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Open-File Report 2008–1220

U.S. Department of the Interior
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Suggested citation:
Dyni, J.R., 2008, Preliminary stratigraphic cross sections of oil shale in the Eocene Green River Formation, Uinta Basin, Utah: U.S. Geological Survey Open-File Report 2008–1220, 11 p.

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Abstract

Oil shale units in the Eocene Green River Formation are shown on two east-west stratigraphic sections across the Uinta Basin in northeastern Utah. Several units have potential value for recovery of shale oil, especially the Mahogany oil shale zone, which is a high grade oil shale that can be traced across most of the Uinta Basin and into the Piceance Basin in northwestern Colorado. Many thin medium to high grade oil shale beds above the Mahogany zone can also be traced for many miles across the basin. Several units below the Mahogany that have slow velocities on sonic logs may be low grade oil shale. These may have value as a source for shale gas.

Introduction

The oil shale deposits of the Eocene Green River Formation in Colorado, Utah, and Wyoming, constitute the world's largest known oil shale resource—an estimated 1.5 trillion barrels of in-place shale oil from units that yield 15 or more gallons of oil per short ton (gpt) (Dyni, 2005, p. 29). For the Uinta Basin in northeastern Utah, 214 billion barrels were estimated by Trudell and others (1983, p. 57), and 320 billion barrels by Cashion (1967); however it seems likely that the total resource for Green River strata in the basin yielding 15 or more gpt will exceed 400 billion barrels.

Early attempts to conduct an oil shale operation in the shale-oil-rich Mahogany zone of the Green River Formation were not successful, owing to the fact that the price of shale oil could not economically compete with more cheaply produced petroleum. Today, with the high prices for crude oil, there is renewed interest in the development of these deposits. Under the auspices of the U.S. Bureau of Land Management, a new research, development, and demonstration (RD&D) program was initiated to attract private companies to develop improved methods of extracting shale oil from the Green River deposits. In Utah, under this program, a company has acquired a

160-acre Federal RD&D lease that includes the abandoned White River oil shale mine located 45 mi southeast of Vernal, Utah.

In response to the renewed interest in shale oil as an alternative energy source, a cooperative project between the U.S. Geological Survey (USGS) and the Utah Geological Survey (UGS) was initiated to compile available assay data and to summarize stratigraphic information on the oil shale-bearing units of the Green River Formation in the Uinta Basin in northeastern Utah.The project was under the direction of the author and D.E. Tabet of the UGS. Part I of the project consisted of (1) collecting digitized Fischer assays of samples from boreholes in the Uinta Basin in cooperation with the U.S. Department of Energy; (2) compiling stratigraphic-unit identifications in boreholes by J.R. Donnell (USGS); and (3) providing the UGS with geophysical logs and other data on wells drilled for oil shale that were collected by the USGS. The results of Part I were published by Dyni and others (2006) and Vanden Berg and others (2006).

Part II of the USGS-UGS cooperative project is the subject of the present report. It consists of (1) preparation of two stratigraphic cross sections showing the detailed correlation of oil shale units in the Green River Formation across the Uinta Basin, and (2) use of geophysical logs and bar graphs of Fischer assays as the primary tools for interpreting subsurface stratigraphic relations.

Acknowledgments

This report was reviewed by Ronald C. Johnson and Kendell A. Dickinson (USGS), and D. E. Tabet (UGS). Michael Brownfield (USGS) prepared the base map for figure 1 and Steve Cazenave (USGS) aided the author with the graphics programs and printed plates 1 and 2.

