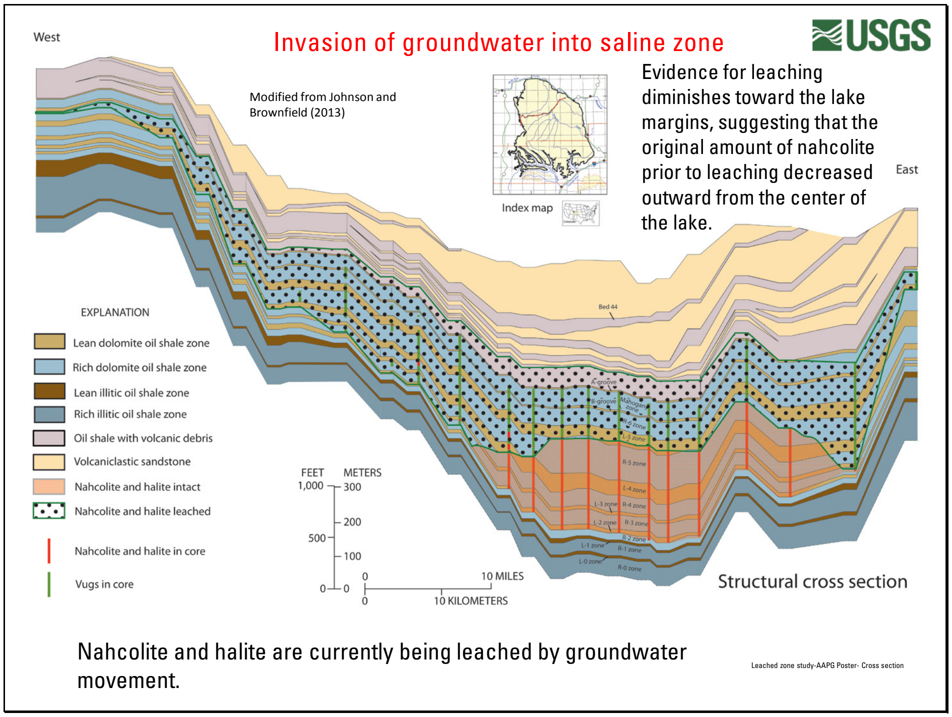

East-west structural cross section showing variations in elevation of the rich and lean oil shale zones in the Piceance Basin. Structural cross sections such as this are more useful to visualize groundwater movement than stratigraphic cross sections where the datum is a stratigraphic horizon. Note the extensive interval where nahcolite and halite have been leached.

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- “Dawsonite occurs as minute crystals 5 microns or less in size, disseminated throughout the oil shale matrix. Over short intervals, dawsonite may compose as much as 25 percent of the rock” (Beard and others, 1974, p. 103).
- Analcime is found in altered tuffs and disseminated in oil shale and other fine-grained rocks.

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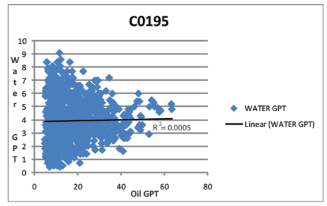
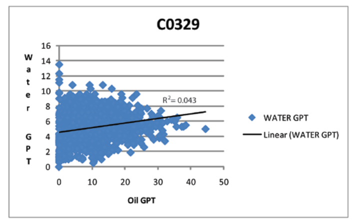
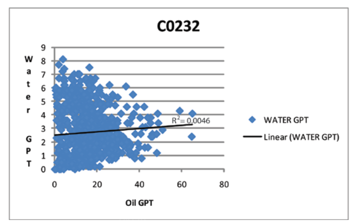
There appears to be no relation between kerogen content (indicated by oil yield) and water content, and kerogen does not appear to be a major source of water produced during retorting.



Colburn and others (1989) determined that dehydration of kerogen was only a minor source of water in Green River oil shales, contributing about 0.2 g of water per 100 g of oil shale.





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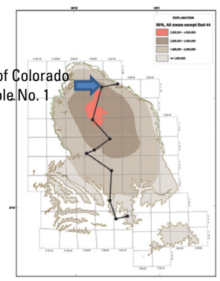
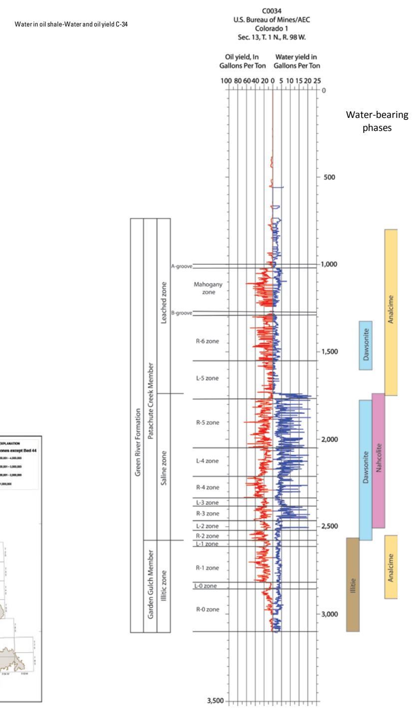
Water-bearing mineral phases in Colorado Core hole No. 1 in the saline depocenter are shown on the oil yield (red line on left) and water yield (blue line to right) histograms (from Robb and Smith, 1974).

High water yields correspond closely to nahcolite-bearing ($NaHCO_3$) interval.

Dawsonite ($NaAl(OH)_2CO_3$) and analcime ($NaAlSi_2O_6{\cdot}H_2O$) generally do not occur together. Analcime is thought to alter into dawsonite and quartz.





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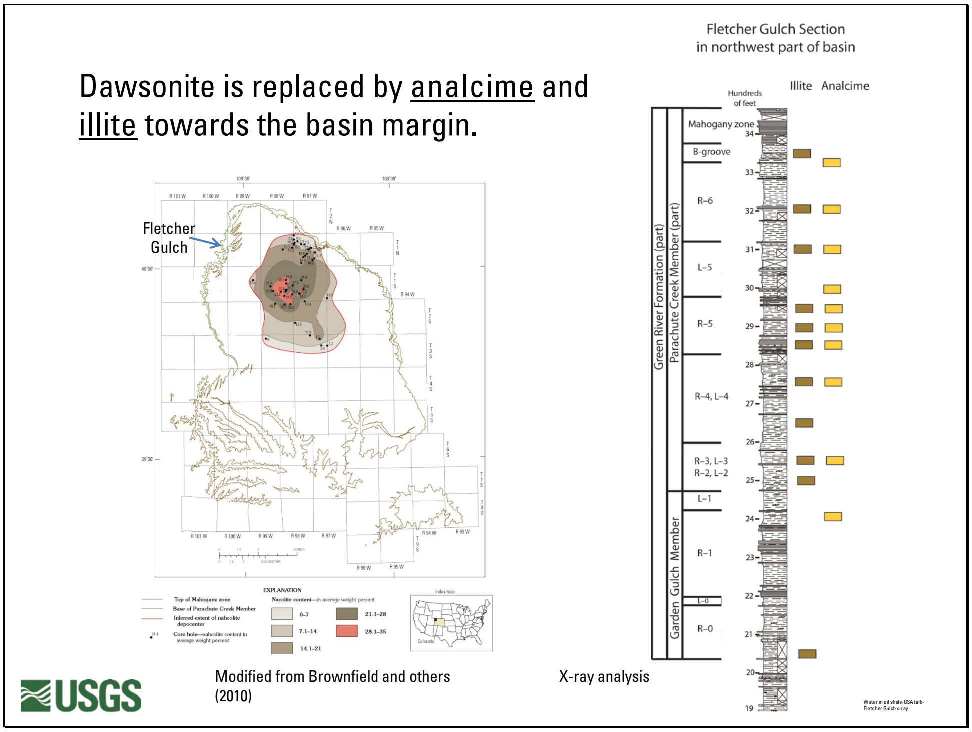

Illite and analcime appear to be the most common water-bearing mineral phases in marginal areas, but data are sparse.

