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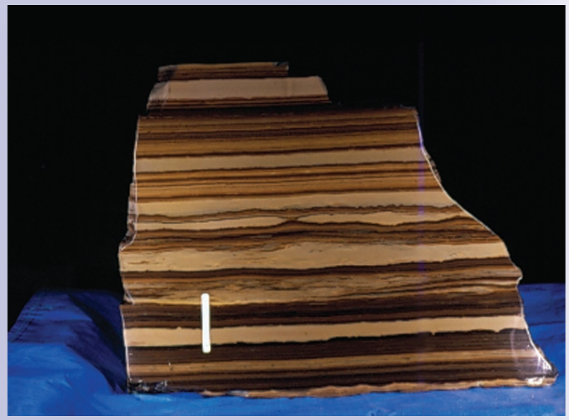
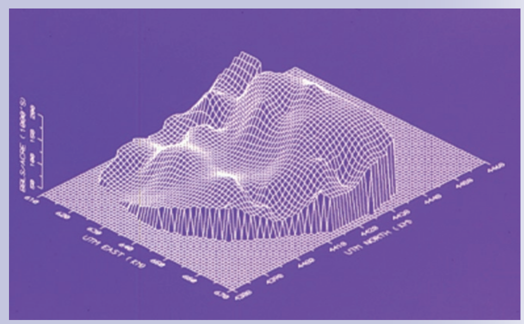
Geology and Resources of Some World Oil-Shale Deposits





Scientific Investigations Report 2005–5294

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

Cover.

Left: New Paraho Co. experimental oil shale retort in the Piceance Creek Basin a few miles west of Rifle, Colorado.

Top right: Photo of large specimen of Green River oil shale interbedded with gray layers of volcanic tuff from the Mahogany zone in the Piceance Creek Basin, Colorado. This specimen is on display at the museum of the Geological Survey of Japan.

Bottom right: Block diagram of the oil shale resources in the Mahogany zone in about 1,100 square miles in the eastern part of the Uinta Basin, Utah. The vertical scale is in thousands of barrels of in-place shale oil per acre and the horizontal scales are in UTM coordinates. Illustration published as figure 17 in U.S. Geological Survey Open-File Report 91-0285.

Geology and Resources of Some World Oil-Shale Deposits

By John R. Dyni

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Dirk Kempthorne, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

Posted onlline June 2006
Version 1.0

This publication is only available online at:
World Wide Web: http://www.usgs.gov/sir/2006/5294

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Suggested citation:
Dyni, J.R., 2006, Geology and resources of some world oil-shale deposits: U.S. Geological Survey Scientific Investigations Report 2005–5294, 42 p.

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Geology and Resources of Some World Oil-Shale Deposits[1]

By John R. Dyni

Abstract

Oil-shale deposits are in many parts of the world. They range in age from Cambrian to Tertiary and were formed in a variety of marine, continental, and lacustrine depositional environments. The largest known deposit is in the Green River Formation in the western United States; it contains an estimated 213 billion tons of in-situ shale oil (about 1.5 trillion U.S. barrels).

Total resources of a selected group of oil shale deposits in 33 countries are estimated at 409 billion tons of in-situ shale oil, which is equivalent to 2.8 trillion U.S. barrels of shale oil. These amounts are very conservative because (1) several deposits mentioned herein have not been explored sufficiently to make accurate estimates, and (2) some deposits were not included in this survey.

Introduction

Oil shale is commonly defined as a fine-grained sedimentary rock containing organic matter that yields substantial amounts of oil and combustible gas upon destructive distillation. Most of the organic matter is insoluble in ordinary organic solvents; therefore, it must be decomposed by heating to release such materials. Underlying most definitions of oil shale is its potential for the economic recovery of energy, including shale oil and combustible gas, as well as a number of byproducts. A deposit of oil shale having economic potential is generally one that is at or near enough to the surface to be developed by open-pit or conventional underground mining or by in-situ methods.

Oil shales range widely in organic content and oil yield. Commercial grades of oil shale, as determined by their yield of shale oil, ranges from about 100 to 200 liters per metric ton (l/t) of rock. The U.S. Geological Survey has used a lower limit of about 40 l/t for classification of Federal oil-shale lands. Others have suggested a limit as low as 25 l/t.

Deposits of oil shale are in many parts of the world. These deposits, which range from Cambrian to Tertiary age, may occur as minor accumulations of little or no economic value or giant deposits that occupy thousands of square kilometers and reach thicknesses of 700 m or more. Oil shales were deposited in a variety of depositional environments, including fresh-water to highly saline lakes, epicontinental marine basins and subtidal shelves, and in limnic and coastal swamps, commonly in association with deposits of coal.

In terms of mineral and elemental content, oil shale differs from coal in several distinct ways. Oil shales typically contain much larger amounts of inert mineral matter (60–90 percent) than coals, which have been defined as containing less than 40 percent mineral matter. The organic matter of oil shale, which is the source of liquid and gaseous hydrocarbons, typically has a higher hydrogen and lower oxygen content than that of lignite and bituminous coal.

In general, the precursors of the organic matter in oil shale and coal also differ. Much of the organic matter in oil shale is of algal origin, but may also include remains of vascular land plants that more commonly compose much of the organic matter in coal. The origin of some of the organic matter in oil shale is obscure because of the lack of recognizable biologic structures that would help identify the precursor organisms. Such materials may be of bacterial origin or the product of bacterial degradation of algae or other organic matter.

The mineral component of some oil shales is composed of carbonates including calcite, dolomite, and siderite, with lesser amounts of aluminosilicates. For other oil shales, the reverse is true—silicates including quartz, feldspar, and clay minerals are dominant and carbonates are a minor component. Many oil-shale deposits contain small, but ubiquitous, amounts of sulfides including pyrite and marcasite, indicating that the sediments probably accumulated in dysaerobic to anoxic waters that prevented the destruction of the organic matter by burrowing organisms and oxidation.

Although shale oil in today's (2004) world market is not competitive with petroleum, natural gas, or coal, it is used in several countries that possess easily exploitable deposits of oil shale but lack other fossil fuel resources. Some oil-shale deposits contain minerals and metals that add byproduct value such as alum [$KAl(SO_4)_2 \cdot 12H_2O$], nahcolite ($NaHCO_3$),

[1]An earlier version of this report was published in Oil Shale, 2003, v. 20, no. 3, p. 193–252.

dawsonite [$NaAl(OH)_2CO_3$], sulfur, ammonium sulfate, vanadium, zinc, copper, and uranium.

The gross heating value of oil shales on a dry-weight basis ranges from about 500 to 4,000 kilocalories per kilogram (kcal/kg) of rock. The high-grade kukersite oil shale of Estonia, which fuels several electric power plants, has a heating value of about 2,000 to 2,200 kcal/kg. By comparison, the heating value of lignitic coal ranges from 3,500 to 4,600 kcal/kg on a dry, mineral-free basis (American Society for Testing Materials, 1966).

Tectonic events and volcanism have altered some deposits. Structural deformation may impair the mining of an oil-shale deposit, whereas igneous intrusions may have thermally degraded the organic matter. Thermal alteration of this type may be restricted to a small part of the deposit, or it may be widespread making most of the deposit unfit for recovery of shale oil.

The purpose of this report is to (1) discuss the geology and summarize the resources of selected deposits of oil shale in varied geologic settings from different parts of the world and (2) present new information on selected deposits developed since 1990 (Russell, 1990).

Recoverable Resources

The commercial development of an oil-shale deposit depends upon many factors. The geologic setting and the physical and chemical characteristics of the resource are of primary importance. Roads, railroads, power lines, water, and available labor are among the factors to be considered in determining the viability of an oil-shale operation. Oil-shale lands that could be mined may be preempted by present land usage such as population centers, parks, and wildlife refuges. Development of new in-situ mining and processing technologies may allow an oil-shale operation in previously restricted areas without causing damage to the surface or posing problems of air and water pollution.

The availability and price of petroleum ultimately effect the viability of a large-scale oil-shale industry. Today, few, if any deposits can be economically mined and processed for shale oil in competition with petroleum. Nevertheless, some countries with oil-shale resources, but lack petroleum reserves, find it expedient to operate an oil-shale industry. As supplies of petroleum diminish in future years and costs for petroleum increase, greater use of oil shale for the production of electric power, transportation fuels, petrochemicals, and other industrial products seems likely.

Determining Grade of Oil Shale

The grade of oil shale has been determined by many different methods with the results expressed in a variety of units. The heating value of the oil shale may be determined using a calorimeter. Values obtained by this method are reported in English or metric units, such as British thermal units (Btu) per pound of oil shale, calories per gram (cal/gm) of rock, kilocalories per kilogram (kcal/kg) of rock, megajoules per kilogram (MJ/kg) of rock, and other units. The heating value is useful for determining the quality of an oil shale that is burned directly in a power plant to produce electricity. Although the heating value of a given oil shale is a useful and fundamental property of the rock, it does not provide information on the amounts of shale oil or combustible gas that would be yielded by retorting (destructive distillation).

The grade of oil shale can be determined by measuring the yield of oil of a shale sample in a laboratory retort. This is perhaps the most common type of analysis that is currently used to evaluate an oil-shale resource. The method commonly used in the United States is called the “modified Fischer assay,” first developed in Germany, then adapted by the U.S. Bureau of Mines for analyzing oil shale of the Green River Formation in the western United States (Stanfield and Frost, 1949). The technique was subsequently standardized as the American Society for Testing and Materials Method D-3904-80 (1984). Some laboratories have further modified the Fischer assay method to better evaluate different types of oil shale and different methods of oil-shale processing.

The standardized Fischer assay method consists of heating a 100-gram sample crushed to –8 mesh (2.38-mm mesh) screen in a small aluminum retort to 500ºC at a rate of 12ºC per minute and held at that temperature for 40 minutes. The distilled vapors of oil, gas, and water are passed through a condenser cooled with ice water into a graduated centrifuge tube. The oil and water are then separated by centrifuging. The quantities reported are the weight percentages of shale oil (and its specific gravity), water, shale residue, and “gas plus loss” by difference.

The Fischer assay method does not determine the total available energy in an oil shale. When oil shale is retorted, the organic matter decomposes into oil, gas, and a residuum of carbon char remaining in the retorted shale. The amounts of individual gases—chiefly hydrocarbons, hydrogen, and carbon dioxide—are not normally determined but are reported collectively as “gas plus loss,” which is the difference of 100 weight percent minus the sum of the weights of oil, water, and spent shale. Some oil shales may have a greater energy potential than that reported by the Fischer assay method depending on the components of the “gas plus loss.”

The Fischer assay method also does not necessarily indicate the maximum amount of oil that can be produced by a given oil shale. Other retorting methods, such as the Tosco II process, are known to yield in excess of 100 percent of the yield reported by Fischer assay. In fact, special methods of retorting, such as the Hytort process, can increase oil yields of some oil shales by as much as three to four times the yield obtained by the Fischer assay method (Schora and others, 1983; Dyni and others, 1990). At best, the Fischer assay method only approximates the energy potential of an oil-shale deposit.

Newer techniques for evaluating oil-shale resources include the Rock-Eval and the "material-balance" Fischer assay methods. Both give more complete information about the grade of oil shale, but are not widely used. The modified Fischer assay, or close variations thereof, is still the major source of information for most deposits.

It would be useful to develop a simple and reliable assay method for determining the energy potential of an oil shale that would include the total heat energy and the amounts of oil, water, combustible gases including hydrogen, and char in sample residue.

Origin of Organic Matter

Organic matter in oil shale includes the remains of algae, 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 organic matter retains enough biological structures so that specific types can be identified as to genus and even species. In some oil shales, the organic matter is unstructured and is best described as amorphous (bituminite). The origin of this amorphous material is not well known, but it is likely a mixture of degraded algal or bacterial remains. Small amounts of plant resins and waxes also contribute to the organic matter. 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 of the organic matter in oil shales is derived from various types of marine and lacustrine algae. It may also include varied admixtures of biologically higher forms of plant debris that depend on the depositional environment and geographic position. Bacterial remains can be volumetrically important in many oil shales, but they are difficult to identify.

Most of the organic matter in oil shale is insoluble in ordinary organic solvents, whereas some is bitumen that is soluble in certain organic solvents. Solid hydrocarbons, including gilsonite, wurtzilite, grahamite, ozokerite, and albertite, are present as veins or pods in some oil shales. These hydrocarbons have somewhat varied chemical and physical characteristics, and several have been mined commercially.

Thermal Maturity of Organic Matter

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 a high enough temperature, as may be the case if the oil shale were deeply buried, the organic matter may thermally decompose to form oil and gas. Under such circumstances, oil shales can be source rocks for petroleum and natural gas. The Green River oil shale, for example, is presumed to be the source of the oil in the Red Wash field in northeastern Utah. On the other hand, oil-shale deposits that have economic potential for their shale-oil and gas yields are geothermally immature and have not been subjected to excessive heating. Such deposits are generally close enough to the surface to be mined by open-pit, underground mining, or by in-situ 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 lighter to darker colors. These color differences can be noted by a petrographer and measured using photometric techniques.

Geothermal maturity of organic matter in oil shale is also determined by the reflectance of vitrinite (a common constituent of coal derived from vascular land plants), if present in the rock. Vitrinite reflectance is commonly used by petroleum explorationists to determine 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 generate oil and gas. However, this method can pose a problem with respect to oil shale, because the reflectance of vitrinite may be depressed by the presence of lipid-rich organic matter.

Vitrinite may be difficult to recognize in oil shale because it resembles other organic material of algal origin and may not have the same reflectance response as vitrinite, thereby leading to erroneous conclusions. For this reason, it may be necessary to measure vitrinite reflectance from laterally equivalent vitrinite-bearing rocks that lack the algal material.

