ORIGIN AND RESOURCES OF WORLD OIL SHALE DEPOSITS

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Summary

Oil shale is a fine-grained organic-rich sedimentary rock that can produce substantial amounts of oil and combustible gas upon destructive distillation. Oil shales are found in many areas of the world. They range from Precambrian to Tertiary in age and occur in terrestrial, lacustrine, and marine depositional settings. Much of the organic matter in oil shale is derived from microscopic forms of algae with admixtures of spores, waxes, pollen, and fragments of vascular land plants as well as other microorganisms of terrestrial, lacustrine, and marine origin. Because of their wide diversity in mineralogy and organic matter, oil shales have received many local names, which has hampered their classification until recent years when blue/ultraviolet fluorescent microscopy began to be used for their study.

The grade of oil shale ranges from a few tens of liters to more than 400 liters per metric ton ($L\ t^{-1}$) of rock. With today's technology, potentially economic grades of oil shale begin at about 80 $L\ t^{-1}$. The total resource of world oil shales that will yield at least 40 $L\ t^{-1}$ is estimated conservatively at 411 billion metric tons (~2.9 trillion US barrels) of in-place shale oil. More than one-third of this total is in the Tertiary Green River Formation in western United States. Other important resources of oil shale are located in Brazil, Estonia, Australia, China, Russia, Jordan, and Israel.

In the next 25 to 50 years, as the supplies of crude oil diminish, oil shale may become an important source of hydrocarbons as well as a source of petrochemicals, building materials, industrial minerals, and metals such as uranium and vanadium. However, mining and processing oil shale will need to overcome significant environmental concerns including contamination of surface and ground waters and air pollution, through development of improved or new extractive technologies.

1. Introduction

Oil shale occurs in many areas of the world. Deposits of oil shale range from Cambrian to Tertiary in age and are found as minor occurrences of no economic value to world-class deposits occupying thousands of square kilometers and reaching 600 meters in thickness.

Oil shales were deposited in a wide variety of depositional environments. These include small to large freshwater to highly saline lakes, epicontinental marine basins and related subtidal shelves, and in association with coal deposits that were deposited in limnic and coastal swamps. Because of this wide diversity of depositional environments, it is not surprising that oil shales range widely in their organic and mineralogical composition.

The precursor organisms whose remains make up the organic matter in oil shale are also diverse. Much of the organic matter, characteristically rich in hydrogen, is of algal origin, but the remains of vascular land-plant materials may constitute a significant component of the organic matter in some oil shales. The origin of some of the organic matter is enigmatic because of the lack of recognizable biologic structures that would identify the precursor organisms. Such materials may be bacterial debris or the product of bacterial degradation of other organic matter.

The mineral fraction of some oil shales is composed of carbonate minerals such as calcite, dolomite, and siderite, with lesser amounts of aluminosilicate minerals whereas, for other oil shales, the reverse is true (quartz, feldspars, and clay minerals are dominant). In many deposits, small but ubiquitous amounts of sulfide minerals (pyrite, marcasite, and pyrrhotite, etc.) attest to dysaerobic or anoxic waters in which the organic matter accumulated and was preserved.

Tectonism and volcanism affected some deposits. Structural deformation leading to folding and faulting may impair recovery of an oil shale resource, whereas volcanism and igneous intrusions can thermally degrade organic matter in oil shale to the point that shale oil can no longer be recovered. Such effects may be local, adversely affecting only a part of a deposit, or they may be widespread, making most or all of the deposit unfit for the recovery of shale oil.

2. Definition of Oil Shale

Underlying most definitions of oil shale is the potential for the economic recovery of energy including shale oil, combustible gas, or heat energy from direct burning. Most oil shales are fine-grained sedimentary rocks containing quantitatively significant amounts of hydrogen-rich organic matter that will yield significant amounts of oil and combustible gas upon destructive distillation. This organic matter, composed chiefly of carbon, hydrogen, and oxygen, is not normally soluble in organic solvents. However, small amounts of bitumen, which is soluble in organic solvents, are often present in oil shale.