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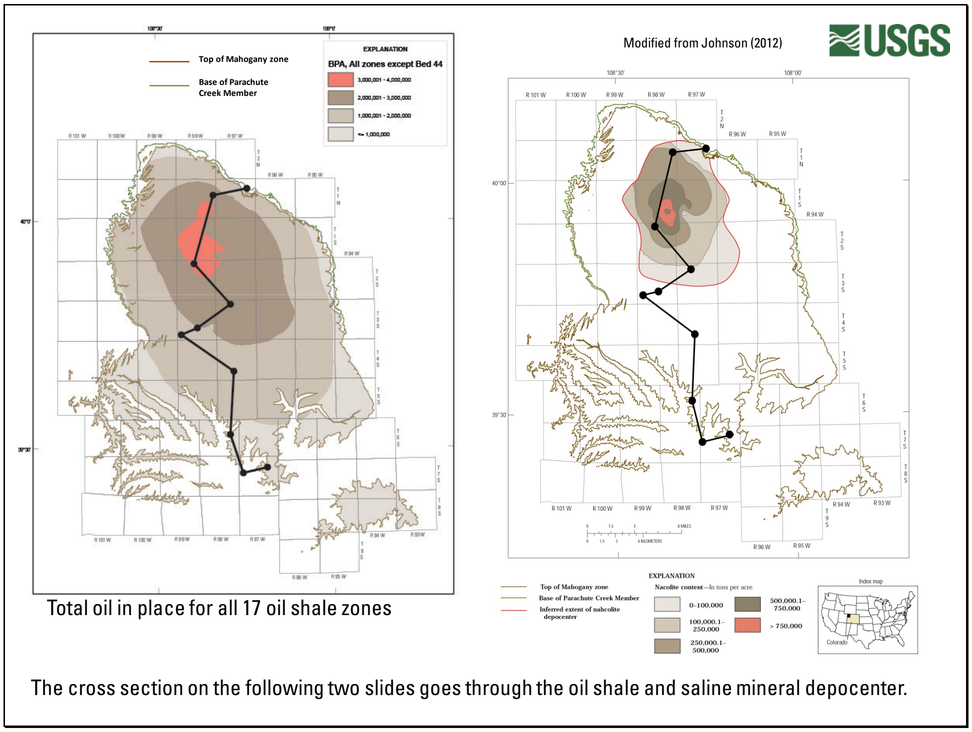

A south-to-north cross section through the Piceance Basin shows the distribution of water-bearing mineral phases in the Green River Formation.

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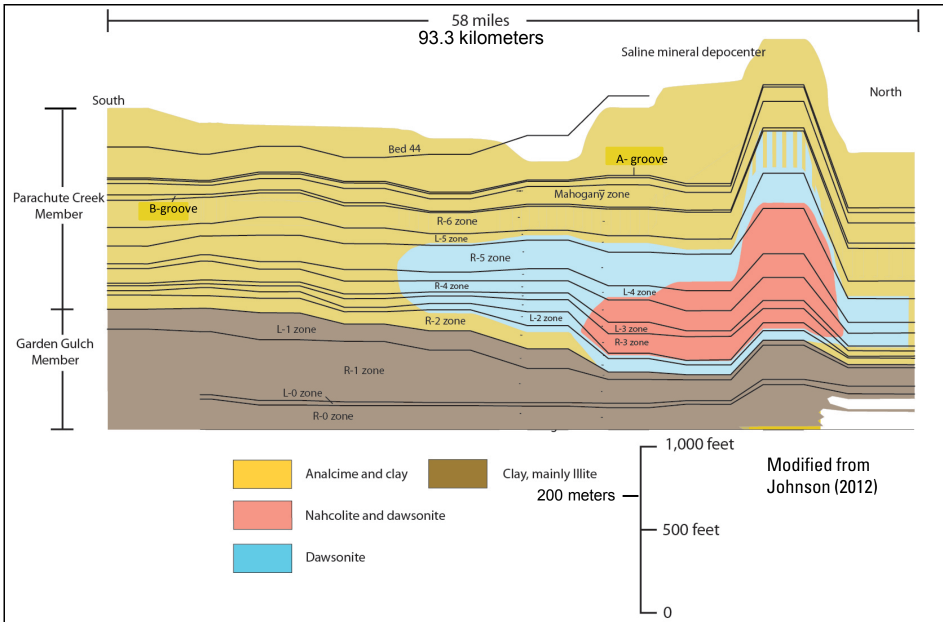

South-to-north cross section showing dominant water-bearing minerals. Dawsonite ($NaAl(OH)_2CO_3$) and analcime ($NaAlSi_2O_6 \cdot H_2O$) generally do not occur together. Analcime is thought to alter into dawsonite and quartz.

USGS

This south-to-north cross section shows members of the Green River Formation, rich and lean zones, and the distribution of water-bearing mineral phases. Nahcolite and dawsonite grade marginward into mainly illite and analcime.

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Maps showing variations in gallons per ton water and gallons per acre water were generated for each oil shale zone.

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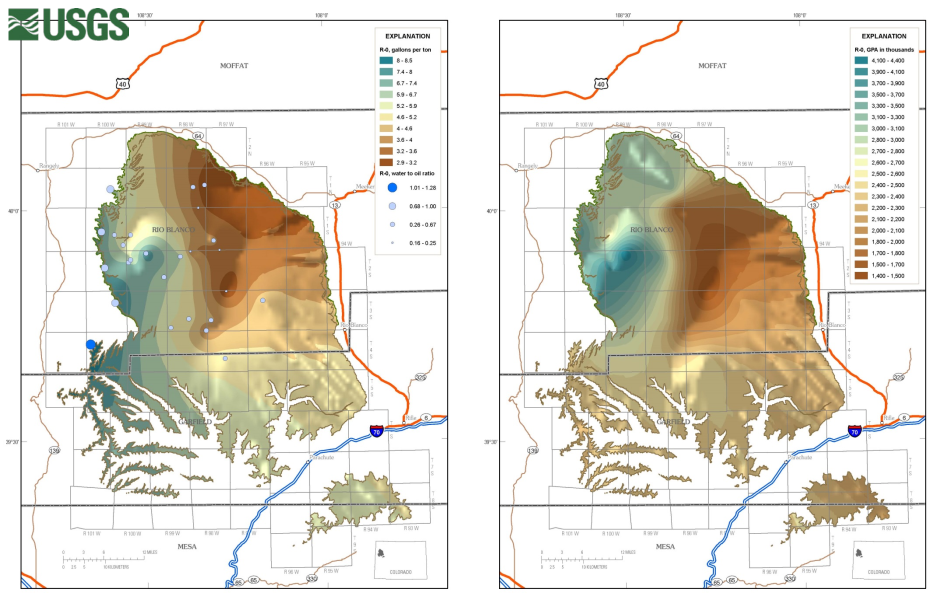

For the R-0 zone, both gallons per ton water (left) and barrels per acre water (right) increase to the west and south. The ratio of water to oil is less than one for all but one core hole. Illite is probably the dominant water-bearing mineral phase throughout the illitic interval (R-0 through L-1).