In areas where the rocks have been subjected to complex folding and faulting or have been intruded by igneous rocks, the geothermal maturity of the oil shale should be evaluated for proper determination of the economic potential of the deposit.

Classification of Oil Shale

Oil shale has received many different names over the years, such as cannel coal, boghead coal, alum shale, stellarite, albertite, kerosene shale, bituminite, gas coal, algal coal, wollongite, schistes bitumineux, torbanite, and kukersite. Some of these names are still used for certain types of oil shale. Recently, however, attempts have been made to systematically classify the many different types of oil shale on the basis of the depositional environment of the deposit, the petrographic character of the organic matter, and the precursor organisms from which the organic matter was derived.

A useful classification of oil shales was developed by A.C. Hutton (1987, 1988, 1991), who pioneered the use of blue/ultraviolet fluorescent microscopy in the study of oil-shale deposits of Australia. Adapting petrographic terms from coal terminology, Hutton developed a classification of oil shale based primarily on the origin of the organic matter. His classification has proved to be useful for correlating different kinds of organic matter in oil shale with the chemistry of the hydrocarbons derived from oil shale.

Hutton (1991) visualized oil shale as one of three broad groups of organic-rich sedimentary rocks: (1) humic coal and carbonaceous shale, (2) bitumen-impregnated rock, and (3) oil shale. He then divided oil shale into three groups based upon their environments of deposition—terrestrial, lacustrine, and marine (fig. 1).

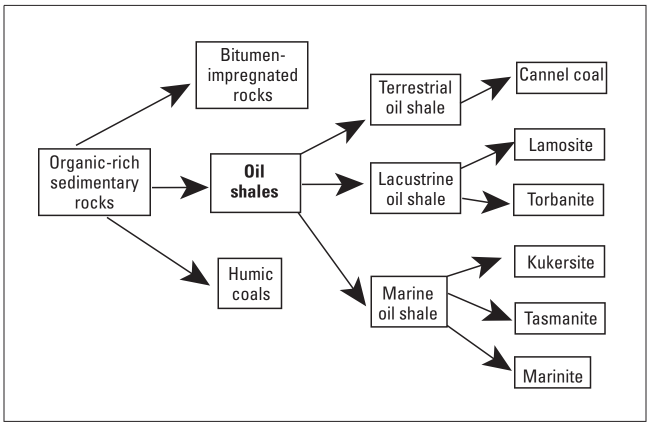


Figure 1. Classification of oil shales. Adapted from Hutton (1987).

Terrestrial oil shales include those composed of lipid-rich organic matter such as resin 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.

Several quantitatively important petrographic components of the organic matter in oil shale—telalginite, lamalginite, and bituminite—are adapted from coal petrography. Telalginite is organic matter derived from large colonial or thick-walled unicellular algae, typified by genera such as Botryococcus. Lamalginite includes thin-walled colonial or unicellular algae that occurs as laminae with little or no recognizable biologic structures. Telalginite and lamalginite fluoresce brightly in shades of yellow under blue/ultraviolet light.

Bituminite, on the other hand, is largely amorphous, lacks recognizable biologic structures, and weakly fluoresces under blue light. It commonly occurs as an organic groundmass with fine-grained mineral matter. The material has not been fully characterized with respect to its composition or origin, but it is commonly an important component of marine oil shales. Coaly materials including vitrinite and inertinite are rare to abundant components of oil shale; both are derived from humic matter of land plants and have moderate and high reflectance, respectively, under the microscope.

Within his three-fold grouping of oil shales (terrestrial, lacustrine, and marine), Hutton (1991) recognized six specific oil-shale types: cannel coal, lamosite, marinite, torbanite, tasmanite, and kukersite. The most abundant and largest deposits are marinites and lamosites.

Cannel coal is brown to black oil shale composed of resins, spores, waxes, and cutinaceous and corky materials derived from terrestrial vascular plants together with varied amounts of vitrinite and inertinite. Cannel coals originate in oxygen-deficient ponds or shallow lakes in peat-forming swamps and bogs (Stach and others, 1975, p. 236–237).

Lamosite is pale- and grayish-brown and dark gray to black oil shale in which the chief organic constituent is lamalginite derived from lacustrine planktonic algae. Other minor components in lamosite 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 in which the chief organic components are lamalginite and bituminite derived chiefly from marine phytoplankton. Marinite may also contain small amounts 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 is restricted and currents are minimal. The Devonian–Mississippian oil shales of eastern United States are typical marinites. Such deposits are generally widespread covering hundreds to thousands of square kilometers, but they are relatively thin, often less than about 100 m.

Torbanite, tasmanite, and kukersite are related to specific kinds of algae from which the organic matter was derived; the names are based on local geographic features. Torbanite, named after Torbane Hill in Scotland, is a black oil shale whose organic matter is composed mainly of telalginite derived largely from lipid-rich Botryococcus and related algal forms found in fresh- to brackish-water lakes. It also contains small amounts of vitrinite and inertinite. The deposits are commonly small, but can be extremely high grade. Tasmanite, named from oil-shale deposits in Tasmania, is a brown to black oil shale. The organic matter consists of telalginite derived chiefly from unicellular tasmanitid algae of marine origin and lesser amounts of vitrinite, lamalginite, and inertinite. Kukersite, which takes its name from Kukruse Manor near the town of Kohtla-Järve, Estonia, is a light brown marine oil shale. Its principal organic component is telalginite derived from the green alga, *Gloeocapsomorpha prisca*. The Estonian oil-shale deposit in northern Estonia along the southern coast of the Gulf of Finland and its eastern extension into Russia, the Leningrad deposit, are kukersites.

Evaluation of Oil-Shale Resources

Relatively little is known about many of the world's deposits of oil shale and much exploratory drilling and analytical work need to be done. Early attempts to determine the total size of world oil-shale resources were based on few facts, and estimating the grade and quantity of many of these resources were speculative, at best. The situation today has not greatly improved, although much information has been published in the past decade or so, notably for deposits in Australia, Canada, Estonia, Israel, and the United States.

Evaluation of world oil-shale resources is especially difficult because of the wide variety of analytical units that are reported. The grade of a deposit is variously expressed in U.S. or Imperial gallons of shale oil per short ton (gpt) of rock, liters of shale oil per metric ton (l/t) of rock, barrels, short or metric tons of shale oil, kilocalories per kilogram (kcal/kg) of oil shale, or gigajoules (GJ) per unit weight of oil shale. To bring some uniformity into this assessment, oil-shale resources in this report are given in both metric tons of shale oil and in equivalent U.S. barrels of shale oil, and the grade of oil shale, where known, is expressed in liters of shale oil per metric ton (l/t) of rock. If the size of the resource is expressed only in volumetric units (barrels, liters, cubic meters, and so on), the density of the shale oil must be known or estimated to convert these values to metric tons. Most oil shales produce shale oil that ranges in density from about 0.85 to 0.97 by the modified Fischer assay method. In cases where the density of the shale oil is unknown, a value of 0.910 is assumed for estimating resources.

Byproducts may add considerable value to some oil-shale deposits. Uranium, vanadium, zinc, alumina, phosphate, sodium carbonate minerals, ammonium sulfate, and sulfur are some of the potential byproducts. The spent shale after retorting is used to manufacture cement, notably in Germany and China. The heat energy obtained by the combustion of the organic matter in oil shale can be used in the cement-making process. Other products that can be made from oil shale include specialty carbon fibers, adsorbent carbons, carbon black, bricks, construction and decorative blocks, soil additives, fertilizers, rock wool insulating material, and glass. Most of these uses are still small or in experimental stages, but the economic potential is large.

This appraisal of world oil-shale resources is far from complete. Many deposits are not reviewed because data or publications are unavailable. Resource data for deeply buried deposits, such as a large part of the Devonian oil-shale deposits in eastern United States, are omitted, because they are not likely to be developed in the foreseeable future. Thus, the total resource numbers reported herein should be regarded as conservative estimates. This review focuses on the larger deposits of oil shale that are being mined or have the best potential for development because of their size and grade.

Australia

The oil-shale deposits of Australia range from small and noneconomic to deposits large enough for commercial development. The "demonstrated" oil-shale resources of Australia total 58 billion tons, from which about 3.1 billion tons of oil (24 billion barrels) is recoverable (Crisp and others, 1987, p. 1) (table 1).

Australian oil-shale deposits range in age from Cambrian to Tertiary and are diverse in origin. The deposits are located in the eastern one-third of the country, including Queensland, New South Wales, South Australia, Victoria, and Tasmania (fig. 2). The deposits having the best potential for economic development are those located in Queensland and include the lacustrine Rundle, Stuart, and Condor deposits of Tertiary age. The marine Toolebuc oil shale of Early Cretaceous age occupies a large area mostly in Queensland. The torbanite deposits at Joadja Creek and Glen Davis in New South Wales and the tasmanite deposits in Tasmania were mined for shale oil in the last half of the 1800s and into the early 1900s. The remaining resources of these high-grade deposits are not commercially important (Alfredson, 1985, p. 162). Some of the colorful history of the oil-shale operations at Joadja Creek is described by Knapman (1988). Glen Davis, which closed in 1952, was the last oil-shale operation in Australia until the Stuart Project began operations in the late 1990s. About 4 million tons of oil shale were mined in Australia between 1860 and 1952 (Crisp and others, 1987, their fig. 2).

Torbanite

Much of the early production of oil shale in Australia was from the torbanite deposits of New South Wales. As many as 16 deposits were exploited between the 1860s and 1960s. During the early years of mining, torbanite was used for gas enrichment in Australia and overseas, but paraffin, kerosene, and wood preserving and lubricating oils were also produced. Later, in the 1900s, torbanite was used to produce gasoline. Although the torbanite assayed as high as 480 to 600 l/t, the average feed to the retort was probably about 220 to 250 l/t. Of 30 deposits in New South Wales, 16 were commercially exploited (Crisp and others, 1987, p. 6).

Two small deposits of torbanite have been investigated in Queensland. These include the small but high-grade Alpha deposit, which constitutes a potential in-situ resource of 19 million U.S. barrels (Noon, 1984, p. 4) and a smaller deposit at Carnarvon Creek.

Tasmanite

Several companies attempted to develop the marine tasmanite deposits of Permian age in Tasmania during the early 1900s. Between 1910 and 1932, a total of 1,100 m^3 (about 7,600 barrels) of shale oil was produced from several

Table 1. Demonstrated resources of oil-shale deposits in Australia (from Crisp and others, 1987, their table 1).

[ton, metric ton; l/t, liters per metric ton of rock; km, kilometer; m, meter; bbl, U.S. barrel]

Deposit	Age	In-situ oil (10^6 tons)	Yield (l/t)	Area (km^2)	Recoverable oil (10^6 m^3)	Recoverable oil (10^6 bbls)
			Queensland			
Alpha	Tertiary	17	200+	10	13	80
Condor	do	17,000	65	60	1,100	6,700
Duaringa	do	10,000	82	720	590	3,700
Julia Creek	Cretaceous	4,000	70	250	270	1,700
Lowmead	Tertiary	1,800	84	25	120	740
Nagoorin	do	6,300	90	24	420	2,700
Nagoorin South	do	1,300	78	18	74	470
Rundle	do	5,000	105	25	420	2,700
Stuart	do	5,200	94	32	400	2,500
Yaamba	do	6,100	95	32	440	2,800
			New South Wales			
Baerami	Permian	11	260	--	3	17
Glen Davis	do	6	420	--	4	23
			Tasmania			
Mersey River	do	55	120	--	8	48
Totals		57,000			3,900	24,000

intermittent operations. Further developments are unlikely unless new resources are found (Crisp and others, 1987, p. 7–8).

Toolebuc Oil Shale

Oil shale in the marine Toolebuc Formation of Early Cretaceous age underlies about 484,000 km^2 in parts of the Eromanga and Carpenteria Basins in Queensland and adjacent States (fig. 2). The oil-shale zone ranges from 6.5 to 7.5 m in thickness but yields on average only about 37 l/t, making it a low-grade resource. However, the Toolebuc Formation is estimated to contain 245 billion m^3 (~1.7 trillion barrels) of in-situ shale oil. Excluding weathered oil shale from the surface to a depth of 50 m, about 20 percent (49 billion m^3 or 340 billion barrels) of the shale-oil resource between the depths of 50 to 200 m could be produced by open-pit mining (Ozimic and Saxby, 1983, p. 1). The oil shale also contains potential resources of uranium and vanadium. One of the more favorable localities for oil-shale development is near Julia Creek, where the Toolebuc oil shale is near the surface and is amenable to open-pit mining. The resources of shale oil in the Toolebuc Formation suitable for open-pit mining total 1.5 billion U.S. barrels, but the oil shale is too low grade for development at present (Noon, 1984, p. 5).

The organic matter of the Toolebuc oil shale is composed largely of bituminite, liptodetrinite, and lamalginite (Hutton, 1988, p. 210; Sherwood and Cook, 1983, p. 36). The atomic hydrogen to carbon (H/C) ratio of the organic matter is about 1.1 ±0.2 with high aromaticity (>50 percent). Only 25 percent of the organic matter converts to oil by conventional retorting (Ozimic and Saxby, 1983).

Eastern Queensland

As a result of the increase in the price of crude oil related to the oil crisis of 1973–74, exploration for oil shale in Australia was greatly accelerated. Several companies identified or confirmed sizable resources of oil shale at Rundle, Condor, Duaringa, Stuart, Byfield, Mt. Coolon, Nagoorin, and Yaamba in eastern Queensland during the late 1970s and early 1980s. However, by 1986, the prices of crude oil dropped dramatically, and interest in the exploitation of oil shale diminished (Crisp and others, 1987, p. 9).

Nine Tertiary oil-shale deposits in eastern Queensland have been investigated by exploratory core drilling—Byfield, Condor, Duaringa, Lowmead, Nagoorin, Nagoorin South, Rundle, Stuart, and Yaamba (fig. 2). Most of these deposits are lamosites that were deposited in freshwater lakes located in grabens, commonly in association with coal-forming swamps.