Although shale oil in today's (1999) world market is not competitive with petroleum, natural gas, or coal, it is still used in several countries that possess easily exploited deposits of oil shale but lack other fossil fuel resources. Some oil shale deposits contain minerals and metals that may have by-product value. A few examples include nahcolite ($NaHCO_3$), dawsonite ($NaAl(OH)_2CO_3$), sulfur, ammonium sulfate, vanadium, zinc, copper, and uranium.

The gross heating value of oil shales on a dry basis is in the range of 500–4000 kcal kg^{-1} of rock. By comparison, the heating value of lignitic coal is in the range of 3500–4610 kcal kg^{-1} on a dry mineral-free basis.

As with most mineral deposits, the value of an oil shale deposit depends upon its depth, thickness, and grade. The assumption that oil shale has economic potential assumes that the deposit is close enough to the earth's surface where it can be mined by open pit or conventional underground methods.

Scotland, Spain, Sweden, France, Australia, and South Africa are some countries that have had sizable oil shale industries in the past, but these have been closed owing to the availability of cheaper supplies of petroleum. However, oil shale is still being mined today in Estonia, China, Brazil, and Russia.

3. Origin of Organic Matter

The organic matter in oil shale includes the remains of algae (cyanobacteria), spores, pollen, plant cuticle and corky fragments of herbaceous and woody plants, and other cellular remains of lacustrine, marine, and land plants. These materials are composed chiefly of carbon, hydrogen, oxygen, nitrogen, and sulfur. Some of the organic matter retains enough biological structures that genus and species can be identified. In many oil shales much of the organic matter is biologically unstructured and is best described as amorphous organic matter called bituminite.

The origin of this amorphous material is enigmatic but it is likely a mixture of degraded algal and bacterial remains. Small amounts of plant resins and waxes also contribute to the organic matter as well as fragments of vascular land plants. Fossil shell and bone fragments composed of phosphatic and carbonate minerals, although of organic origin, are excluded from the definition of organic matter used herein and are considered to be part of the mineral matrix of the oil shale.

Most oil shales contain a preponderance of organic matter derived from various types of marine and lacustrine algae with admixtures of biologically higher forms of land-plant debris, depending upon the depositional environment and geographic position of the accumulating organic-rich sediments. Bacterial remains may be volumetrically important in many oil shales; however, their identity in oil shales is difficult to determine. Indirect evidence suggests that bacterial processes were important during the deposition and early diagenesis of most oil shales, leading to the formation of authigenic sulfide and carbonate minerals.

Solid hydrocarbons including gilsonite, wurtzilite, grahamite, ozokerite, albertite, and others are found as veins or pods in association with oil shale and related rocks. These hydrocarbons have different chemical and physical characteristics than the oil shales. Several of these hydrocarbons have been mined commercially.

4. Oil Shale Types

Oil shale has been an enigmatic type of rock that has received many different names over the past 200 years. Some of the more colorful names that have been used include cannel coal, boghead coal, alum shale, stellarite, albertite, kerosene shale, bituminite, gas coal, algal coal, wollongite, schistes bitumineux, torbanite, kukersite, and others. Some of these names are still used for certain types of oil shale.

Professor A. C. Hutton, University of Wollongong, Australia, developed a useful classification of oil shales in the 1980s with the aid of blue/ultraviolet fluorescent microscopy. Hutton classified oil shales based on the depositional environment of the oil shale and on the types of the organic matter found in oil shale. His classification has proved to be useful for correlating different kinds of organic matter in oil shale with the chemical properties of the hydrocarbons derived from oil shale.