The ratio of water generated by Fischer assay and oil generated by Fischer assay is represented by bubbles on each of the gallons per ton water maps. The ratio of water needed for retorting a ton of oil shale compared to oil generated per ton of oil shale is a commonly used ratio in estimating water needed to develop an oil shale industry (Boak and Mattson, 2009)

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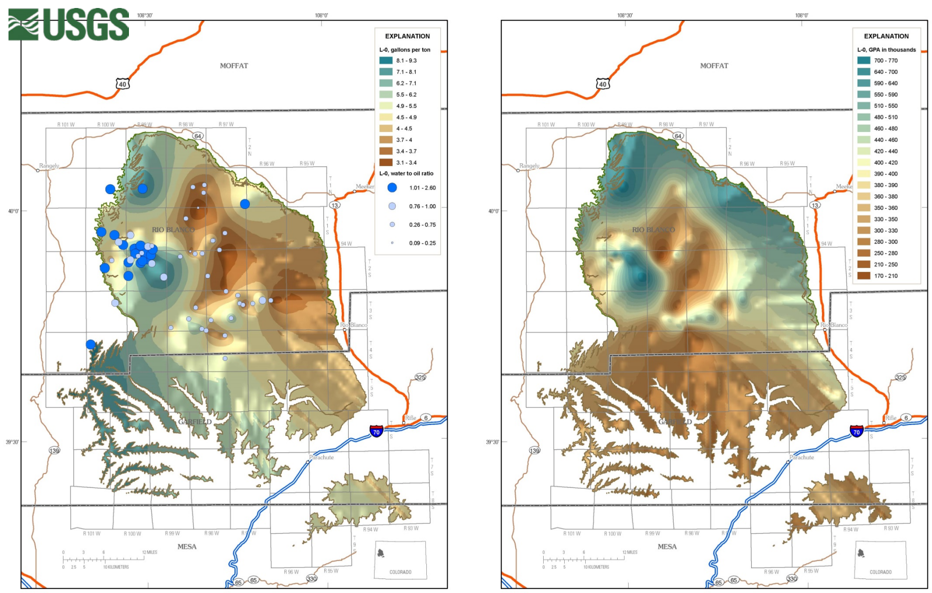

Distribution of water in the comparatively thin and lean L-0 zone is highly variable with gallons per ton water increasing to the west and south and gallons per acre water increasing to the northeast and northwest. The ratio of water to oil is greater than one along the western margin of the basin.

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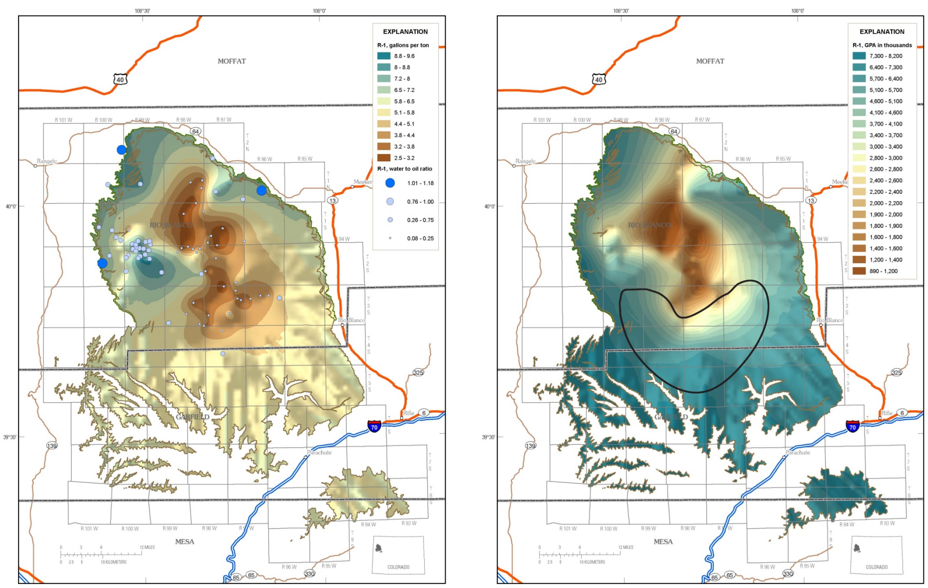

For the R-1 zone, both gallons per ton water and gallons per acre water increase toward the basin margins with a water-to-oil ratio of greater than one at three core holes around the perimeter of the basin. The area of maximum in-place oil is outlined on the gallons per acre map in black to demonstrate that there is no relation between water in place and oil in place.

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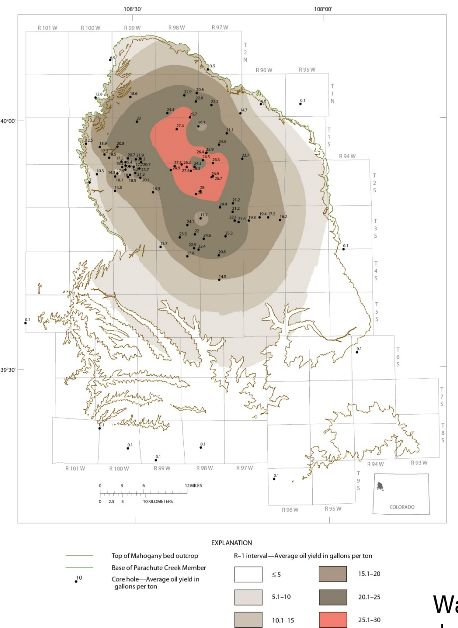
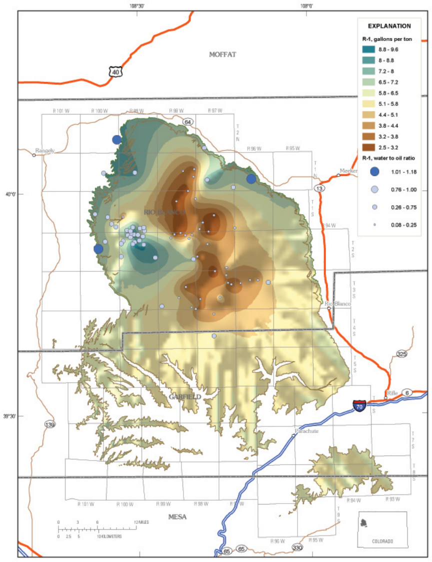


Gallons per ton oil in the R-1 zone



Gallons per ton water in the R-1 zone

Water content in the R-1 zone generally decreases towards increasing oil content. Based on this study, this is typical for oil shale zones that do not contain nahcolite.