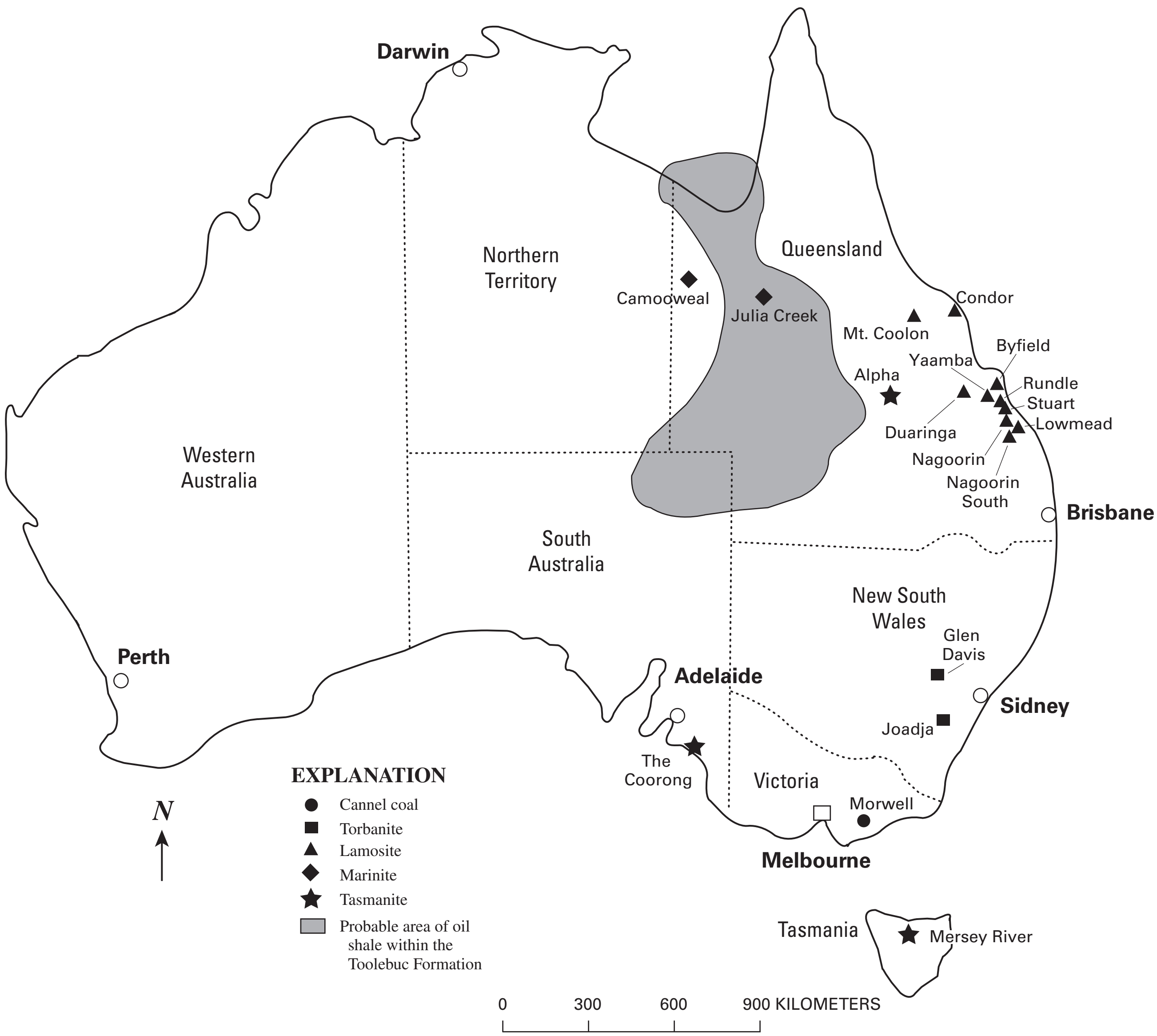


Figure 2. Deposits of oil shale in Australia. From Crisp and others (1987, their fig. 1). Area of Toolebuc oil shale from Cook and Sherwood (1989, their fig. 2).

The mineral fraction is typically composed of quartz and clay minerals with lesser amounts of siderite, carbonate minerals, and pyrite. The sizes of the deposits range from 1 to 17.4 billion tons of in-situ shale oil with cutoff grades of around 50 l/t. Three of the largest deposits are Condor (17.4 billion tons), Nagoorin (6.3 billion tons), and Rundle (5.0 billion tons) (Crisp and others, 1987).

The Stuart oil-shale deposit, estimated to contain 3 billion barrels of in-situ shale oil, is under development by the Southern Pacific Petroleum (SPP) and Central Pacific Minerals (CPM) companies. As of February 2003, 1.16 million tons of oil shale were mined by open pit from which 702,000 barrels of shale oil were recovered by the Taciuk retorting process. Shale-oil production runs during 87 days of operation from September 20, 2003, to January 19, 2004, peaked at 3,700 barrels per day and averaged 3,083 barrels per day (SSP/CPM Dec. 2003 Quarterly Report, January 21, 2004). The Stuart operation shut down in October 2004 for further evaluation.

Brazil

At least nine deposits of oil shale ranging from Devonian to Tertiary age have been reported in different parts of Brazil (Padula, 1969). Of these, two deposits have received the most interest: (1) the lacustrine oil shale of Tertiary age in the Paraíba Valley in the State of São Paulo northeast of the city of São Paulo; and (2) the oil shale of the Permian Iratí Formation, a widespread unit in the southern part of the country (fig. 3).

Paraíba Valley

Two areas in Paraíba Valley totaling 86 km^2 contain a reserve of 840 million barrels of in-situ shale oil as determined by drilling. The total resource is estimated at 2 billion barrels. The unit of interest, which is 45 m thick, includes several types of oil shale: (1) brown to dark brown fossiliferous laminated paper shale that contains 8.5 to 13 weight percent oil equivalent, (2) semipapery oil shale of the same color containing 3 to 9 weight percent oil equivalent, and (3) dark olive, sparsely fossiliferous, low-grade oil shale that fractures semi-conchoidally.

Iratí Formation

Oil shale of the Permian Iratí Formation has the greatest potential for economic development because of its accessibility, grade, and widespread distribution. The Iratí Formation crops out in the northeastern part of the State of São Paulo and extends southward for 1,700 km to the southern border of

Figure 3. Deposits of oil shale in Brazil. From Padula (1969, his fig. 1).

Rio Grande do Sul into northern Uruguay (fig. 3). The total area underlain by the Iratí Formation is unknown because the western part of the deposit is covered by lava flows.

In the State of Rio Grande do Sul, the oil shale is in two beds separated by 12 m of shale and limestone. The beds are thickest in the vicinity of São Gabriel, where the upper bed is 9 m thick and thins to the south and east, and the lower bed is 4.5 m thick and also thins to the south. In the State of Paraná, in the vicinity of São Mateus do Sul-Iratí, the upper and lower oil-shale beds are 6.5 and 3.2 m thick, respectively (fig. 4). In the State of São Paulo and part of Santa Catarina, there are as many as 80 beds of oil shale, each ranging from a few millimeters to several meters in thickness, which are distributed irregularly through a sequence of limestone and dolomite.

Core drilling outlined an area of about 82 km^2 that contains an oil-shale reserve of more than 600 million barrels (about 86 million tons) of shale-oil equivalent, or about 7.3 million barrels/km^2 near São Mateus do Sul in southern Paraná. In the San Gabriel and Dom Pedrito areas of Rio Grande do Sul, the lower bed yields about 7 weight percent shale oil and contains similar resources, but the upper bed yields only 2–3 percent oil and is not considered suitable for exploitation (Padula, 1969).

The Iratí oil shale is dark gray, brown, and black, very fine grained, and laminated. Clay minerals compose 60–70 percent of the rock and organic matter makes up much of the remainder, with minor contributions of detrital quartz, feldspar, pyrite, and other minerals. Carbonate minerals are

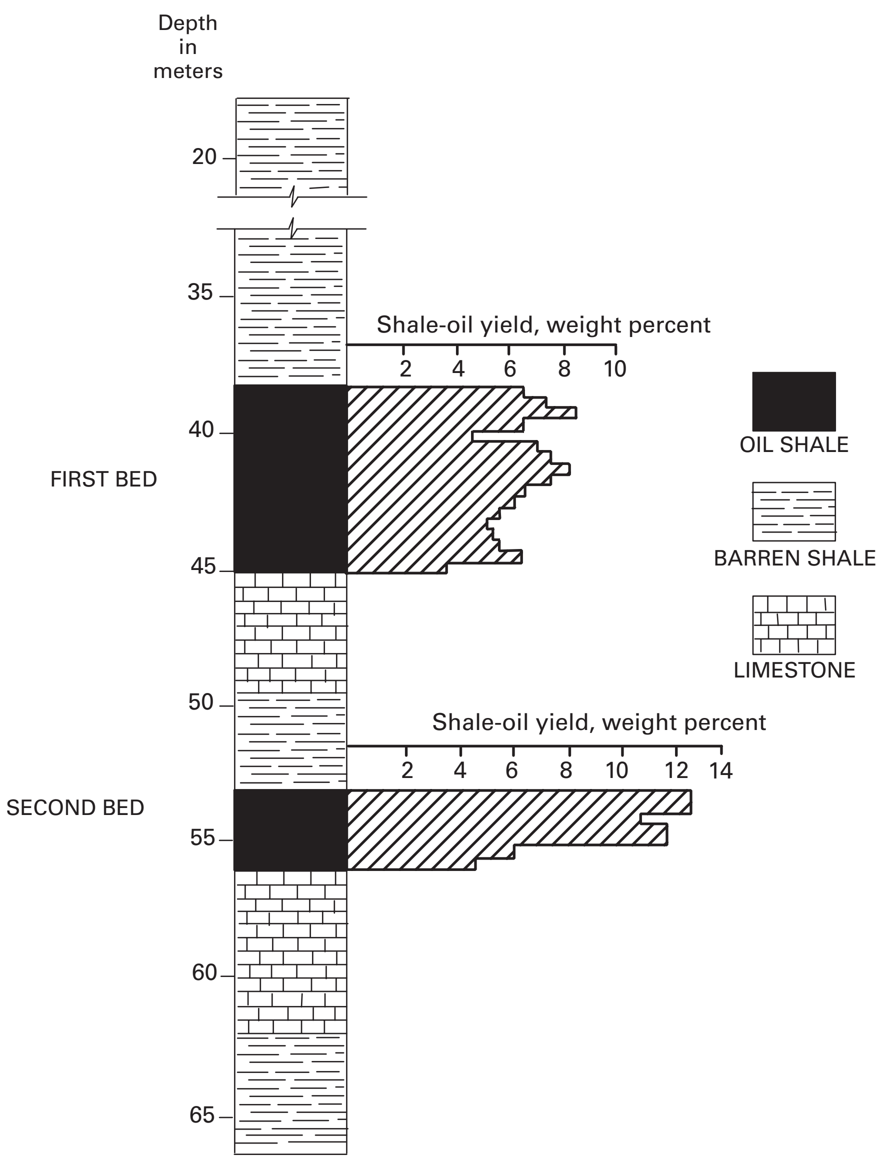


Figure 4. Typical lithologic log and shale-oil yield of the First and Second beds of the Iratí oil shale at São Mateus do Sul, Brazil. From L. Carta, Petrobras (1985, unpublished data).

sparse. The Iratí oil shale is not notably enriched in metals, unlike marine oil shales such as the Devonian oil shales of eastern United States. Some properties of the Iratí oil shale are given in table 2.

Table 2. Average properties of Iratí oil shale mined at São Mateus do Sul (Petrobras, 1985, unpub. data).

[Wt %, weight percent; kcal/kg, kilocalories per kilogram; l/t, liters per metric ton]

Analysis	Wt %
Moisture content	5.3
Organic carbon (dry basis)	12.7
Organic hydrogen (dry basis)	1.5
Fischer assay (dry basis)	
Shale oil	7.6
Water	1.7
Gas	3.2
Spent shale	87.5
Total sulfur (dry basis)	4.0
Gross heating value (dry basis, kcal/kg)	1,480
Oil-shale feed stock (l/t)	70–125

The origin of the Iratí Formation is controversial. Some researchers have concluded that the organic matter is derived from a predominantly algal/microbial source in a freshwater to brackish lacustrine environment as indicated by the geochemistry of the shale oil (Afonso and others, 1994). On the other hand, Padula (1969), quoting earlier researchers, hypothesizes that the organic-rich sediments were deposited in a partially enclosed intracontinental marine (Paraná) basin of reduced salinity that was in communication with the open sea. The basin formed after the close of Late Carboniferous glaciation. Hutton (1988) classified the Iratí oil shale as a marine oil shale (marinite).

Development of the Brazilian oil-shale industry began with the establishment of the Brazilian national oil company, Petrobras, in 1954. A division of that company, Superintendéncia da Industrialização do Xisto (SIX), was charged with the development of the oil-shale deposits. Early work concentrated on the Paraíba oil shale, but later focused on the Iratí shale. A prototype oil-shale retort and UPI (Usina Prototipo do Iratí) plant constructed near São Mateus do Sul (fig. 3) began operations in 1972 with a design capacity of 1,600 tons of oil shale per day. In 1991 an industrial-size retort, 11 m in diameter, was put into operation with a design capacity of about 550 tons (~3,800 barrels) of shale oil per day. More than 1.5 million tons (~10.4 million barrels) of shale oil and other products including liquefied petroleum gas (LPG), methane, and sulfur have been produced from startup of the UPI plant through 1998.