Hutton recognized oil shale as one of three broad groups of organic-rich sedimentary rocks: (1) humic coal and carbonaceous shale, (2) bitumen-impregnated rock (tar sands and petroleum reservoir rocks), and (3) oil shale. He divided oil shales into three groups based upon their environment of deposition: (a) terrestrial, (b) lacustrine, and (c) marine (Figure 1).

Terrestrial oil shales include those composed of lipid-rich organic matter such as resins, spores, waxy cuticles, and corky tissue of roots and stems of vascular terrestrial plants commonly found in coal-forming swamps and bogs. Lacustrine oil shales include lipid-rich organic matter derived from algae that lived in freshwater, brackish, or saline lakes. Marine oil shales are composed of lipid-rich organic matter derived from marine algae, acritarchs (unicellular organisms of questionable origin), and marine dinoflagellates (one-celled organisms with a flagellum).

Several quantitatively important components of the organic matter in oil shale adapted from coal petrography include telalginite, lamalginite, and bituminite. Telalginite is organic matter derived from large colonial or thick-walled unicellular algae that possess recognizable biologic structures, such as *Botryococcus* and *Tasmanites*. Lamalginite includes thin-walled colonial or unicellular algae that occur as laminae with little or no recognizable biologic structures. Telalginite and lamalginite fluoresce brightly (shades of yellow) under blue/ultraviolet light.

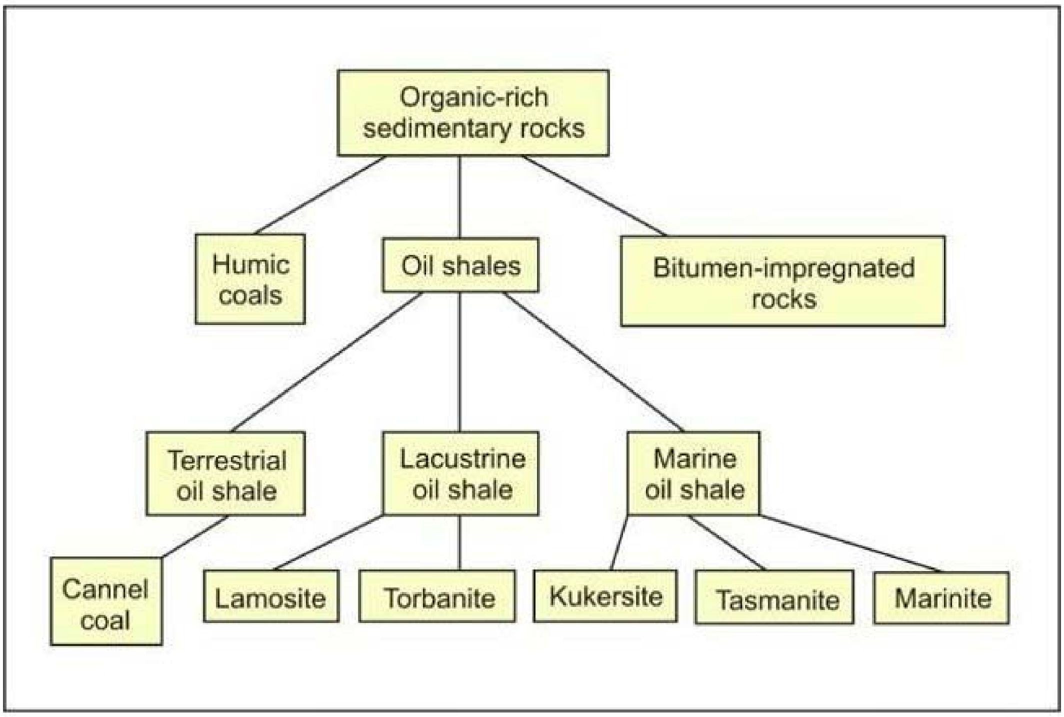

Figure 1. Classification of oil shales. Adapted from Hutton A. C. (1987). Petrographic classification of oil shales. *International Journal of Coal Geology* **8**, 203–231.