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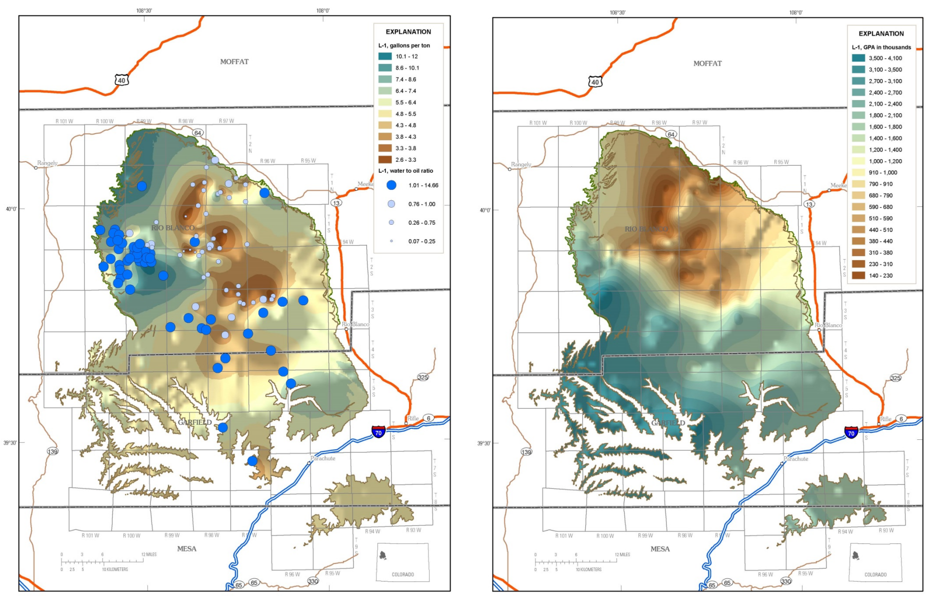

For the L-1 zone, gallons per ton water increases toward the basin margins with water to oil ratios of greater than one throughout much of the basin. Gallons per acre water increases toward the south.

USGS

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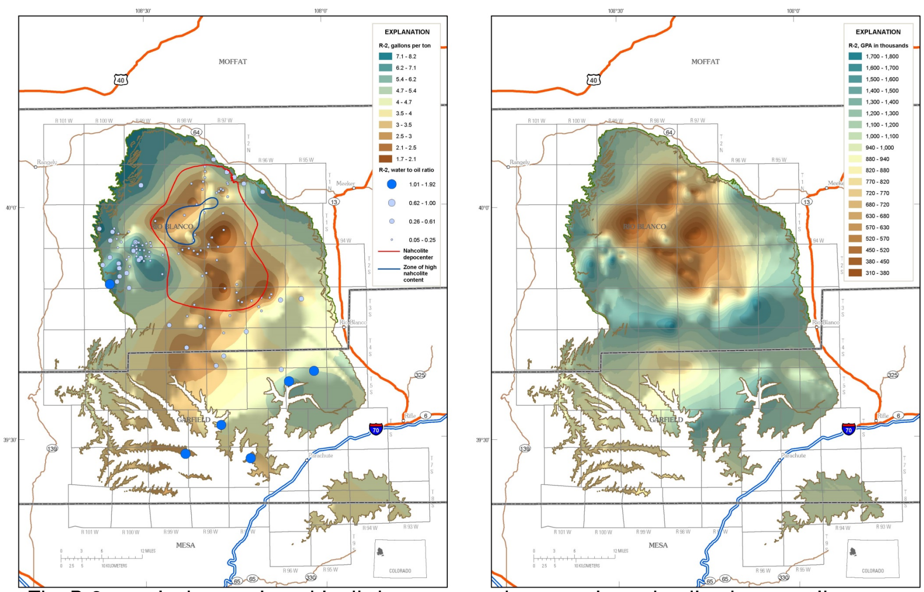

The R-2 zone is the stratigraphically lowest zone that contains nahcolite that contributes to the water content. Total nahcolite content is low, however, with nahcolite confined to a small area outlined in blue. Both gallons per ton water and gallons per acre water increase toward the basin margins.

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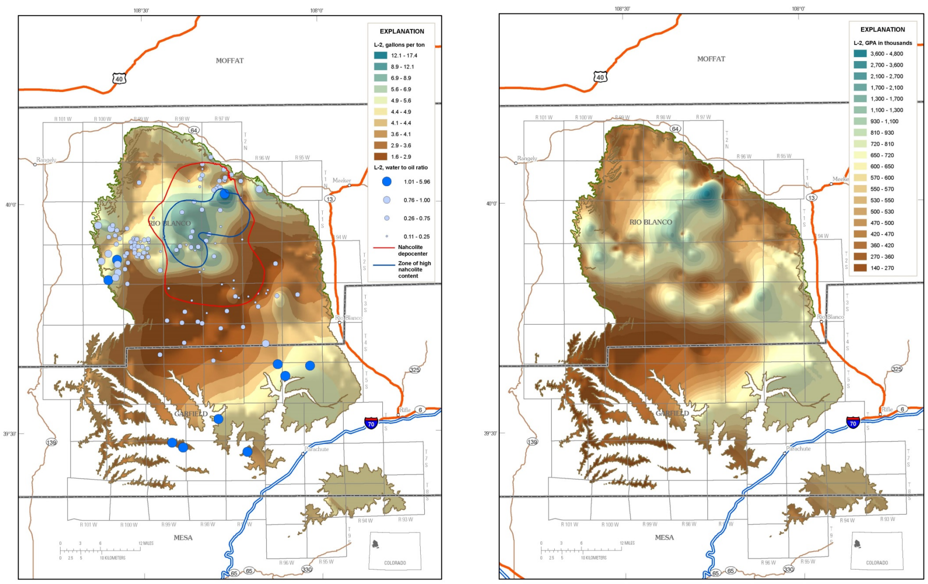

The L-2 zone is the stratigraphically lowest zone in which nahcolite (extent outlined in blue) is abundant enough to noticeably add to overall mineral-water content. Note that both gallons per ton water and gallons per acre water are highest in the nahcolite area.