Canada

Canada's oil-shale deposits range from Ordovician to Cretaceous age and include deposits of lacustrine and marine origin; as many as 19 deposits have been identified (Macauley, 1981; Davies and Nassichuk, 1988) (fig. 5 and table 3). During the 1980s, a number of the deposits were explored by core drilling (Macauley, 1981, 1984a, 1984b; Macauley and others, 1985; Smith and Naylor, 1990). Investigations included geologic studies, Rock-Eval and X-ray diffraction analyses, organic petrology, gas chromatography and mass spectrometry of the shale oil, and hydroretorting analyses.

The oil shales of the New Brunswick Albert Formation, lamosites of Mississippian age, have the greatest potential for development (fig. 5). The Albert oil shale averages 100 l/t of shale oil and has potential for recovery of oil and may also be used for co-combustion with coal for electric power generation.

Marinites, including the Devonian Kettle Point Formation and the Ordovician Collingwood Shale of southern Ontario, yield relatively small amounts of shale oil (about 40 l/t), but the yield can be doubled by hydroretorting. The Cretaceous Boyne and Favel marinites form large resources of low-grade oil shale in the Prairie Provinces of Manitoba, Saskatchewan, and Alberta. Upper Cretaceous oil shales on the Anderson Plain and the Mackenzie Delta in the Northwest Territories have been little explored, but may be of future economic interest.

Outcrops of Lower Carboniferous lacustrine oil shale on Grinnell Peninsula, Devon Island, in the Canadian Arctic Archipelago, are as much as 100 m thick and samples yield up to 387 kilograms of shale oil per ton of rock by Rock-Eval (equivalent to about 406 l/t). For most Canadian deposits, the resources of in-situ shale oil remain poorly known.

New Brunswick Oil Shale

The oil-shale deposits of the lacustrine Albert Formation of Mississippian age are located in the Moncton sub-basin of the Fundy Basin that lies roughly between St. Johns and Moncton in southern New Brunswick (no. 1 in fig. 6 and no. 9 of table 3). The principal part of the deposit lies at the east end of the sub-basin at Albert Mines about 25 km south-southeast of Moncton, where one borehole penetrated more than 500 m of oil shale. However, complex folding and faulting obscure the true thickness of the oil-shale beds, which may be much thinner.

The richest part of the sequence, the Albert Mines zone, measures about 120 m thick in one borehole, which may be double the true stratigraphic thickness because of structural complexity as noted above. The shale-oil yield ranges from less than 25 to more than 150 l/t; the average specific gravity is 0.871. Shale-oil reserves for the Albert Mines zone, which yields an estimated 94 l/t of shale oil by Fischer assay, is estimated at 67 million barrels. The shale-oil resource for the

Figure 5. Oil-shale deposits in Canada. Numbered deposits are keyed to table 3. Adapted from Macauley (1981). Areas in blue are lakes

entire oil-shale sequence is estimated at 270 million barrels (Macauley and others, 1984), or about 37 million tons of shale oil.

The oil shale consists of interbedded dolomitic marlstone, laminated marlstone, and clayey marlstone. The mineral matrix is composed of dolomite, local calcite, and minor siderite with quartz, feldspar, some analcime, abundant illite, and minor amounts of smectite. The presence of dolomite and analcime, as well as the presence of overlying beds of halite, indicates that the oil shale was probably deposited in an alkaline saline lake.

The first commercial development was of a single vein of albertite, a solid hydrocarbon cutting across the oil-shale deposits, that was mined from 1863 to 1874 to a depth of 335 m. During that period, 140,000 tons of albertite were sold in the U.S. for $18/ton. A 41-ton sample sent to England in the early 1900s yielded 420 l/t and 450 m^3 of methane gas/ton of albertite. In 1942 the Canadian Department of Mines and Resources initiated a core-drilling program to test the deposit. A total of 79 boreholes were drilled and a resource of 91 million tons of oil shale above a depth of 122 m was estimated. The grade of the oil shale averaged 44.2 l/t. An additional 10 boreholes were drilled by Atlantic-Richfield Company in 1967–68 to test the deeper oil shales, and still further exploration drilling was carried out by Canadian Occidental Petroleum, Ltd. in 1976 (Macauley, 1981).

Table 3. Oil-shale deposits in Canada.

No. on figure 5	Deposit	Geologic unit	Age	Oil-shale type	Thickness (meters)	Grade (liters/ton)
1	Manitoulin-Collingwood trend, Ontario	Collingwood Shale	Ordovician	Marinite	2–6	<40
2	Ottawa area, Ontario	Billings Shale	Ordovician	Marinite	–	Unknown
3	Southhampton Island, Northwest Territories	Collingwood Shale equivalent (?)	Ordovician	Marinite	–	Unknown
4	North shore of Lake Erie, Elgin and Norfold Counties, Ontario	Marcellus Formation	Devonian	Marinite	–	Probably low
5	Norman Wells area, Northwest Territories	Canol Formation	Devonian	Marinite	≤100	Unknown
6	Gaspé Peninsula, Quebec	York River Formation	Devonian	Marinite	–	Unknown
7	Windsor-Sarnia area, southwest Ontario	Kettle Point Formation	Devonian	Marinite	10	41
8	Moose River Basin, Ontario	Long Rapids Formation	Devonian	Marinite	–	Unknown
9	Moncton sub-basin, New Brunswick	Albert Formation	Carboniferous	Lamosite	15–360	35–95
10	Antigonish Basin, Nova Scotia	Horton Group	Carboniferous	Lamosite	60–125	≤59
11	Deer Lake, Humber Valley, Newfoundland	Deer Lake Group	Carboniferous	Lamosite	<2	15–146
12	Conche area, Newfoundland	Cape Rouge Formation	Early Mississippian	Torbanite?	–	Unknown
13	Stellarton Basin, Pictou County, Nova Scotia	Pictou Group	Pennsylvanian	Torbanite and lamosite	<5–35 (in 60 beds)	25–140
14	Queen Charlotte Islands, British Columbia	Kunga Formation	Jurassic	Marinite	≤35	≤35
15	Cariboo district, British Columbia	?	Early Jurassic	Marinite?	–	Minor oil yields
16	Manitoba Escarpment, Manitoba and Saskatchewan	Boyne and Favel Formations	Cretaceous	Marinite	40 and 30, respectively	20–60
17	Anderson Plain, Northwest Territories	Smoking Hills Formation	Late Cretaceous	Marinite	30	>40
18	Mackenzie Delta, Northwest and Yukon Territories	Boundary Creek Formation	Late Cretaceous	Marinite	–	Unknown
19	Grinnell Peninsula, Devon Island, Nunavut	Emma Fiord Formation	Mississippian	Lacustrine: lamosite?	>100	11–406

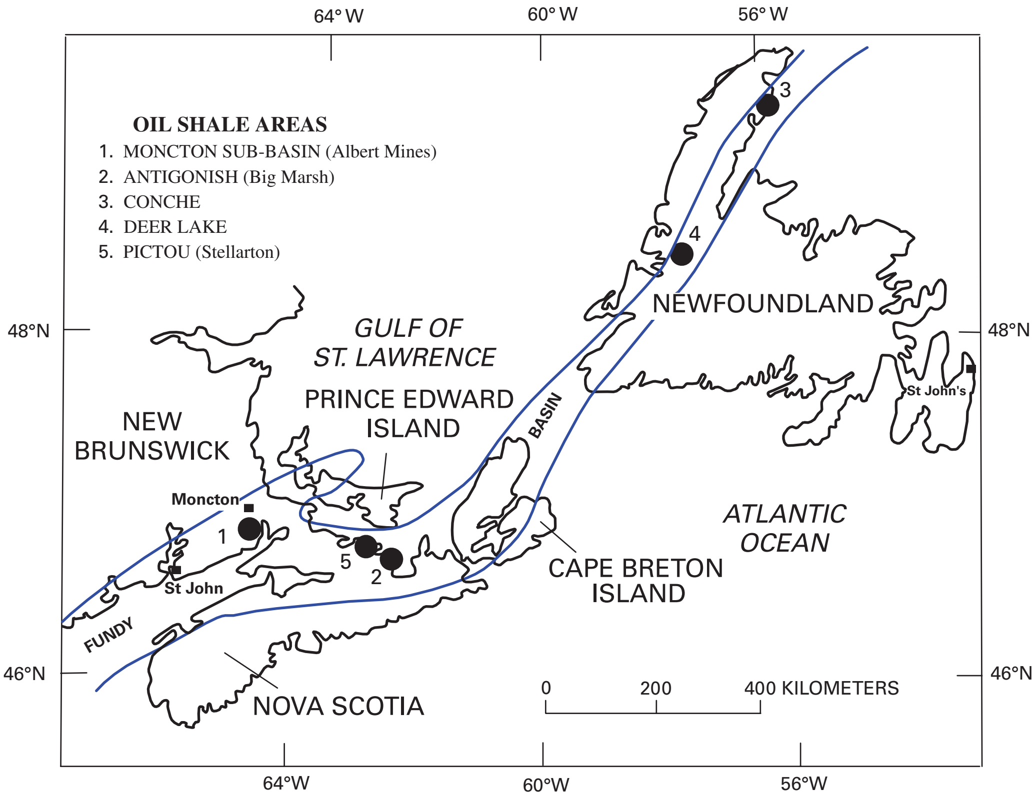


Figure 6. Oil-shale deposits in the Maritime Provinces of Canada. Adapted from Kalkreuth and Macauley (1987, their fig. 1).

China

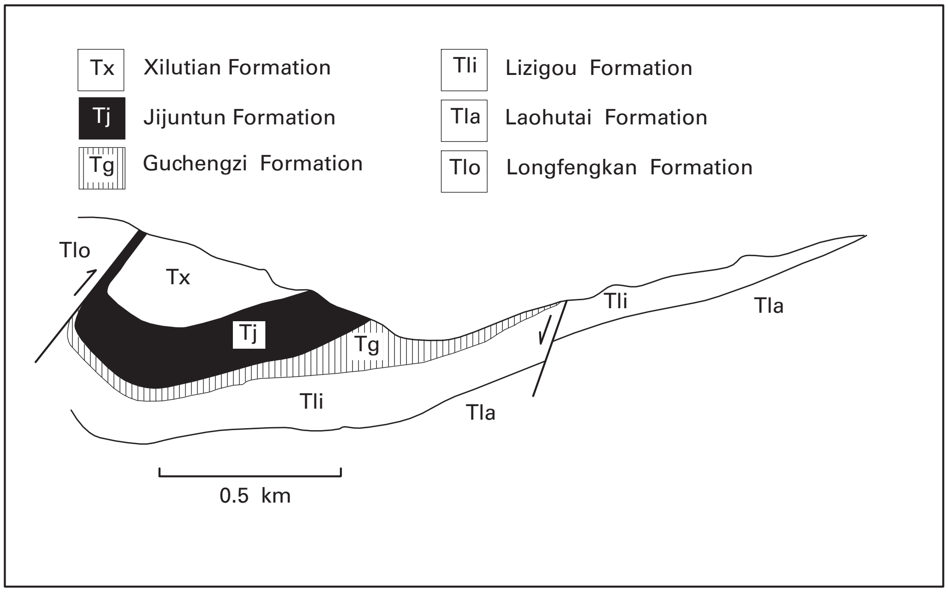
Two of China's principal resources of oil shale are those at Fushun and Maoming. The first commercial production of shale oil began at Fushun in 1930 with the construction of "Refinery No. 1;" this was followed by "Refinery No. 2," which began production in 1954, and a third facility that began producing shale oil at Maoming in 1963. The three plants eventually switched from shale oil to the refining of cheaper crude oil. A new plant for retorting oil shale was constructed at Fushun, with production beginning in 1992. Sixty Fushun-type retorts, each having a capacity of 100 tons of oil shale per day, produce 60,000 tons (about 415,000 bbls) of shale oil per year at Fushun (Chilin, 1995).

Fushun

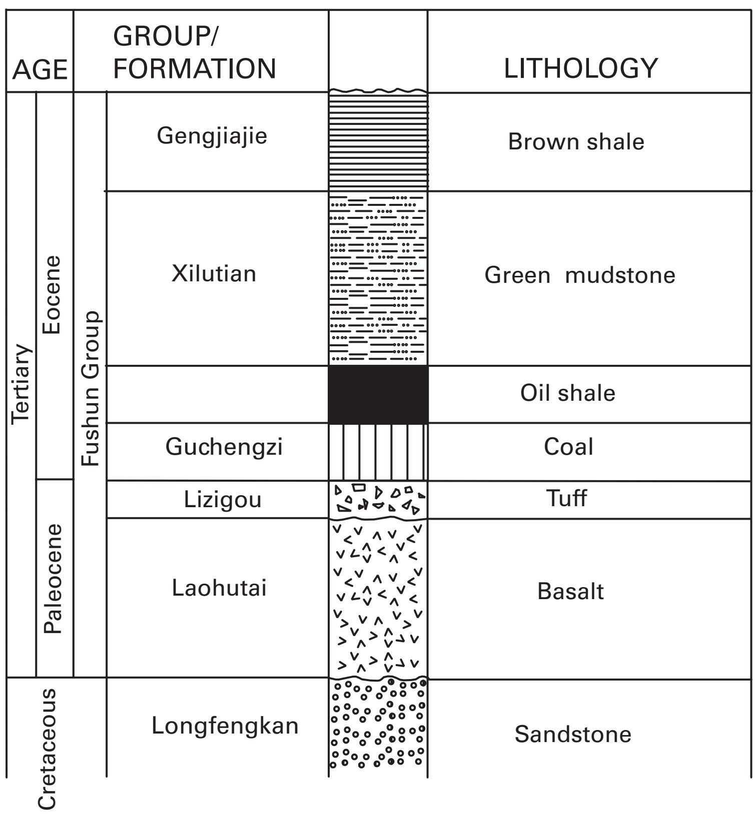
The Fushun oil-shale and coal deposit of Eocene age is located in northeastern China just south of the town of Fushun in Liaoning Province. Coal and oil shale are in a small outlier of Mesozoic and Tertiary sedimentary and volcanic rocks underlain by Precambrian granitic gneiss (Johnson, 1990). In this area, subbituminous to bituminous coal, carbonaceous mudstone and shale, and lenses of sandstone compose the Guchengzi Formation of Eocene age. The formation ranges from 20 to 145 m and averages 55 m in thickness. In the West Open Pit coal mine near Fushun, 6 coal beds are present, as well as a cannel coal 1 to 15 m thick that is used for decorative carving. The coal contains red to yellow gem-quality amber.