Bituminite is an enigmatic component of many oil shales. It is largely amorphous, lacks recognizable biologic structures and displays relatively low fluorescence. Bituminite commonly occurs as an organic groundmass mixed with fine-grained mineral matter. The material has not been fully characterized with respect to its composition or origin but it is often a quantitatively important component in many marine oil shales. Coaly materials including vitrinite and inertinite are present in varied amounts; both are derived from humic matter of land plants and have moderate and high reflectance, respectively, under the microscope.

Within this threefold grouping of oil shales, there are six types of oil shale: cannel coal, lamosite, marinite, torbanite, tasmanite, and kukersite. The economically most important of these are the marinites and the lamosites.

Cannel coal is brown to black oil shale composed of resins, spores, waxes, cutinaceous and corky materials, as well as varied amounts of vitrinite and inertinite, derived from terrestrial vascular plants. Cannel coals originate in oxygen-deficient ponds or shallow lakes in peat-forming swamps and bogs.

Lamosite is pale brown and grayish-brown to dark gray to black oil shale in which the chief organic constituent is lamalginite derived from lacustrine planktonic algae. Other minor components include vitrinite, inertinite, telalginite, and bitumen. The Green River oil shale deposits in western United States and a number of the Tertiary lacustrine deposits in eastern Queensland, Australia, are lamosites.

Marinite is a gray to dark gray to black oil shale of marine origin. The chief organic components are lamalginite and bituminite derived from marine phytoplankton with admixtures of bitumen, telalginite, and vitrinite. Marinites are deposited typically in epeiric seas such as on broad shallow marine shelves or inland seas where wave action and currents are minimal or restricted. The Devonian-Mississippian oil shales of eastern United States are typical marinites. Such deposits can form laterally extensive (thousands of square kilometers), but relatively thin (less than about 100 meters) deposits.

Torbanite, named after Torbane Hill in Scotland, is a black oil shale whose organic matter is telalginite derived largely from lipid-rich *Botryococcus* and related algal forms found in fresh- to brackish-water lakes. Vitrinite and inertinite occur in varied but subordinate amounts.

Tasmanite, named from oil shale deposits in Tasmania, is a brown to black oil shale whose organic matter consists of telalginite derived chiefly from unicellular tasmanitid algae of marine origin with lesser amounts of vitrinite, lamalginite, and inertinite.

Kukersite, which takes its name after Kukruse Manor near the town of Kohtla-Järve, Estonia, is a light brown marine oil shale whose principal organic component is telalginite derived from the green alga *Gloeocapsomorpha prisca*. The important Estonian and Leningrad oil shale deposits of Ordovician age along the southern coast of the Baltic Sea in northern Estonia and eastward into Russia are kukersites.

5. Thermal Maturity

The thermal maturity of an oil shale refers to the degree to which the organic matter has been altered by geothermal heating. If the oil shale is heated to high enough temperatures, as may be the case if the oil shale was deeply buried, the organic matter will decompose to form oil and gas. Under these circumstances, oil shales can become source rocks for petroleum and natural gas. On the other hand, oil shale deposits that have economic potential for production of shale oil and combustible gases are mostly geothermally immature and have not been subjected to excessive heating. Such deposits are generally close enough to the surface to be available for mining by open pit or underground methods.

The degree of thermal maturity of an oil shale can be determined in the laboratory by several methods. One technique is to observe the changes in color of the organic matter in samples collected from varied depths in a borehole. Assuming that the organic matter is subjected to geothermal heating as a function of depth, the colors of certain types of organic matter change from brighter to darker colors with depth. These changes in color can be visually estimated or they can be measured by instrumental techniques.

The geothermal maturity of organic matter in an oil shale can also be determined by measuring the reflectance of vitrinite (a common constituent of coal derived from vascular land plants) that may be present. Vitrinite reflectance determinations are commonly used by petroleum explorers to assess the degree of geothermal alteration of petroleum source rocks in a sedimentary basin. A scale of vitrinite reflectances has been developed that indicates when the organic matter in a sedimentary rock has reached temperatures high enough to form oil and gas.