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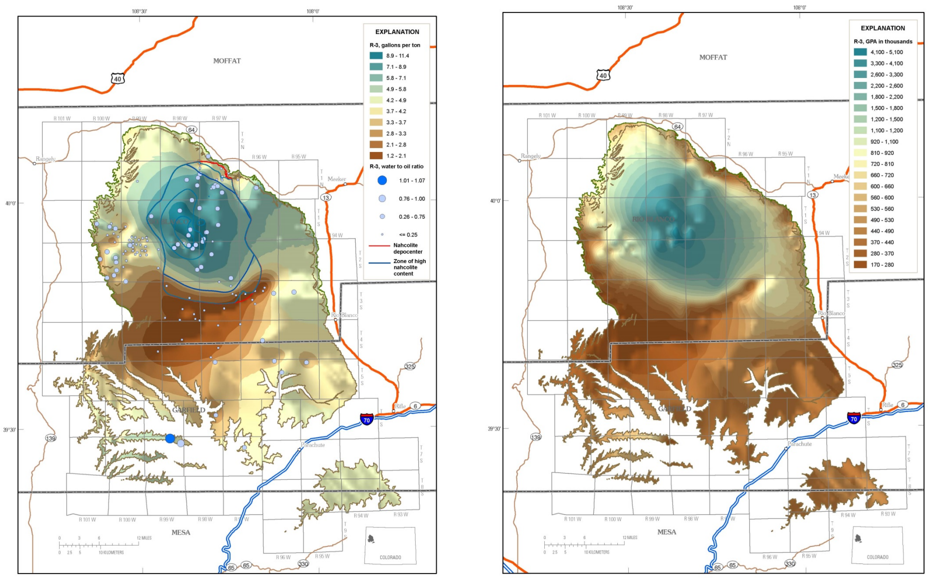

The R-3 zone contains large quantities of nahcolite (nahcolite area outlined in blue), and nahcolite appears to be the dominant water-bearing phase.

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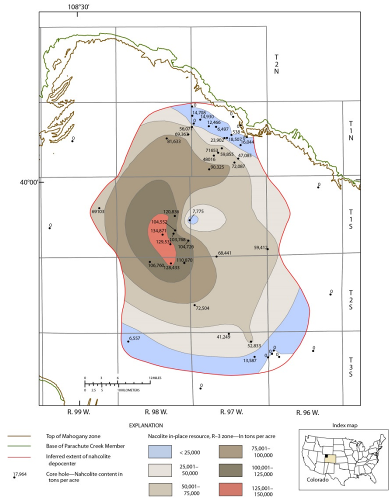
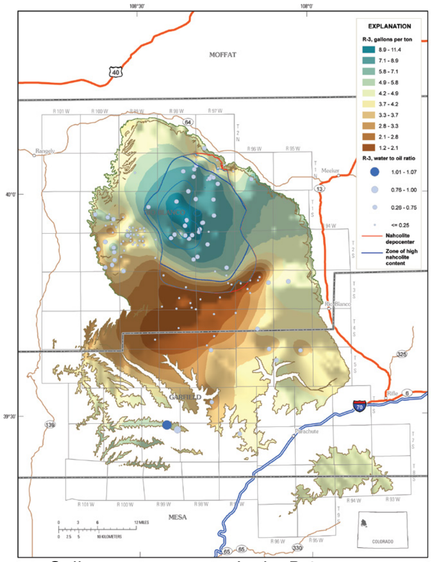


In-place nahcolite resources in the R-3 zone (modified from Brownfield and others, 2010)



Gallons per ton water in the R-3 zone

Increasing water content in the R-3 zone corresponds closely to increasing nahcolite content. Water to oil ratios approach 1 in the nahcolite area.

USGS

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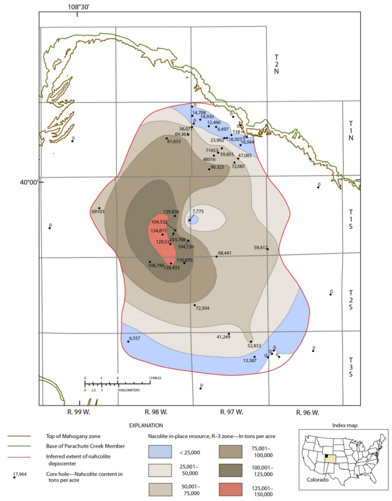
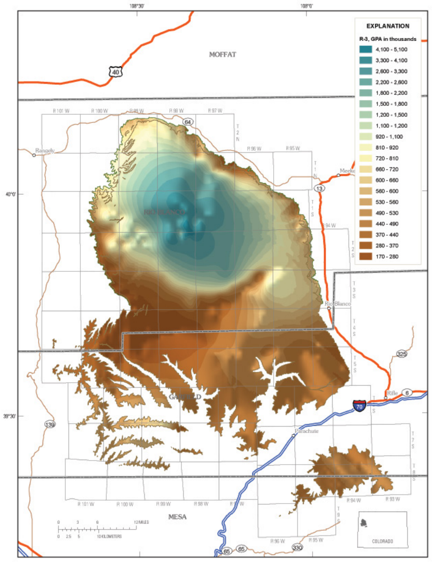


In-place nahcolite resources in the R-3 zone (modified from Brownfield and others, 2010)



Total water content in the R-3 zone is also closely related to total nahcolite content.

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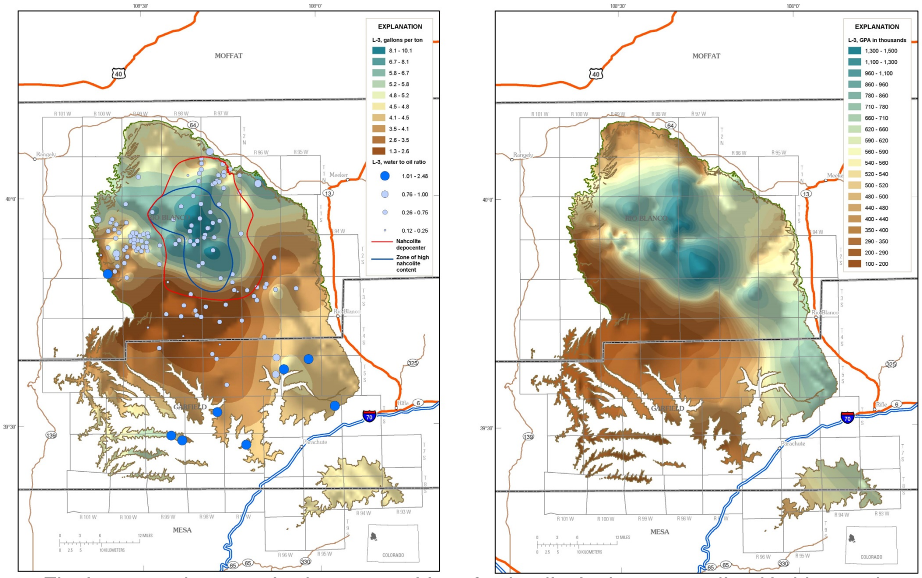

The L-3 zone also contains large quantities of nahcolite in the area outlined in blue, and its influence on the gallons per ton water and barrels per acre water are obvious. Water to oil ratio only exceeds one around the south margins of the basin where the L-3 zone contains little oil.