Overlying the Guchengzi Formation is the Eocene Jijuntun Formation that consists of oil shale of lacustrine origin. The oil shale is in gradational contact both with the underlying coal of the Guchengzi Formation and with the overlying lacustrine green mudstone of the Xilutian Formation (fig. 7). The Jijuntun Formation, which ranges from 48 to 190 m in thickness, is well exposed in the main West Open Pit coal mine where it is 115 m thick. The lower 15 m consists of low-grade light-brown oil shale and the remaining upper 100 m consists of richer grade brown to dark brown, finely laminated oil shale in beds of thin to medium thickness.

The oil shale contains abundant megafossils of fern, pine, oak, cypress, ginkgo, and sumac. Small fossil mollusks and crustaceans (ostracodes) are also present. The gradational contact between the oil shale and underlying coal indicates a depositional environment of an interior paludal basin that gradually subsided and was replaced by a lake in which the oil shale was deposited (Johnson, 1990, p. 227).



A. North-south stratigraphic cross section through the West Open Pit coal mine (no vertical scale).



B. Generalized stratigraphic section (no scale).

Figure 7. Geologic cross section (*A*) and stratigraphic section (*B*) of the Fushun oil-shale deposit, Liaoning Province, China. From Johnson (1990, his figs. 4 and 6).

The oil yield of the shale ranges from about 4.7 to 16 percent by weight of the rock, and the mined shale averages 7 to 8 percent (~78–89 l/t) oil. In the vicinity of the mine, oil-shale resources are estimated at 260 million tons, of which 235 million tons (90 percent) are considered mineable. The total resource of oil shale at Fushun is estimated at 3,600 million tons.

The West Open Pit mine is located in a tightly folded syncline (fig. 7) that trends east-west and is cut by several compressional and tensional faults. The pit is about 6.6 km long in an east-west direction, 2.0 km wide, and 300 m deep at the west end. In addition, two underground mines lie just east of the open-pit mine. The floor of the open-pit mine is on the south limb of the syncline and dips 22–45° to the north toward the fold axis. The overturned north flank of the syncline is bounded by an east-west thrust fault that places sandstone of the Cretaceous Longfengkan Formation in contact with the Jijuntun oil shale (fig. 7).

Coal mining at Fushun began about 1901. Production increased, first under the Russians and later under the Japanese, reaching a peak in 1945, then dropped sharply and remained low until 1953 when production increased again under the first 5-year plan of the People's Republic of China.

For the first 10 to 15 years of mining coal at Fushun, oil shale was discarded with the overburden. Production of oil shale began in 1926 under the Japanese and peaked in the early 1970s with about 60 million tons of oil shale mined annually then dropped to about 8 million tons in 1978. This reduction was partly due to increased discovery and production of cheaper crude oil within China. Baker and Hook (1979) have published additional details on oil-shale processing at Fushun.

Maoming

The Maoming oil-shale deposit, of Tertiary age, is 50 km long, 10 km wide, and 20 to 25 m thick. Total reserves of oil shale are 5 billion tons, of which 860 million tons are in the Jintang mine. The Fischer assay yield of the oil shale is 4 to 12 percent and averages 6.5 percent. The ore is yellow brown and the bulk density is about 1.85. The oil shale contains 72.1 percent ash, 10.8 percent moisture, 1.2 percent sulfur, with a heating value of 1,745 kcal/kg (dry basis). About 3.5 million tons of oil shale are mined yearly (Guo-Quan, 1988). The 8-mm fraction has a heating value of 1,158 kcal/kg and a moisture content of 16.3 percent. It cannot be retorted but is being tested for burning in a fluidized bed boiler. Cement is manufactured with a content of about 15 to 25 percent of the oil-shale ash.

Estonia

The Ordovician kukersite deposits of Estonia have been known since the 1700s. However, active exploration only began as a result of fuel shortages brought on by World War I. Full-scale mining began in 1918. Oil-shale production in that year was 17,000 tons by open-pit mining, and by 1940, the annual production reached 1.7 million tons. However, it was not until after World War II, during the Soviet era, that production climbed dramatically, peaking in 1980 when 31.4 million tons of oil shale were mined from eleven open-pit and underground mines.

The annual production of oil shale decreased after 1980 to about 14 million tons in 1994–95 (Katti and Lokk, 1998; Reinsalu, 1998a) then began to increase again. In 1997, 22 million tons of oil shale were produced from six room-and-pillar underground mines and three open-pit mines (Opik, 1998). Of this amount, 81 percent was used to fuel electric power plants, 16 percent was processed into petrochemicals, and the remainder was used to manufacture cement as well as other minor products. State subsidies for oil-shale companies in 1997 amounted to 132.4 million Estonian kroons (9.7 million U.S. dollars) (Reinsalu, 1998a).

The kukersite deposits occupy more than 50,000 km^2 in northern Estonia (the Estonia deposit, fig. 8) and extend eastward into Russia toward St. Petersburg where it is known as the Leningrad deposit. In Estonia a somewhat younger deposit of kukersite, the Tapa deposit, overlies the Estonia deposit (fig. 8).

As many as 50 beds of kukersite and kerogen-rich limestone alternating with biomicritic limestone are in the Kõrgekallas and Viivikonna Formations of Middle Ordovician age. These beds form a 20- to 30-m-thick sequence in the middle of the Estonia field. Individual kukersite beds are commonly 10–40 cm thick and reach as much as 2.4 m. The organic content of the richest kukersite beds reaches 40–45 weight percent (Bauert, 1994).

Rock-Eval analyses of the richest-grade kukersite in Estonia show oil yields as high as 300 to 470 mg/g of shale, which is equivalent to about 320 to 500 l/t. The calorific value in seven open-pit mines ranges from 2,440 to 3,020 kcal/kg (Reinsalu, 1998a, his table 5). Most of the organic matter is derived from the fossil green alga, *Gloeocapsomorpha prisca*, which has affinities to the modern cyanobacterium, *Entophysalis major*, an extant species that forms algal mats in intertidal to very shallow subtidal waters (Bauert, 1994).

Matrix minerals in Estonian kukersite and interbedded limestones includes dominantly low-Mg calcite (>50 percent), dolomite (<10–15 percent), and siliciclastic minerals including quartz, feldspars, illite, chlorite, and pyrite (<10–15 percent). The kukersite beds and associated limestones are evidently not enriched in heavy metals, unlike the Lower Ordovician Dictyonema Shale of northern Estonia and Sweden (Bauert, 1994; Andersson and others, 1985).

Bauert (1994, p. 418–420) suggested that the kukersite and limestone sequence was deposited in a series of east-west "stacked belts" in a shallow subtidal marine basin adjacent to a shallow coastal area on the north side of the Baltic Sea near Finland. The abundance of marine macrofossils and low pyrite content indicate an oxygenated-water setting with negligible

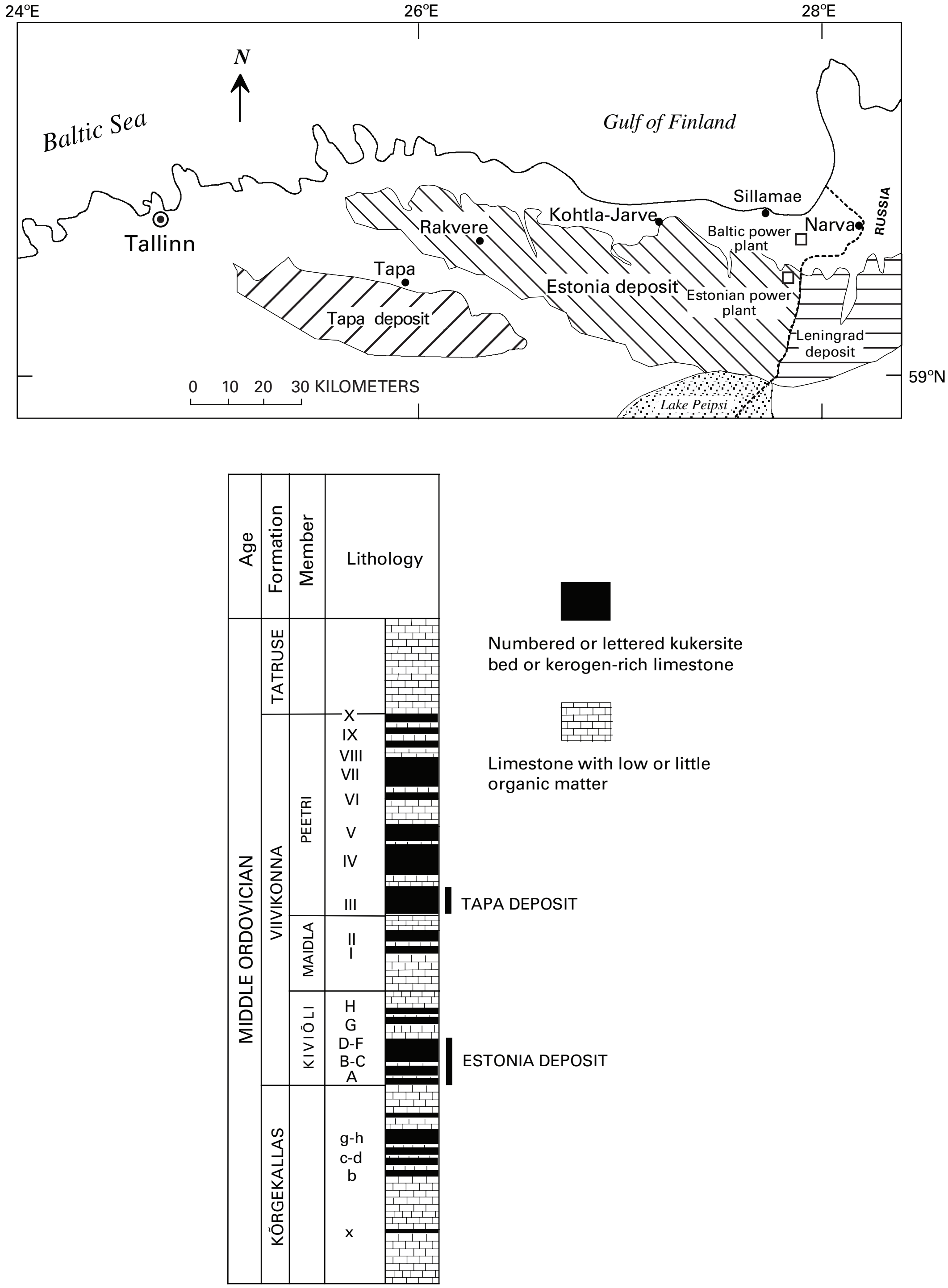


Figure 8. Location and stratigraphic section of the kukersite deposits in northern Estonia and Russia. Adapted from Kattai and Lokk (1998, their fig. 1) and Bauert (1994, his fig. 3).

Table 4. Characteristics of 10 deposits of oil shale in Israel. Data from PAMA, Ltd. (2000?).

Deposit	Overburden thickness (meters)	Oil-shale thickness (meters)	Percent organic matter in oil shale	Oil-shale resources (tons x 10^6)
Nabi Musa	0–30	25–40	14–18	200
Shefela-Hartuv	25–50	150–200	14–15.5	1,100
‘En Boqeq	30–100	40–60	15.0	200
Mishor Rotem	20–150	20–150	11–17	2,260
Mishor Yamin	20–170	20–120	10–18.5	5,200
Yeroham	70–130	10–50	16.0	200
Oron	0–80	10–60	15–21	700
Nahal Zin	5–50	5–30	12–16	1,500
Zenifim	30–50	10–60	8.0	1,000
Sde Boker	50–150	15–70	15–18	3,000

bottom currents as evidenced by widespread lateral continuity of uniformly thin beds of kukersite.

Kattai and Lokk (1998, p. 109) estimated the proved and probable reserves of kukersite to be 5.94 billion tons. A good review of the criteria for estimating Estonia’s resources of kukersite oil shale was made by Reinsalu (1998b). In addition to thickness of overburden and thickness and grade of the oil shale, Reinsalu defined a given bed of kukersite as constituting a reserve, if the cost of mining and delivering the oil shale to the consumer was less than the cost of the delivery of the equivalent amount of coal having an energy value of 7,000 kcal/kg. He defined a bed of kukersite as a resource as one having an energy rating exceeding 25 GJ/m^2 of bed area. On this basis, the total resources of Estonian kukersite in beds A through F (fig. 8) are estimated to be 6.3 billion tons, which includes 2 billion tons of “active” reserves (defined as oil shale “worth mining”). The Tapa deposit is not included in these estimates.

The number of exploratory drill holes in the Estonia field exceeds 10,000. The Estonia kukersite has been relatively thoroughly explored, whereas the Tapa deposit is currently in the prospecting stage.

Dictyonema Shale

Another older oil-shale deposit, the marine Dictyonema Shale of Early Ordovician age, underlies most of northern Estonia. Until recently, little has been published about this unit because it was covertly mined for uranium during the Soviet era. The unit ranges from less than 0.5 to more than 5 m in thickness (fig. 9). A total of 22.5 tons of elemental uranium was produced from 271,575 tons of Dictyonema Shale from an underground mine near Sillamäe. The uranium (U_3O_8) was extracted from the ore in a processing plant at Sillamäe (Lippmaa and Maramäe, 1999, 2000, 2001).