In some tectonically complex areas where the rocks have been subjected to folding and faulting or have been intruded by igneous rocks, the geothermal maturity of the oil shale must be evaluated in order to determine the economic potential of the deposit.

6. Recoverable Resources

How much shale oil can be recovered from a deposit depends upon many factors. In addition to the tectonic and geothermal history of a deposit, other factors including depth, thickness, grade, by-products, as well as the methods of mining and retorting, determine the overall economics of a profitable oil shale operation. Infrastructure consisting of roads, railroads, power lines, water, available labor, and other factors will also influence the viability of an oil shale operation in a given region. Availability of potential oil shale lands will be determined by their ownership, whether they are in private hands or controlled by the government.

Mining oil shale may be also restricted by surface uses. Densely populated areas (cities and towns), national and state parks, wildlife refuges, and similar entities may limit the available reserves restricting oil shale operations to areas smaller than the original areal extent of the deposit. On the other hand, the development of new *in situ* technologies for recovery of energy from buried deposits of oil shale may allow oil shale facilities to operate closer to population centers without causing significant problems of air and water pollution.

7. Determining the Grade of Oil Shale

The grade of oil shale is determined by many methods and the results are expressed in a variety of units. One method is the determination of the heating value of an oil shale with a calorimeter. The results are commonly reported in English or metric units, such as British thermal units per pound (Btu) of oil shale, calories per gram (cal g^{-1}), kilocalories per kilogram (kcal kg^{-1}), and megajoules per kilogram. The heating value is useful for determining the quality of an oil shale used as a solid fuel in an electric power plant. Although the heating value of an oil shale is a useful and fundamental property of an oil shale, it does not provide information on the amounts of shale oil or combustible gas that an oil shale is capable of producing.

Another way of determining the grade of an oil shale is to measure the quantity of oil that an oil shale can produce by destructive distillation. This type of analysis has been widely used in the past up to the present day. The most common method for determining the oil yield is the Fischer assay.

The standardized Fischer assay method consists of heating a 100-gram sample of minus 8-mesh (minus 2.38 mm mesh) crushed oil shale in a small aluminum retort at a heating rate of 12° per minute up to 500° and holding that temperature for 40 minutes. The distilled vapors of oil, gas, and water from the sample are passed through a condenser cooled with ice water into a graduated centrifuge tube. The oil and water are separated by centrifuging. The weight percentages of shale oil (and its specific gravity), water, retorted shale, and "as plus" by difference are reported in the analysis.

A shortcoming of the Fischer assay method is that it does not measure all of the available energy in an oil shale. When a sample of an oil shale is retorted, the organic matter decomposes into shale oil, gas, and a residuum of organic carbon that remains with the retorted shale. The amounts of individual gases (commonly methane, ethane, hydrogen, and carbon dioxide) and the residual carbon in the retorted shale are not reported.

Another problem with the Fischer assay method is that the oil yield may not be indicative of the maximum amount of oil that can be produced. Some methods can increase the oil yield by as much as 300 to 400% of that obtained by Fischer assay. Thus, the energy potential of an oil shale deposit is only approximated by Fischer assay analyses.

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Biographical Sketch

Dr. John R. Dyni holds degrees from Wayne State University (BS in Geology, 1953), University of Illinois (MS in Geology, 1955), and University of Colorado (Ph.D., 1981). Most of his career has been with the United States Geological Survey in Denver, Colorado (1958–1995). He has published numerous articles on sodium carbonate and oil shale deposits, especially those of the Green River Formation in Colorado, Wyoming, and Utah. Dr. Dyni retired in 1996, but he continues his studies of oil shale and sodium carbonate deposits as Scientist Emeritus with the Geological Survey.