USGS

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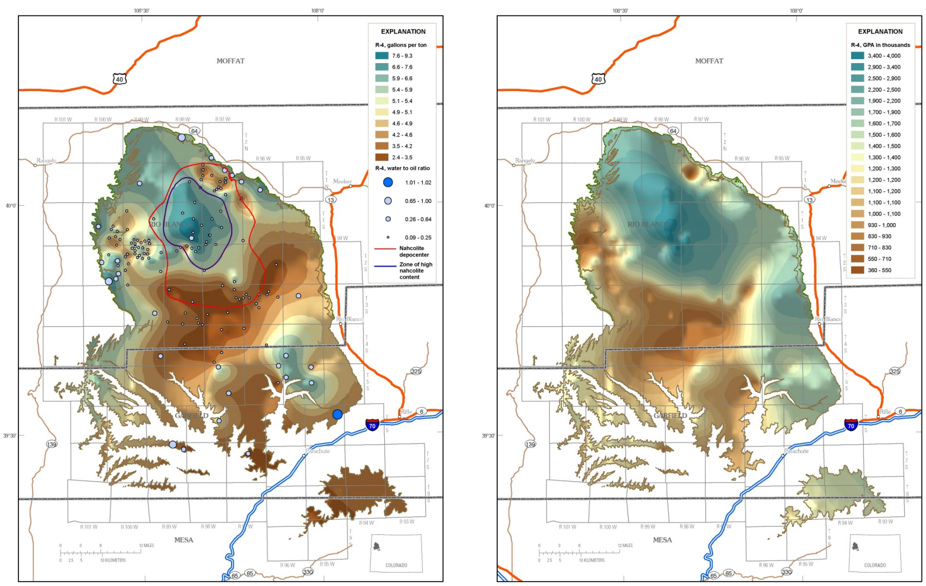

As with underlying nahcolite-bearing zones, where nahcolite is present, it is the main water-bearing mineral phase in the R-4 zone. Water to oil ratio exceeds one at a single corehole in the southeast part of the basin.

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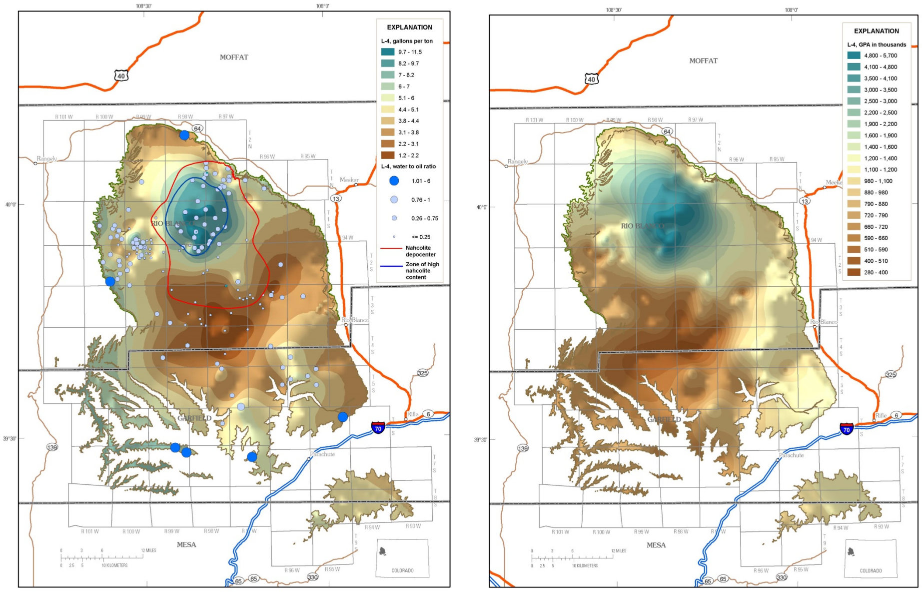

Nahcolite, where present, is again the main water-bearing phase in the L-4 zone; due largely to low oil content. However, the oil-to-water ratio exceeds one around much of the perimeter of the basin.

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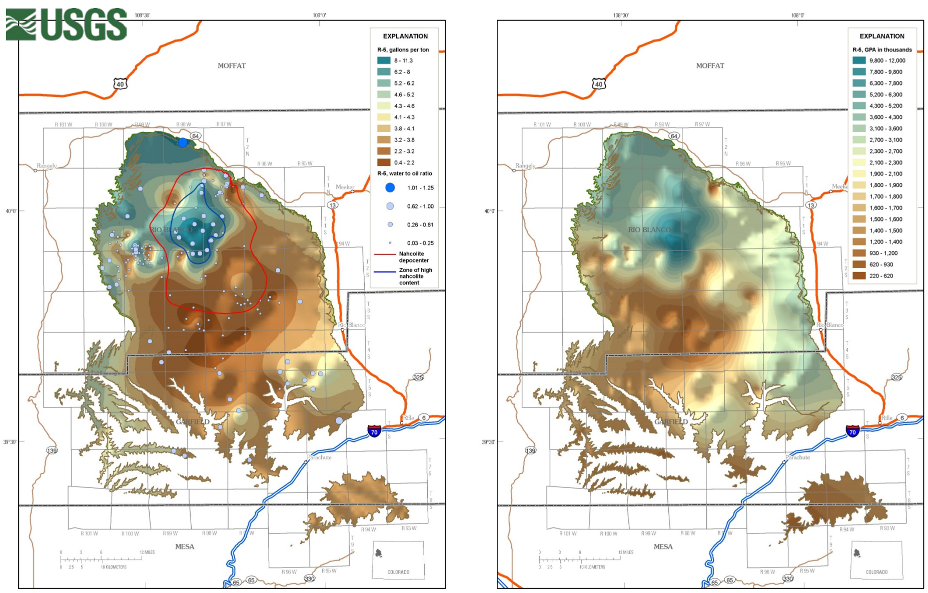

The area where nahcolite is present in the R-5 zone is smaller than in underlying nahcolite-bearing zones due to the incursion of groundwater and the resultant dissolution of nahcolite around the perimeter of the original nahcolite-bearing area. The effect of nahcolite on gallons per ton and gallons per acre water is still apparent where nahcolite is not leached.

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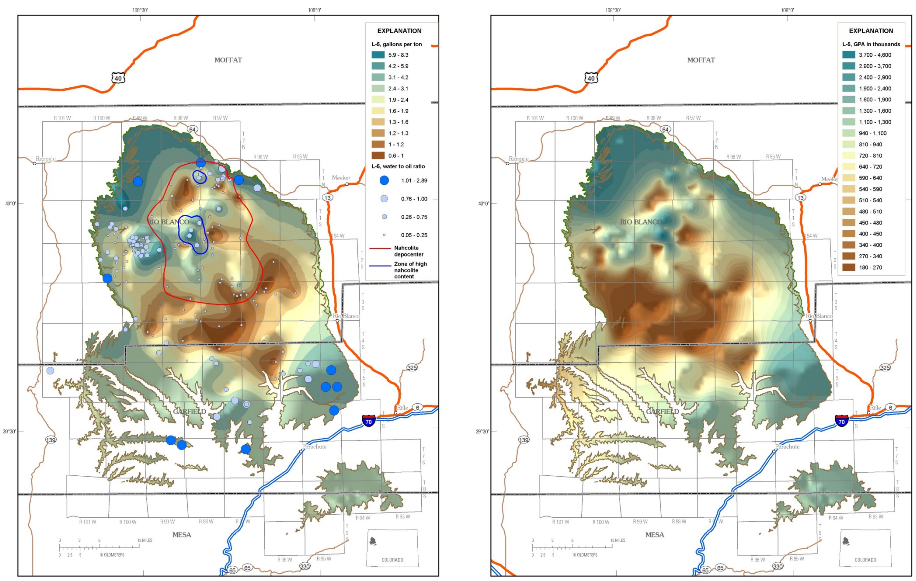

Groundwater has removed nahcolite from all but a small area in the L-5 zone. Water to oil ratios exceed one in most marginal areas due to low oil yield there.