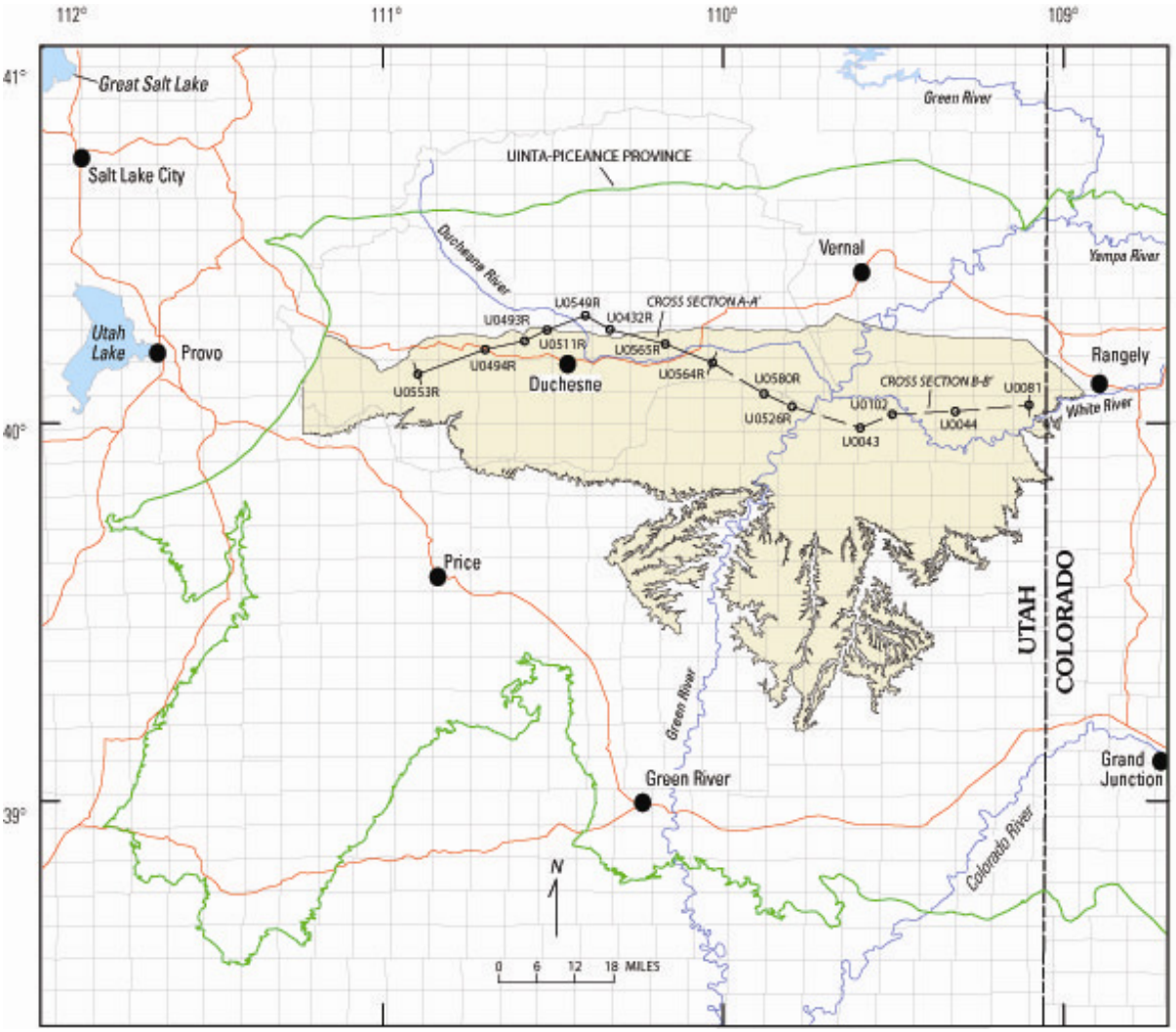

Figure 1. Map of the Uinta Basin showing the lines of cross sections A-A'(solid line) and B-B' (dashed line) across the Uinta Basin, Utah. The boundary of the Uinta-Piceance Province is shown in green. The shaded area depicts the areal distribution of oil shale in the Green River Formation that crops out on the south side and dips northward beneath overburden to an arbitrary depth of 6,000 ft below the surface on the north side. Sources for the geologic data for this illustration are from Cashion (1973), Johnson and Roberts (2003), Rowley and others (1985), and Witkind (1995).