The future of oil-shale mining in Estonia faces a number of problems including competition from natural gas, petroleum, and coal. The present open-pit mines in the kukersite deposits will eventually need to be converted to more expensive underground operations as the deeper oil shale is mined. Serious air and ground-water pollution have resulted from burning oil shale and leaching of trace metals and organic compounds from spoil piles left from many years of mining and processing the oil shales. Reclamation of mined-out areas and their associated piles of spent shale, and studies to ameliorate the environmental degradation of the mined lands by the oil-shale industry are underway. The geology, mining, and reclamation of the Estonia kukersite deposit were reviewed in detail by Kattai and others (2000).

Israel

Twenty marinite deposits of Late Cretaceous age have been identified in Israel (fig. 10; Minster, 1994), containing about 12 billion tons of oil-shale reserves with an average heating value of 1,150 kcal/kg of rock and an average oil yield of 6 weight percent. Thicknesses ranging from 35 to 80 m were reported by Fainberg in Kogerman (1996, p. 263) and 5 to 200 m by PAMA, Ltd. (2000?) (table 4). The organic content of the oil shales is relatively low, ranging from 6 to 17 weight percent, with an oil yield of only 60 to 71 l/t. The moisture content is high (~20 percent) as is the carbonate content (45 to 70 percent calcite) and the sulfur content (5 to 7 weight percent) (Minster, 1994). Some of the deposits can be mined by open-pit methods. A commercially exploitable bed of phosphate rock, 8 to 15 m thick, underlies the oil shale in the Mishor Rotem open-pit mine.

Utilizing oil shale from the Rotem-Yamin deposit (deposits 10 and 11 in fig. 10), about 55 tons of oil shale per

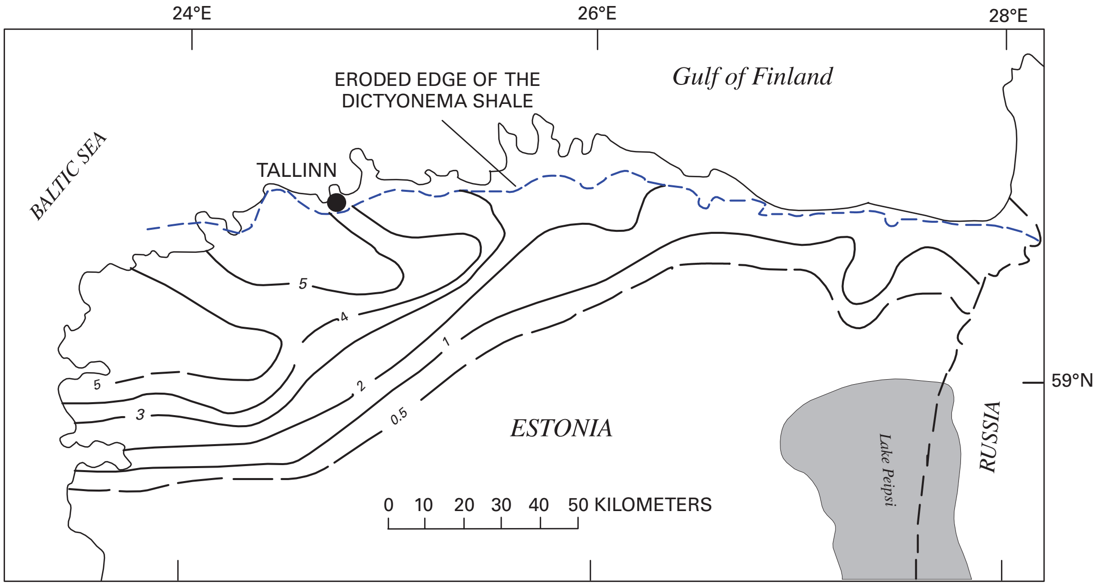


Figure 9. Isopach map of the Ordovician Dictyonema Shale in northern Estonia. From Loog and others (1996, their fig. 1). Thickness in meters.

hour were burned in a fluidized bed boiler to power a steam turbo-generator in a 25-megawatt experimental electric power plant operated by PAMA Company. The plant began operation in 1989 (Fainberg and Hetsroni, 1996) but is now closed. The grade of the Rotem oil shale is not uniform; the heating values range from 650 to 1200 kcal/kg.

Jordan[2]

Jordan has few resources of oil and gas and no commercial deposits of coal. However, there are about 26 known deposits of oil shale, some of which are large and relatively high-grade (Jaber and others, 1997; Hamarneh, 1998, p. 2). The eight most important of these are the Juref ed Darawish, Sultani, Wadi Maghar, El Lajjun, Attarat Umm Ghudran, Khan ez Zabib, Siwaga, and Wadi Thamad deposits (fig. 11). These eight deposits are located in west central Jordan within 20 to 75 km east of the Dead Sea. The El Lajjun, Sultani, and Juref ed Darawish have been the most extensively explored by boreholes and many samples have been analyzed. Table 5 summarizes some of the geologic and resource data for the eight deposits.

The Jordanian oil-shale deposits are marinites of Late Cretaceous (Maastrichtian) to early Tertiary age. A number of deposits are in grabens and some may prove to be parts of larger deposits, such as the Wadi Maghar deposit that is now considered to be the southern extension of the Attarat Umm Ghudran deposit (fig 11). The deposits listed in table 5 are at shallow depths, in essentially horizontal beds. As much as 90 percent of the oil shale is amenable to open-pit mining (Hamarneh, 1998, p. 5). The overburden consists of unconsolidated gravel and silt containing some stringers of marlstone and limestone and, in some areas, basalt. Overall, the oil shales thicken northward toward the Yarmouk deposit near the northern border of Jordan where the latter apparently extends into Syria (fig. 11) and may prove to be an exceptionally large deposit—underlying several hundred square kilometers and reaching 400 m in thickness (Tsevi Minster, 1999, written commun.).

The oil shales in central Jordan are in the marine Chalk-Marl unit, which is underlain by phosphatic limestone and chert of the Phosphorite unit. The oil shales are typically brown, gray, or black and weather to a distinctive light bluish-gray. The moisture content of the oil shale is low (2 to 5.5 weight percent), whereas comparable deposits of oil shale in Israel have a much higher moisture content of 10 to 24 percent (Tsevi Minster, 1999, written commun.). Calcite, quartz, kaolinite, and apatite make up the major mineral components of the El Lajjun oil shale (fig. 11), along with small amounts of dolomite, feldspar, pyrite, illite, goethite, and gypsum. The sulfur content of Jordanian oil shale ranges from 0.3 to 4.3 percent. The sulfur content of shale oil from the Jurf ed Darawish and the Sultani deposits is high, 8 and 10 percent, respectively. Of interest is the relatively high metal content of

[2]Many of the names of the Jordanian oil-shale deposits are spelled in different ways by Jordanian and other authors, probably owing to the difficulty of translating from Arabic to English. The names in this report are selected from several sources and not necessarily the best ones to use.

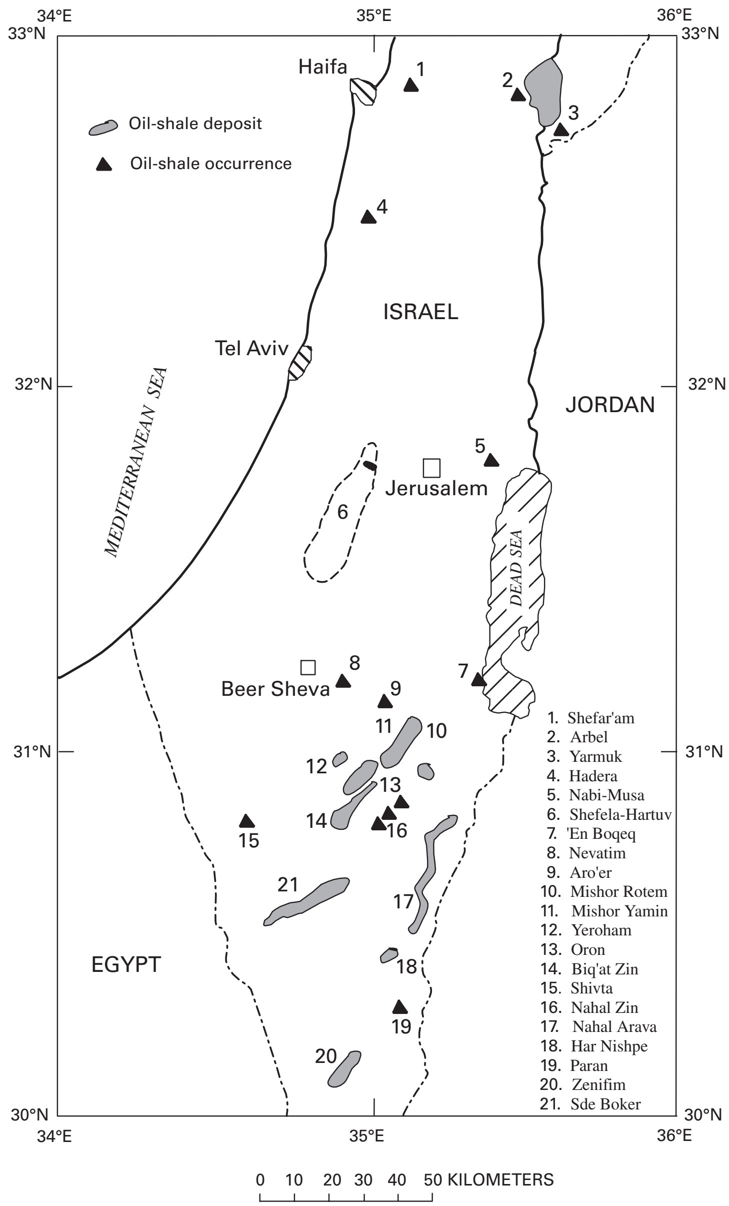


Figure 10. Deposits of oil shale in Israel. From Minster (1994, his fig. 1).

Table 5. Resource data for eight deposits of oil shale in Jordan (from Jaber and others, 1997, their table 1; and Hamarneh, 1998). Some data are rounded.

[km², square kilometers; wt %, weight percent]

Deposit	Number of boreholes	Area (km²)	Overburden (meters)	Thickness of oil shale (meters)	Shale oil (wt %)	Oil shale (10^9 tons)	Shale oil (10^6 tons)
El Lajjun	173	20	30	29	10.5	1.3	126
Sultani	60	24	70	32	7.5	1.0	74
Jurf ed Darawish	50	1,500	70	31	?	8.6	510
Attarat Umm Ghudran	41	670	50	36	11	11	1,245
Wadi Maghar	21	19	40	40	6.8	31.6	2,150
Wadi Thamad	12	150	140–200	70–200	10.5	11.4	1,140
Khan ez Zabib	–	?	70	40	6.9	?	–
Siwaga	–	–	–	–	7.0	–	–
Total	–	2,385	–	–	–	64.9+	5,246+

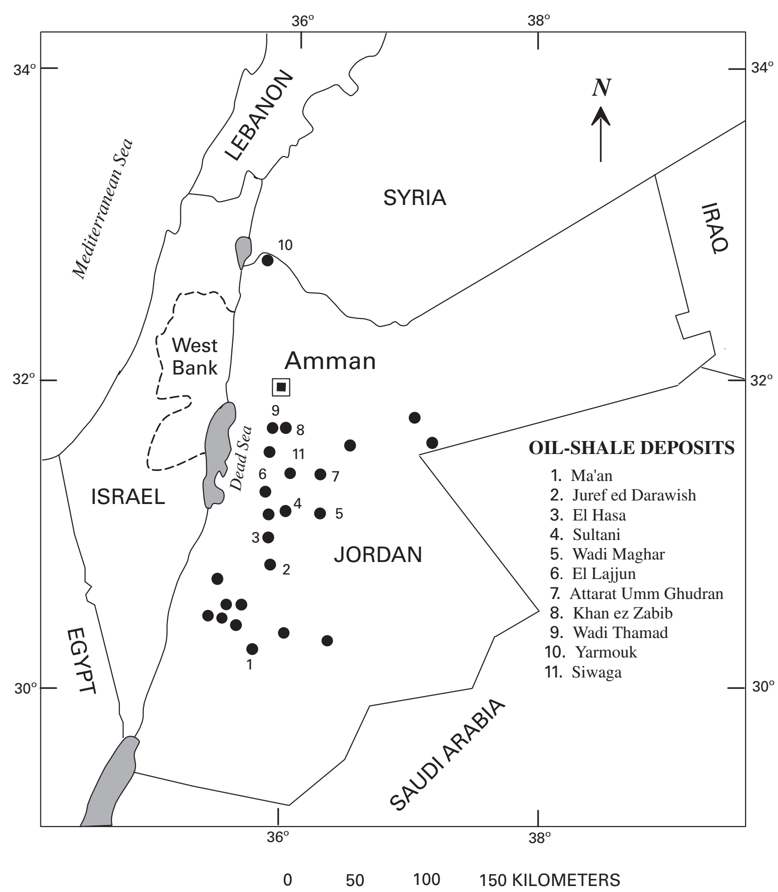


Figure 11. Oil-shale deposits in Jordan. Adapted from Jaber and others (1997, their fig. 1) and Hamarneh (1998, his figure on p. 4).

the oil shales from the Jurf el Darawish, Sultani, and El Lajjun deposits, notably Cu (68–115 ppm), Ni (102–167 ppm), Zn (190–649 ppm), Cr (226–431 ppm), and V (101–268 ppm) (Hamarneh, 1998, p. 8). Phosphate rock underlies the El Hasa deposit (deposit 3 in fig. 11).