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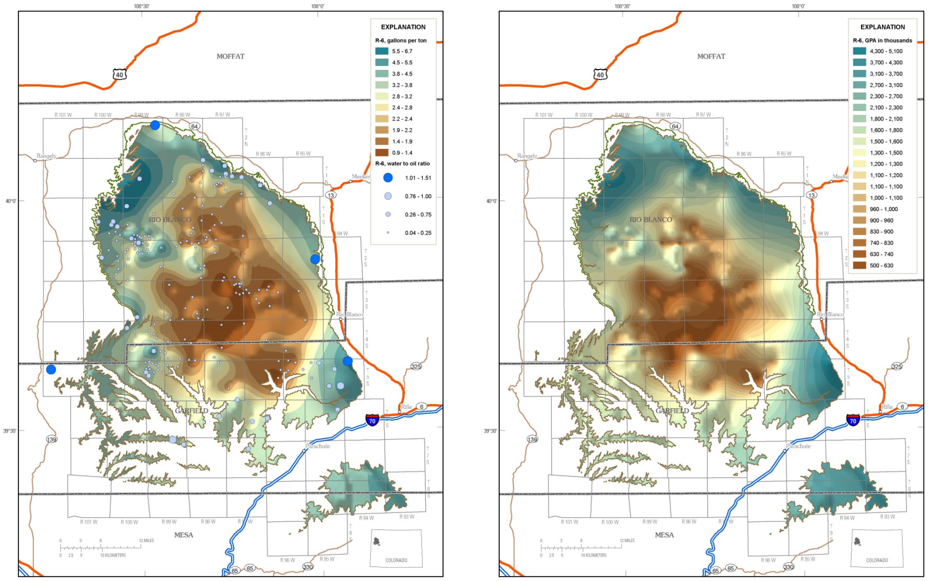

Almost all nahcolite has been removed by groundwater in the R-6 zone. Gallons per ton and gallons per acre water increase toward the basin margins in part due to a decrease in oil yields there.

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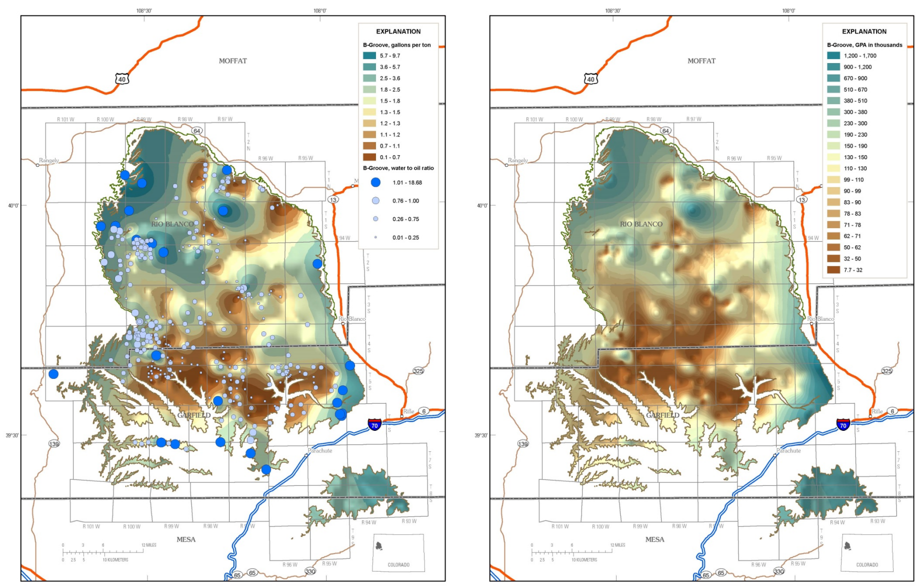

B-groove is a thin interval with low oil yields. As a result, water to oil ratios exceed one over large parts of the basin.

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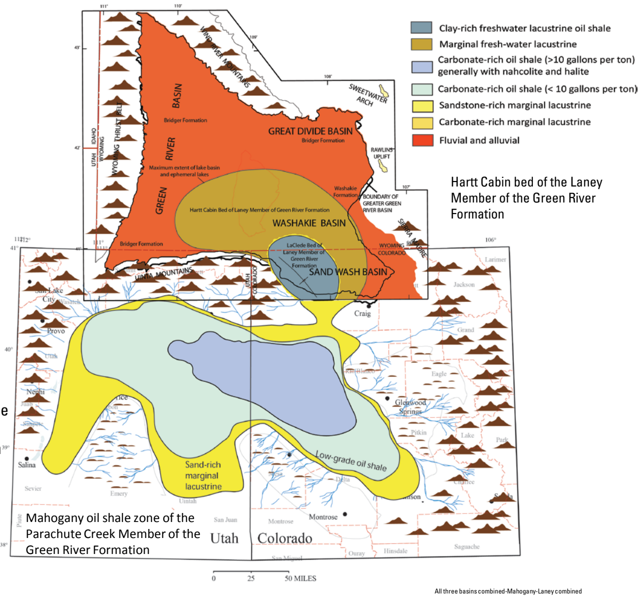
By Mahogany time, Lake Gosiute had largely filled in.

Outflow from Lake Gosiute caused Lake Uinta to expand and the area of oil shale deposition to expand to near the mountain fronts.

Volcaniclastic sediment reached the north shore of Lake Uinta late in Mahogany time, signaling the final infilling of Lake Gosiute.

Paleogeographic map during deposition of the Mahogany zone of the Parachute Creek Member of the Green River Formation is from Johnson (1985).

Paleogeographic map during the Hartt Cabin bed of the Laney Member of the Green River Formation is from Roehler (1993).



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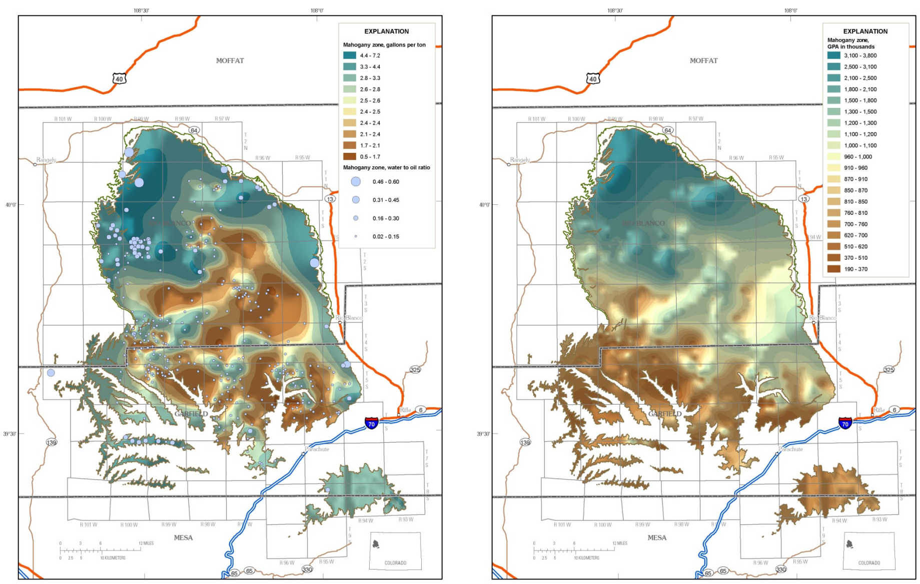

The Mahogany zone is one of the richest, most widespread zones in the basin. Gallons per ton and gallons per acre water generally increase to the north, whereas the maximum water to oil ratio is only about 0.60.