Methodology

Figure 1 shows the locations of the two stratigraphic sections A-A' (pl. 1) and B-B' (pl. 2) that were constructed to show the subsurface correlation of units of oil shale in the Green River Formation along an east-west line across the Uinta Basin in northeastern Utah. The two sections generally follow the same lines as were used for two stratigraphic cross sections prepared earlier by Johnson (1989). However, the units of oil shale are shown in greater detail than his sections,

which portrayed, at a smaller scale, the subsurface stratigraphy of a sequence that included both Upper Cretaceous and lower Tertiary rocks across the Uinta Basin and extending into the Piceance Basin in northwestern Colorado.

Cross section A-A' (pl. 1) begins in the western part of the Uinta Basin at oil and gas well U553R (Shell Oil Co., Ute 1-16, in section 16, T. 4 S., R. 9 W., Wasatch County), and extends about 50 mi eastward to oil and gas well U564R (Sun Oil Co., Daniel Uresk 1, in sec. 6, T. 4 S., R. 1 W., Duchesne County). Section B-B' (pl. 2) extends eastward from well U564R to core hole U081 (Quintana Minerals, SYN-1, in sec. 16, T. 9 S., R. 25 E., Uintah County), a distance of about 56 mi. The total distance represented by the two cross sections is 106 mi.

The stratigraphic datum for the two sections is the Mahogany oil shale bed, a thin bed of high-grade oil shale that forms a prominent unit in the upper middle part of the Mahogany zone in the upper part of the Green River Formation. The bed is easily recognized on most sonic logs and assay bar graphs, and can be traced across the entire width of the Piceance Basin in Colorado, and for more than 100 mi westward across the Uinta Basin.

Fischer assays of rotary cuttings from wells drilled for oil and gas were commonly made on samples representing 5 or 10 ft of drilled hole. As a result, the bar graphs of cuttings do not show as much detail as bar graphs of core holes in which continuous 1 to 2 ft of core were assayed. In addition, rotary cuttings must be adjusted (lagged) to the depths being drilled; otherwise, the assays of the samples may not coincide with the oil shale units depicted on the sonic log (for example, see note with borehole U511R near the Mahogany bed). Cavings from upper parts of the hole may mix with the cuttings at the drill bit, giving erroneous assay results. The bar graphs of oil yields of well cuttings, however, show some useful details when used in conjunction with sonic logs.

Cross sections A-A' and B-B' were constructed from available sonic logs and bar graphs of shale oil (Fischer) assays from boreholes in the Uinta Basin. Ideally, the best data set includes a sonic log combined with assays made on core samples from boreholes drilled specifically for oil shale. However, in areas lacking core information, assays of rotary cuttings from some oil and gas test holes made by the former U.S. Bureau of Mines (USBM) were used if a good sonic log was also available. Density logs could also be used, but they seemed to be less reliable for defining oil shale beds.

Because of the large increase in the thickness of the Green River Formation from east to west in the Uinta Basin, the vertical scale of the cross sections changes from 1 in = 200 ft on

section A-A' to 1 in = 100 ft on section B-B' in order to provide as much detail as practicable. These original scales are preserved in the digital files of both sections, but the printed scales are less because of printer restrictions.

The two stratigraphic sections were prepared in Adobe Illustrator© using oil shale analyses (Fischer assays) and sonic logs. The assays were made by the former USBM, Laramie, Wyoming.

Sonic logs have long been recognized as a useful tool for defining beds of oil shale (for example, Cashion and Donnell, 1972; Trudell and others, 1983). These logs, being sensitive to changes in bulk rock density record the high contrast in density between the organic matter (~1.0 gm/cc) and mineral matrix (~2.7-2.8 gm/cc) that characterizes Green River oil shale strata. (See the sonic logs and assay bar graphs for core holes U043 and U044 on Section B-B'.) The sonic curve can be used to approximate the shale-oil content when calibrated with Fischer assays. However, some sonic logs are not wholly reliable predictors of the shale oil yield, because the logging tool may not have compensated for borehole rugosity, owing in part to older logging tool technology. This results in "cycle skips" which appear as sharp prominent peaks on the sonic log.