Surface water for oil-shale operations is scarce in Jordan; therefore, ground water will need to be tapped for oil-shale operations. A shallow aquifer that underlies the El Lajjun deposit, and provides fresh water to Amman and other municipalities in central Jordan, is too small in capacity to also meet the demands of an oil-shale industry. A deeper aquifer in the Kurnub Formation, 1,000 m below the surface, may be capable of providing an adequate supply of water, but this and other potential ground-water sources need further study.

Syria

Puura and others (1984) described oil shales from the Wadi Yarmouk Basin at the southern border of Syria that are presumably part of the Yarmouk deposit described above in northern Jordan. The strata are marine limestones (marinites) of Late Cretaceous to Paleogene age, consisting of carbonate and siliceous carbonate shelf deposits that are common in the Mediterranean area. Fossil remains constitute 10 to 15 percent of the rock. The mineral components of the oil shales are 78 to 96 percent carbonates (mostly calcite), with small amounts of quartz (1 to 9 percent), clay minerals (1 to 9 percent), and apatite (2 to 19 percent). The sulfur content is 0.7 to 2.9 percent. Oil yields by Fischer assay are 7 to 12 percent.

Morocco

Oil-shale deposits have been identified at ten localities in Morocco (fig. 12), the most important of which are Upper Cretaceous marinites, not unlike those of Egypt, Israel, and Jordan. The two deposits that have been explored most extensively are the Timahdit and the Tarfaya deposits; about 69,000 analyses have been made of samples from 157 boreholes totaling 34,632 m in length and from 800 m of mine workings.

The Timahdit deposit, located about 250 km southeast of Rabat, underlies an area about 70 km long and 4 to10 km wide within a northeast-trending syncline (fig. 12). The thickness of the oil shale ranges from 80 to 170 m (fig. 13). The moisture content ranges from 6 to 11 percent, and the sulfur content averages 2 percent. Total oil-shale reserves are estimated at 18 billion tons within an area of 196 km^2; oil yields range from 20 to 100 l/t and average 70 l/t.

The Tarfaya deposit is located in the southwesternmost part of Morocco, near the border with Western Sahara (fig. 12). The oil shale averages 22 m in thickness and its grade averages 62 l/t. The total oil-shale resource is estimated at 86 billion tons within a 2,000-km^2 area. The moisture content of the Tarfaya oil shale averages 20 percent and the sulfur content averages about 2 percent.

Phosphate rock and uranium are also associated with the Cretaceous marinites. One drill core (location uncertain) revealed a maximum P_2O_5 content of about 17 percent and U_30_8 concentrations of as much as about 150 ppm.

In the 1980s several energy companies from North America and Europe conducted exploratory drilling and experimental mining and processing of Moroccan oil shale, but no shale oil was produced (Bouchta, 1984; Office National de Recherches et D'exploitation Petrolieres, 1983?).

Russia

More than 80 deposits of oil shale have been identified in Russia. The kukersite deposit in the Leningrad district (fig. 8) is burned as fuel in the Slansky electric power plant near St. Petersburg. In addition to the Leningrad deposit, the best deposits for exploitation are those in the Volga-Pechersk oil-shale province, including the Perelyub-Blagodatovsk, Kotsebinsk, and the Rubezhinsk deposits. These deposits contain beds of oil shale ranging from 0.8 to 2.6 m in thickness but are high in sulfur (4–6 percent, dry basis). The oil shale was used to fuel two electric power plants; however, the operation was shut down owing to high SO_2 emissions. As of about 1995, an oil-shale plant at Syzran was processing not more than 50,000 tons of oil shale per year (Kashirskii, 1996).

Russell (1990) listed the resources of 13 deposits in the former Soviet Union, including the Estonian and Leningrad kukersite deposits and the Estonian Dictyonema Shale, at greater than 107 billion tons of oil shale.

Sweden

The Alum Shale is a unit of black organic-rich marinite about 20–60 m thick that was deposited in a shallow marine-shelf environment on the tectonically stable Baltoscandian Platform in Cambrian to earliest Ordovician time in Sweden and adjacent areas. The Alum Shale is present in outliers, partly bounded by local faults, on Precambrian rocks in southern Sweden as well as in the tectonically disturbed Caledonides of western Sweden and Norway, where it reaches thicknesses of 200 m or more in repeated sequences owing to multiple thrust faults (fig. 14).

Black shales, equivalent in part to the Alum Shale, are present on the islands of Öland and Götland, underlie parts of the Baltic Sea, and crop out along the north shore of Estonia where they form the Dictyonema Shale of Early Ordovician (Tremadocian) age (Andersson and others, 1985, their figs. 3 and 4). The Alum Shale represents slow deposition in shallow, near-anoxic waters that were little disturbed by wave- and bottom-current action.

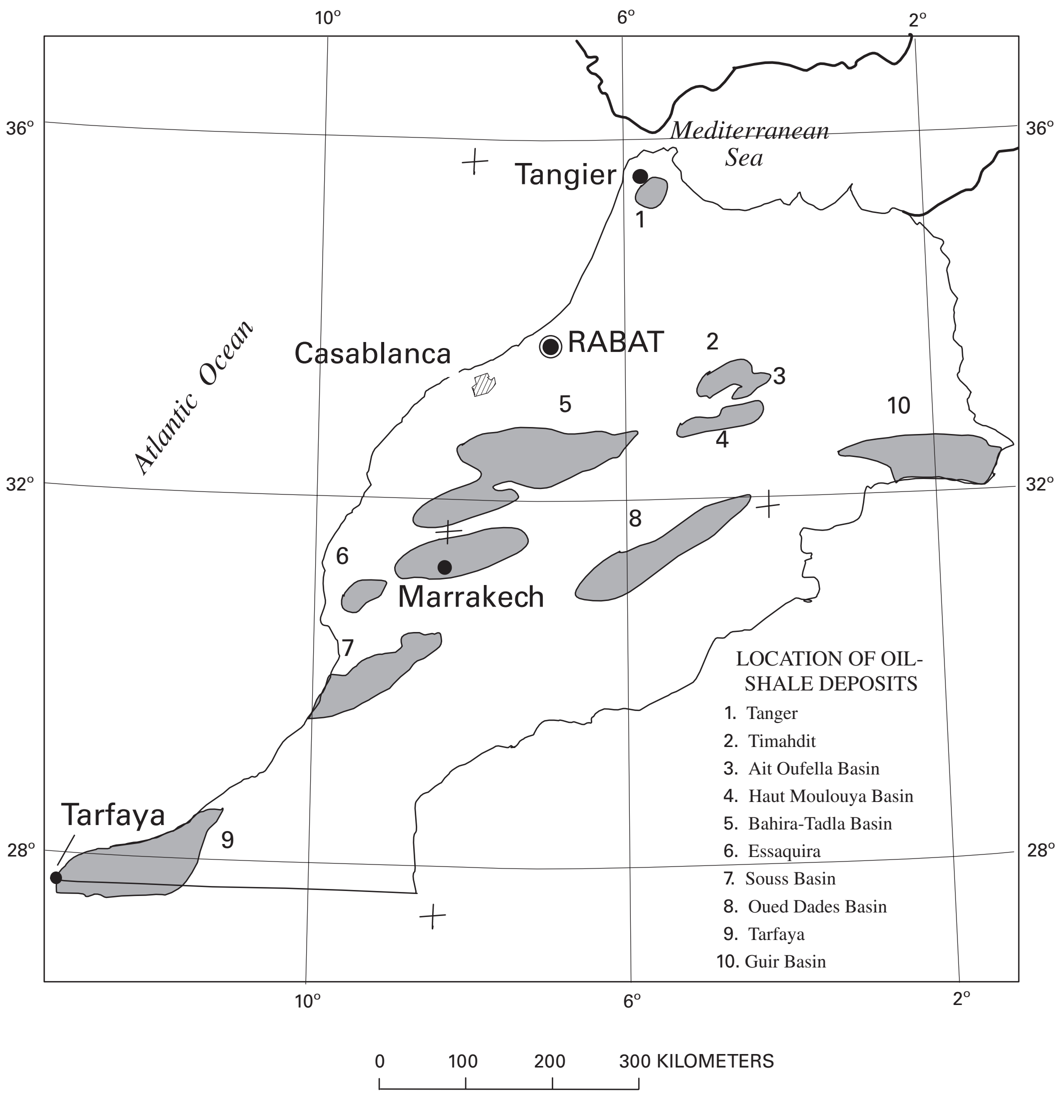


Figure 12. Oil-shale deposits in Morocco. From Bouchta (1984, his fig. 1).

The Cambrian and Lower Ordovician Alum Shale of Sweden has been known for more than 350 years. It was a source of potassium aluminum sulfate that was used in the leather tanning industry, for fixing colors in textiles, and as a pharmaceutical astringent. Mining the shales for alum began in 1637 in Skåne. The Alum Shale was also recognized as a source of fossil energy and, toward the end of the 1800s, attempts were made to extract and refine hydrocarbons (Andersson and others, 1985, p. 8–9).

Before and during World War II, Alum Shale was retorted for its oil, but production ceased in 1966 owing to the availability of cheaper supplies of crude petroleum. During this period, about 50 million tons of shale was mined at Kinnekulle in Västergötland and at Närke (fig. 14).

The Alum Shale is remarkable for its high content of metals including uranium, vanadium, nickel, and molybdenum. Small amounts of vanadium were produced during World War II. A pilot plant built at Kvarntorp produced more than 62 tons of uranium between 1950 and 1961. Later, higher-grade ore was identified at Ranstad in Västergötland, where an open-pit mine and mill were established. About 50 tons of uranium per year were produced between 1965 and 1969. During the 1980s, production of uranium from high-grade deposits elsewhere in the world caused a drop in the world price of uranium to levels too low to profitably operate the Ranstad plant, and it closed in 1989 (Bergh, 1994).

Alum Shale was also burned with limestone to manufacture “breeze blocks,” a lightweight porous building block that was used widely in the Swedish construction industry. Production stopped when it was realized that the blocks were radioactive and emitted unacceptably large amounts of radon. Nevertheless, the Alum Shale remains an important potential

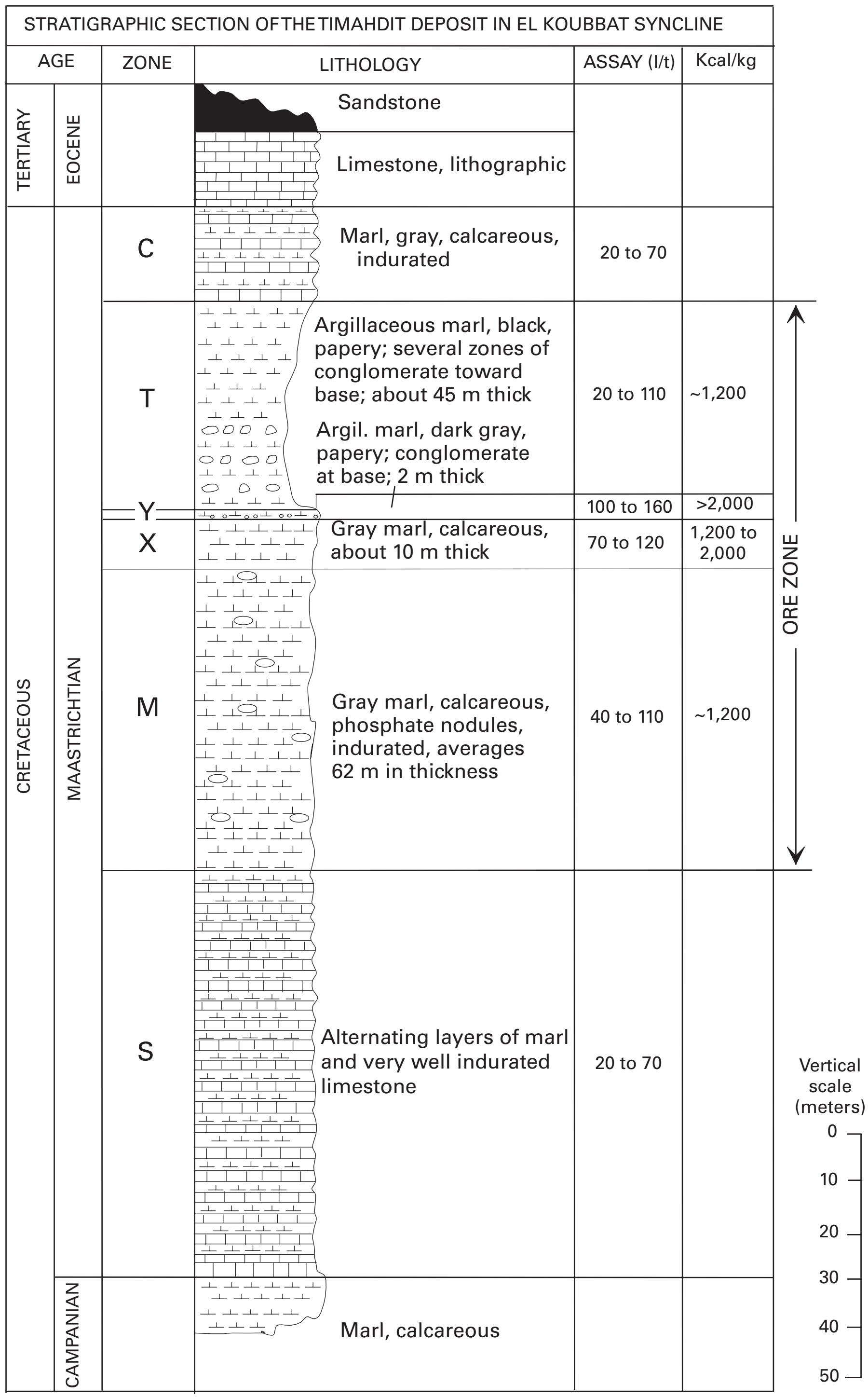


Figure 13. Generalized stratigraphic section of the Timahdit oil-shale deposit in the El Koubbat syncline, Morocco. Adapted from Office National de Recherches et D'exploitation Petrolieres (1983?); l/t, liters per metric ton of rock; kcal/kg, kilocalories per kilogram.