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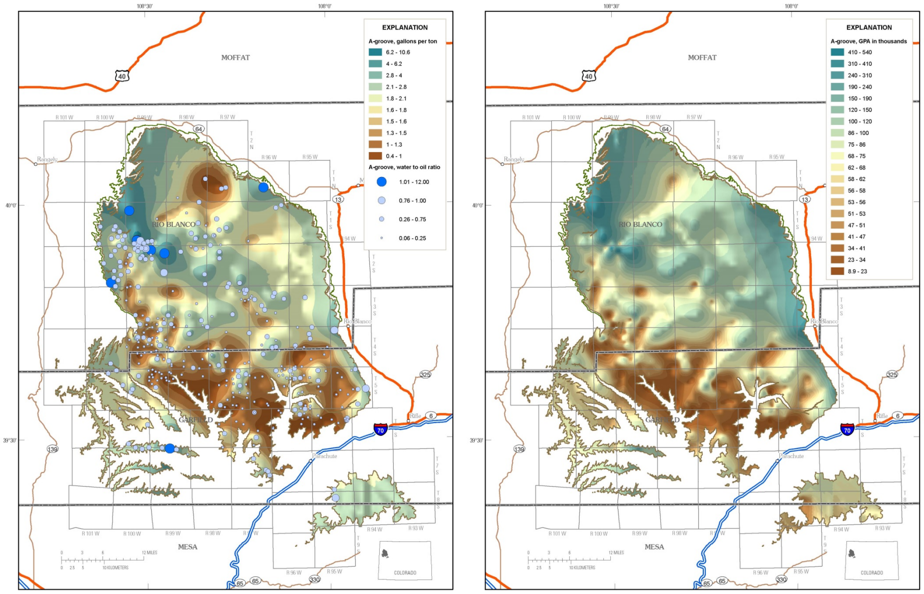

A-groove is another thin interval with low oil yields. Water to oil yield ratios exceed one in many areas of the basin.

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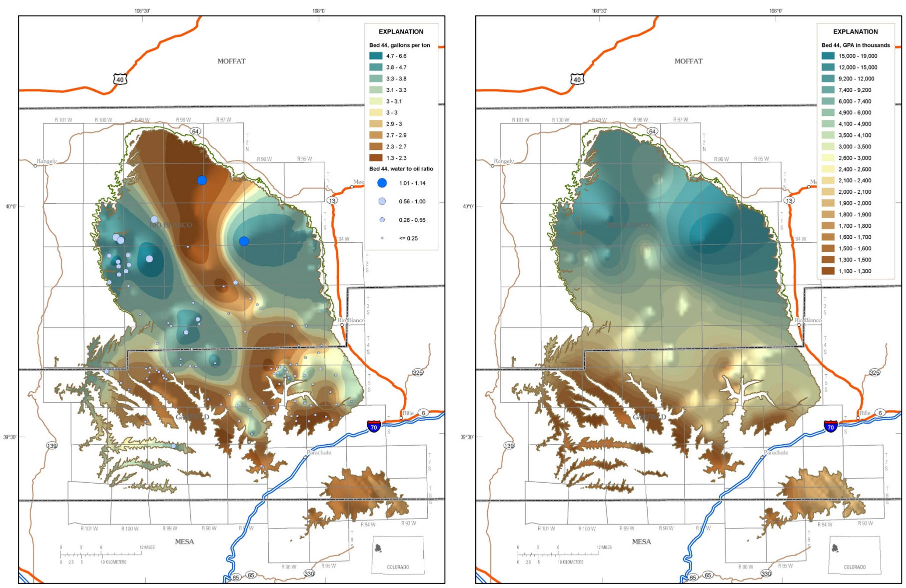

The distribution of water in the Bed 44 interval is variable, but generally increases toward the northeast and northwest. Water to oil ratio is greater than one in two core holes.

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Total oil and water in each oil shale zone for the entire basin

Oil shale zone	Oil in place (barrels)	Oil (gallons)	Water (gallons)	Water-to-oil ratio	Gallons nahcolite water
Top A-groove-top bed 44	186,467,922,130	7,831,652,729,460	1,998,106,673,820	0.26	
A-groove	6,283,095,737	263,890,020,954	82,625,917,016	0.31	
Mahogany zone	191,716,681,060	8,052,100,604,520	1,041,608,945,649	0.13	
B-groove	7,819,053,970	328,400,266,753	180,017,089,140	0.55	
R-6	185,366,007,632	7,785,372,320,544	1,483,898,265,214	0.19	
L-5	66,063,806,739	2,774,679,883,021	925,448,082,043	0.33	21,864,577,865
R-5	198,239,468,346	8,326,057,670,511	2,171,609,181,340	0.26	331,170,248,638
L-4	69,126,949,762	2,903,331,889,987	1,110,976,025,839	0.38	259,258,548,159
R-4	127,150,178,615	5,340,307,501,822	1,344,462,390,313	0.25	176,006,054,131
L-3	22,504,056,571	945,170,375,974	460,854,193,170	0.49	59,734,235,466
R-3	68,084,658,284	2,859,555,647,907	796,058,728,967	0.28	257,777,258,489
L-2	24,216,677,409	1,017,100,451,164	470,305,000,205	0.46	70,695,491,533
R-2	66,768,689,056	2,804,284,940,347	897,236,803,448	0.32	9,907,247,673
L-1	15,066,851,989	632,807,783,545	1,462,550,104,275	2.31	
R-1	195,372,090,899	8,205,627,817,758	4,645,047,388,502	0.57	
L-0	8,265,472,203	347,149,832,506	351,526,505,881	1.01	
R-0	83,416,642,063	3,503,498,966,642	2,110,984,168,748	0.60	
	1,521,928,302,462	**63,920,988,703,414**	**21,533,315,463,568**	**0.34**	**1,186,413,661,954**

Overall water-to-oil ratios are significantly less than one except for two lean zones.

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Conclusions

- Clay, mainly illite, is the most important source of water in the lower, illite rich part of the oil shale interval (R-0 through L-1 zones) and throughout the Green River Formation in basin margin areas.
- Nahcolite and dawsonite are the dominant sources of water in the oil shale and saline mineral depocenter.
- Analcime is an important source of water in the upper part of the Parachute Creek Member in the central part of the basin and throughout that member in basin-margin areas.

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Conclusions

- Organic matter does not appear to be a major source of water. *Water content is, in general, inversely related to oil content in non-nahcolite-bearing zones suggesting that organic-matter is diluting water-bearing phases.*
- The ratio of water-to-oil generated with retorting is significantly less than one for most areas of the basin and for most stratigraphic intervals; therefore, water within oil shale can provide only a fraction of the water needed for an oil shale industry.

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