The sonic log curves shown on sections A-A' and B-B' (pls. 1,2) were digitized from paper copies of the logs using Golden Software program, Didger©. Graphs of the assays and sonic logs were prepared using Golden Software Grapher©. The Grapher files, in vector format, were copied directly into Adobe Illustrator©. Vector files are preferable to raster files because (1) the latter files can be very large, (2) paper copies of the sonic logs commonly contain errors in depths that are difficult to correct, and (3) paper copies are commonly faded and difficult to read, requiring interpretation. These problems make raster files of older geophysical logs difficult to manipulate in the final illustrations.

The sonic log curve and the Fischer assay bar graph of rotary cuttings from boreholes commonly do not coincide in depth probably owing to discrepancies in sampling. Therefore, it is assumed that the depths for the sonic log are accurate and the assayed sample depths are then adjusted to fit the sonic log.

The horizontal scales for the sonic logs (sonic transit time in microseconds/ft) and bar graphs of the Fischer assays change from borehole to borehole in order to emphasize the details in both sets of data. The boreholes are not proportionally spaced on the sections to actual distances between them.

Previous Work

Several studies of the stratigraphy and shale-oil resources of the Green River Formation oil shale deposits in the Uinta Basin have been published. Cashion and Donnell (1972) correlated the rich Mahogany oil shale zone and other key units of oil shale from the eastern part of the Piceance Basin, Colorado, to the Gulf Oil Corp., Five Mile Draw No. 2 oil and gas test in T. 6 S., R. 5 W. in the southwestern part of the Uinta Basin, Duchesne County, Utah,. Trudell and others (1983) published a study of the Mahogany zone and associated oil shale resources of the Green River Basin in eastern Uinta Basin but used different stratigraphic terminology than that used by the USGS. Several oil shale zones were recognized in the eastern part of the Uinta Basin by Dyni and others (1991) in a study of the shale oil resources of the Mahogany oil shale zone. Johnson (1989) showed two stratigraphic sections correlating Upper Cretaceous and lower Tertiary rocks in the Uinta and Piceance Basins, including the major oil shale zones stratigraphically upward from the R-4 unit through the Mahogany oil shale zone.

Stratigraphy

The Eocene Green River Formation, host to the world's largest resource of oil shale in Colorado, Wyoming, and Utah, occupies much of the Uinta Basin in northeastern Utah. In the eastern and southern parts of the basin, Green River rocks, including oil shale, reach the surface. The formation dips northward at low angles beneath younger Tertiary rocks toward the axis of the basin.

The Green River consists largely of fine-grained lacustrine and fluvial-lacustrine rocks that were deposited in a large epicontinental lake occupying the present sites of the Uinta and Piceance Basins during Eocene time. Much of the Green River sequence contains at least some organic matter derived from aquatic microorganisms, including probable cyanobacteria and other organisms such as sulfate-reducers. The bottom sediments were probably largely anaerobic and interstitial waters were alkaline and rich in H2S and CO2, which favored the accumulation and preservation of organic matter in the basin sediments. Aperiodically, volcanic ash of latitic and dacitic composition fell directly into the Eocene lake or was washed in from surrounding land areas. The formation thickens from east to west across the Uinta Basin. In borehole, U549R on section A-A' (pl. 1), it reaches a thickness of about 10,300 ft (Johnson, 1989).

The most prominent beds of oil shale are in a sequence ranging in thickness from about 750 ft on the east side of the basin to about 1260 ft in borehole U494R. This sequence consists of the

Mahogany oil shale zone and, in descending order, the R-6, R-5, and R-4 oil shale zones below (pls. 1 and 2).

Stratigraphically lower, rich oil shale zones, including R-1, R-2, and R-3, are present In the Piceance Basin in Colorado, but are not recognized in the Uinta Basin where they have graded laterally into organically lean rocks. However, further study may show them to be present. In the depocenter of the Piceance Basin, all of the R zones and the Mahogany zone are composed of medium- to high-grade oil shale. The Mahogany zone is relatively high grade over much of the Piceance and Uinta Basins, although it thins westward across the Uinta Basin. Most of the fine-grained rocks of the formation yield at least a few gallons of shale oil per ton.

A series of thin oil shale beds above the Mahogany zone can be traced over many hundreds of square miles in the Piceance and Uinta Basins. No attempt was made to correlate these beds on cross sections A-A' and B-B' (pls. 1,2). However, they are identified on the Fischer assay bar graph for core hole U043 on plate 2 and in greater detail in figure 2. In this figure, 40 individual beds are labeled 2 through 76?, mostly in even-numbered beds. Donnell (1997, fig. 2) has shown that most of these beds can be traced from the Piceance Basin westward into the Uinta Basin. Prominent oil shale beds in this sequence include the Four Senators, the Stillwater zone, and the Big 3. These units were formally named by Cashion and Donnell (1972) but were used informally in earlier geologic mapping in the Piceance Basin by Duncan and Denson (1949) and other workers.

Relatively thick unnamed units of oil shale are present above and below the Mahogany zone. One unit, about 100 ft thick and lying about 70 ft above the A Groove, is defined by the sequence extending from the base of oil shale bed 22 upward to a few feet above oil shale bed 38 (see borehole U043 on pl. 2 and fig. 2). It is a continuous unit on section B-B' but loses its identity westward on section A-A' (pl. 1). Other possible oil shale units are present below the R-4 zone; these are shown on both cross sections.

In the western part of the Uinta Basin, an unit, ranging from about 800 to 1,000 ft thick, is present in boreholes U493R and U494R' (pl. 1) at depths about 1,600 and 1,800 ft, respectively. Although the unit consists of low-grade oil shale (~5-10 gpt), it might thicken westward and become richer in grade.

The deepest units of questionable oil shale on the two cross sections are in borehole U549R (pl. 1) between the depths of 12,250 and 12,600 ft. If these units prove to be organic-rich, they may have potential value for shale gas.

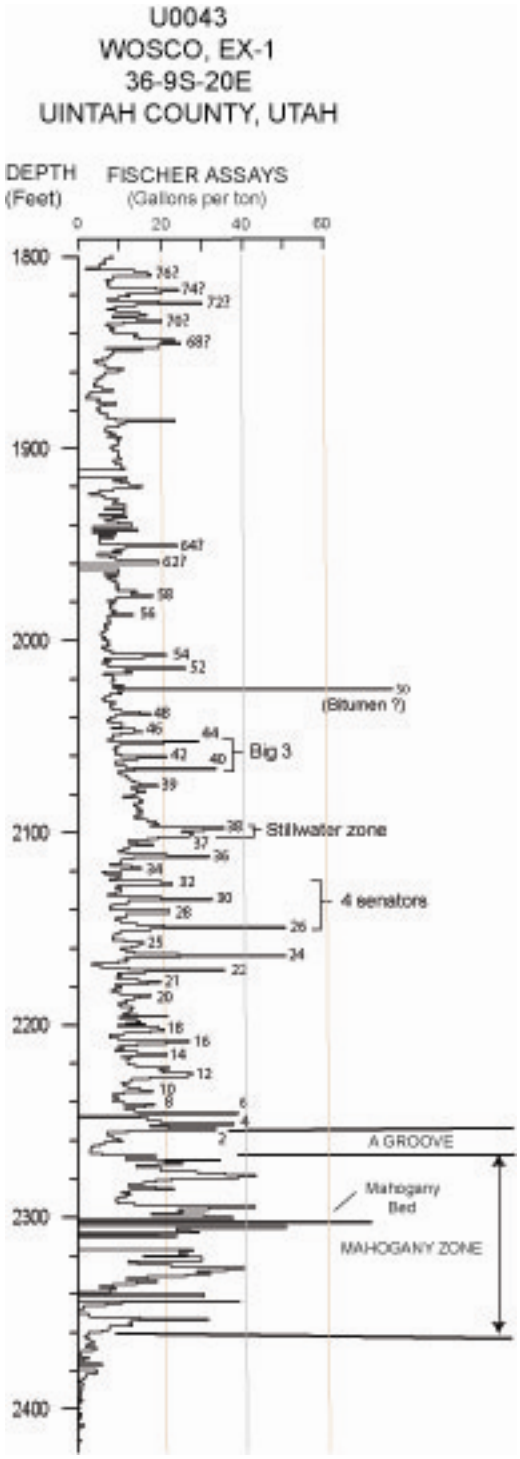

Figure 2. Numbered oil shale beds in core hole U0043 in the upper part of the Green River Formation above the Mahogany oil shale zone.

Non-Oil-Shale Marker Beds

Some marker beds shown on Johnson's (1989) cross sections were not recognized on cross sections A-A' and B-B', but are traceable on resistivity and lithologic logs. One such unit is the Horse Bench Sandstone Bed, which crops out in Indian Canyon southwest of Duchesne, Utah, and in adjacent drainages. In an unpublished surface section measured in Indian Canyon by the author and W.B. Cashion, the Horse Bench is 33 ft thick and lies 538 ft above the Mahogany bed. It can be traced northward into the subsurface on resistivity logs, but it disappears farther to the north toward the depocenter of the Uinta Basin. The Horse Bench Sandstone appears to be correlative with the Bird's nest zone, an evaporite facies that crops out in the eastern part of the Uinta Basin.

A number of tuffs within the Green River Formation can be traced throughout the Uinta and Piceance Basins, but because they are thin, commonly less than 1 ft thick, they are difficult to recognize on sonic logs. The thickest tuff noted in this study, the Porcupine Creek tuff, about 20 to 25 ft thick between oil shale beds 70 and 72 (Donnell, 1997, fig. 2), is thought to be correlative with the Horse Bench Sandstone Bed of Indian Canyon , although the interval between the Horse Bench and the Mahogany zone seems too small.

The carbonate marker bed of Ryder and others (1976) and the Long Point bed of the Garden Gulch? Member are prominent units in the lower part of the Green River Formation (Johnson, 1989). These beds are shown on sections A-A' and B-B', although they were not recognized on the sonic logs.

Oil Shale Resources

In this study resources were not estimated, but others have made estimates for the eastern part of the basin with emphasis on the Mahogany zone (Cashion, 1967; Trudell and others, 1983; Dyni and others, 1991). The development of newer retorting techniques, especially by *in situ* methods, which is being pursued by several energy companies in Colorado, may result in shale oil production from deeper , previously unrecognized, oil shale beds.

Recommendations for Future Work

Detailed lithologic logs, which are available for some boreholes shown on the two cross sections, were not included. In future work, it would be desirable to show lithostratigraphic units to gain a better understanding of the overall lithostratigraphy of the Green River Formation in the Uinta Basin.

Lithologic logs of some core holes, which are available at the UGS and the USGS, should be digitized. A consistent nomenclature for different lithologies encountered in logging oil shale cores should be developed. Geophysical logs, especially sonic and density logs, for selected boreholes that penetrate the Green River Formation should be digitized as vector files in ASCII format. This would facilitate the construction of cross sections, the modeling of the thickness and grade of economic beds of oil shale, and the processing of data for other purposes.

Preliminary review of geophysical logs of core holes south of cross sections A-A' and B-B' indicate that the oil shale units in the Parachute Creek Member are better defined that the units shown on plates 1 and 2. Additional stratigraphic sections would help clarify the stratigraphy of oil shale units in the southern part of the Uinta Basin.

In the southwestern part of the Uinta Basin, few exploratory core holes have been drilled for oil shale. Reconnaissance field studies indicate that evaporitic organic marlstones in the southwestern part of the basin may equate with the evaporite facies exposed in the lower reaches of Indian Canyon southwest of Duchesne, Utah. Examination of sonic and gravity logs of oil and gas tests would furnish additional details of the stratigraphy of the Green River Formation in this part of the basin.

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