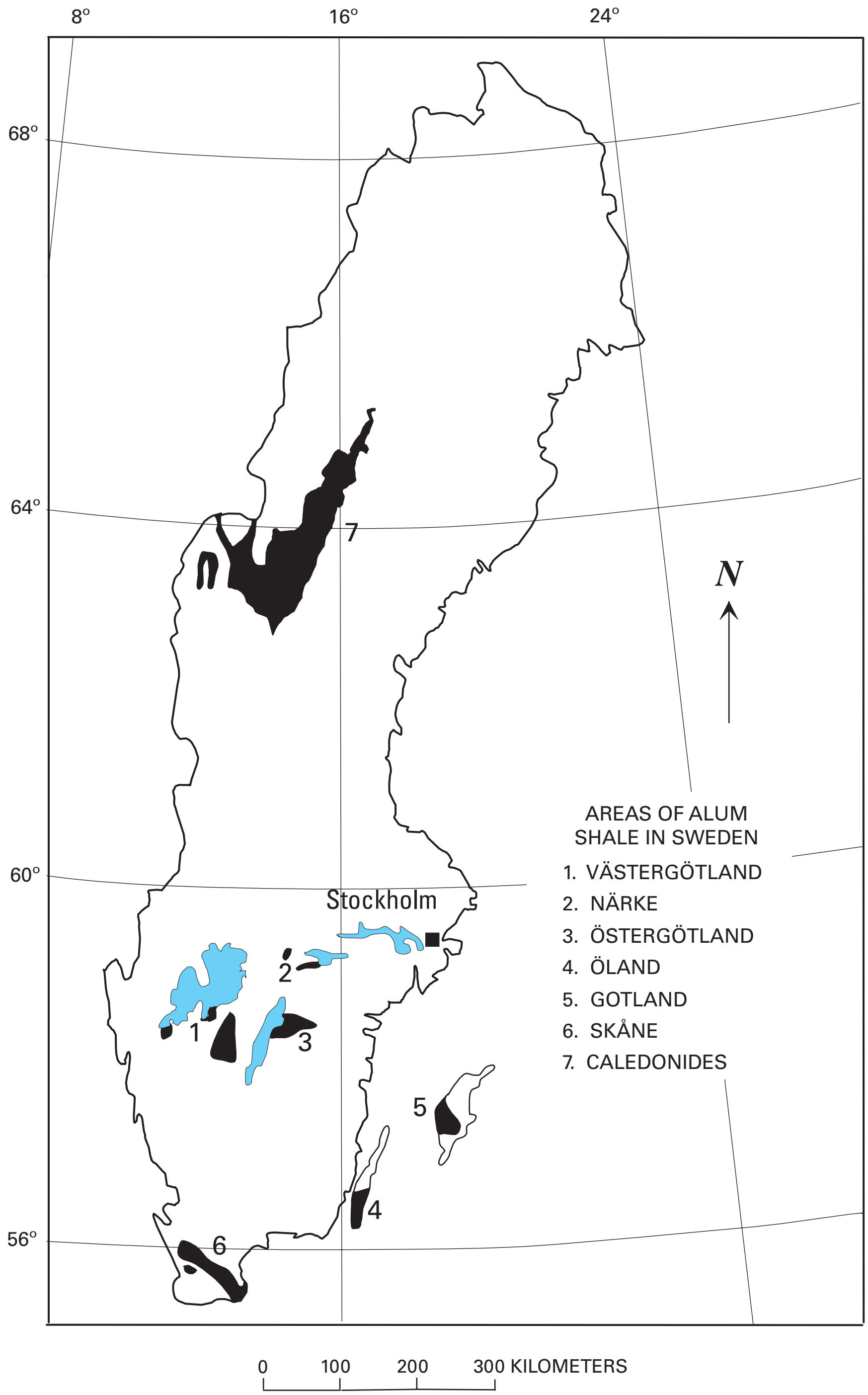


Figure 14. Map showing areas (in black) of Alum Shale in Sweden. Adapted from Andersson and others (1985, their fig. 3). Areas in blue are lakes.

resource of fossil and nuclear energy, sulfur, fertilizer, metal alloy elements, and aluminum products for the future. The fossil energy resources of the Alum Shale in Sweden are summarized in table 6.

The organic content of Alum Shale ranges from a few percent to more than 20 percent, being highest in the upper part of the shale sequence (fig. 15). Oil yields, however, are not in proportion to the organic content from one area to another because of variations in the geothermal history of the areas underlain by the formation. For example, at Skåne (fig. 14) and Jämtland in west-central Sweden, the Alum Shale is overmature and oil yields are nil, although the organic content of the shale is 11–12 percent. In areas less affected by geothermal alteration, oil yields range from 2 to 6 percent by Fischer assay. Hydroretorting can increase the Fischer assay yields by as much as 300 to 400 percent (Andersson and others, 1985, their fig. 24).

The uranium resources of the Alum Shale of Sweden, although low grade, are enormous. In the Ranstad area of Västergötland, for example, the uranium content of a 3.6-m-thick zone in the upper part of the formation reaches 306 ppm, and concentrations reach 2,000 to 5,000 ppm in small black coal-like lenses of hydrocarbon (kolm) that are scattered through the zone.

The Alum Shale in the Ranstad area underlies about 490 km^2, of which the upper member, 8 to 9 m thick, contains an estimated 1.7 million tons of uranium metal (Andersson and others, 1985, their table 4). Figure 15 shows a lithologic log of a core hole drilled at Ranstad with plots of Fischer assays and uranium analyses.

Thailand

Lacustrine oil-shale deposits of Tertiary age are near Mae Sot, Tak Province, and at Li, Lampoon Province. The Thai Department of Mineral Resources has explored the Mae Sot deposit with the drilling of many core holes. The oil shale is a lamosite similar in some respects to the Green River oil shale in Colorado. The Mae Sot deposit underlies about 53 km^2 in the Mae Sot Basin in northwestern Thailand near the Myanmar (Burma) border. It contains an estimated 18.7 billion tons of oil shale, which is estimated to yield 6.4 billion barrels (916 million tons) of shale oil. The gross heating value ranges from 287 to 3,700 kcal/kg, the moisture content ranges from 1 to 13 percent, and the sulfur content is about 1 percent. The deposit at Li is probably also a lamosite but the reserves are small—estimated at 15 million tons of oil shale yielding 12–41 gallons of shale oil per ton of rock (50–171 l/t) (Vanichseni and others, 1988, p. 515–516).

Turkey

Lacustrine oil-shale deposits of Paleocene to Eocene age and of late Miocene age are widely distributed in middle and western Anatolia in western Turkey. The host rocks are marlstone and claystone in which the organic matter is finely dispersed. The presence of authigenic zeolites indicates probable deposition in hypersaline lacustrine waters in closed basins.

Data on the shale-oil resources are sparse because only a few of the deposits have been investigated. Güleç and Önen (1993) reported a total of 5.2 billion tons of oil shale in seven deposits with their ranges in calorific values; however, the shale-oil resources of these deposits are not reported. The oil-shale resources of Turkey may be large, but further studies are needed before reliable resource estimates can be made. On the basis of available data, total resources of in-situ shale oil for eight Turkish deposits are estimated at 284 million tons (about 2.0 billion bbls) (table 7).

United States

Numerous deposits of oil shale, ranging from Precambrian to Tertiary age, are present in the United States. The two most important deposits are in the Eocene Green River Formation in Colorado, Wyoming, and Utah and in the Devonian–Mississippian black shales in the eastern United States. Oil shale associated with coal deposits of Pennsylvanian age is also in the eastern United States. Other deposits are known to be in Nevada, Montana, Alaska, Kansas, and elsewhere, but these are either too small, too low grade, or have not yet been well enough explored (Russell, 1990, p. 82–157) to be considered as resources for the purposes of this report. Because of their size and grade, most investigations have focused on the Green River and the Devonian–Mississippian deposits.

Green River Formation

Geology

Lacustrine sediments of the Green River Formation were deposited in two large lakes that occupied 65,000 km^2 in several sedimentary-structural basins in Colorado, Wyoming, and Utah during early through middle Eocene time (fig. 16). The Uinta Mountain uplift and its eastward extension, the Axial Basin anticline, separate these basins. The Green River lake system was in existence for more than 10 million years during a time of a warm temperate to subtropical climate.

Table 6. Summary of the fossil energy potential of the Alum Shale in Sweden for shale containing more than 10 percent organic matter (from Andersson and others, 1985, their table 2).

[wt %, weight percent; MJ, megajoules]

Area	Shale tons (10^6)	Organic matter wt %	Organic matter tons (10^6)	Shale oil wt %	Shale oil tons (10^6)	Energy in gas and coke (10^12 MJ)
Närke	1,700	20	340	5	85	8,800
Östergötland	12,000	14	1,600	3.5	400	41,900
Västergötland	14,000	~13	1,840	0–3.4	220	53,300
Öland	6,000	12	700	2.7	170	18,000
Skåne	15,000	11	1,600	0	0	58,600
Jämtland (Caledonides)	26,000	12	3,200	0	0	117,200
Total	74,700		9,280		875	297,800

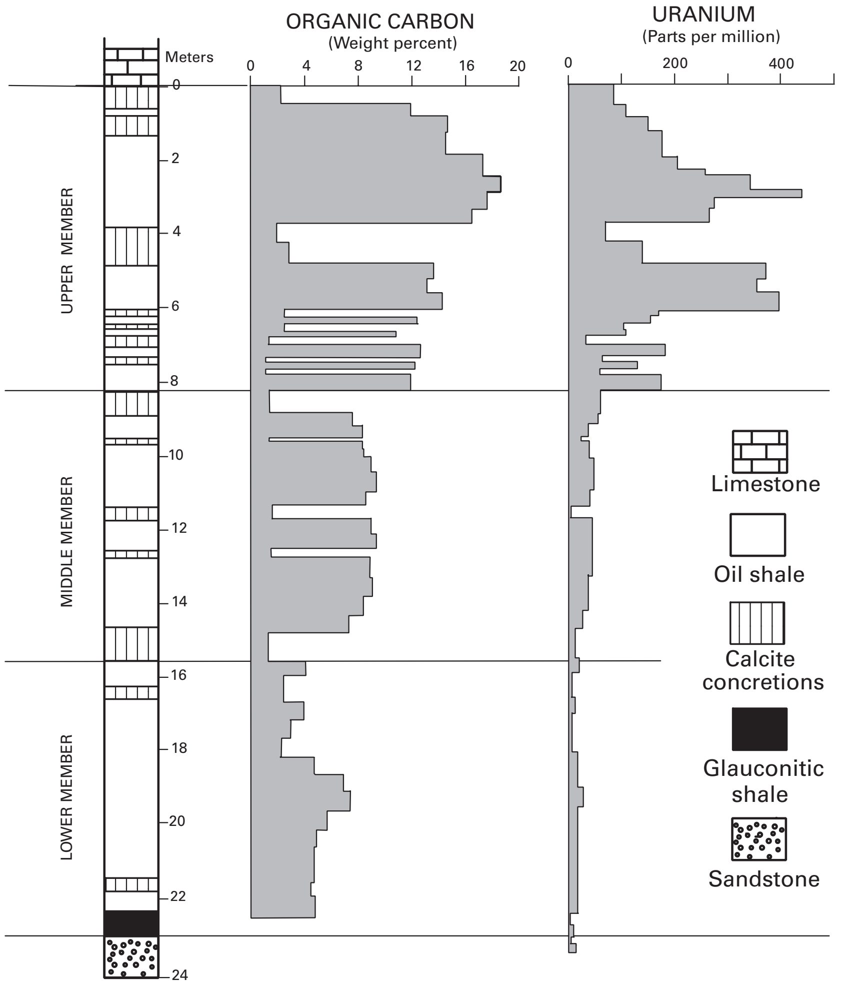


Figure 15. Lithology and plots of the abundances of organic carbon and uranium in a drill core from the Alum Shale at Ranstad, Sweden. From Andersson and others (1985, their fig. 9).

Table 7. Oil-shale deposits of Turkey. Data from Güleç and Önen (1993) and Sener and others (1995).

[wt %, weight percent; kcal/kg, kilocalories per kilogram of rock; MJ/kg, megajoules per kilogram. For those deposits lacking average oil yields, an estimated yield of 5 weight percent was assumed. For deposits where two tonnages were given in the references, the larger number was used]

Deposit and province	Calorific value	Average oil yield (wt %)	Total sulfur (wt %)	Oil-shale resource (10^6 tons)	Shale-oil resource (10^6 tons)
Bahçecik (Izmit)	418–1,875 kcal/kg	–	–	100	5
Beypazari (Ankara)	3.40 MJ/kg	5.4	1.4	1,058	57
Burhaniye (Balikesir)	0–1,768 kcal/kg	–	–	80	4
Gölpazari (Bilecik)	0–1,265 kcal/kg	–	–	356	18
Göynük (Bolu)	3.25 MJ/kg	4.6	0.9	2.500	115
Hatildag (Bolu)	3.24 MJ/kg	5.3	1.3	547	29
Seyitömer (Kütahya)	3.55 MJ/kg	5.0	0.9	1,000	50
Ulukisla (Nigde)	630–2,790 kcal/kg	–	–	130	6
Total				5,771	284

During parts of their history, the lake basins were closed, and the waters became highly saline.

Fluctuations in the amount of inflowing stream waters caused large expansions and contractions of the lakes as evidenced by widespread intertonguing of marly lacustrine strata with beds of land-derived sandstone and siltstone. During arid times, the lakes contracted, and the waters became increasingly saline and alkaline. The lake-water content of soluble sodium carbonates and chloride increased, whereas the less soluble divalent Ca+Mg+Fe carbonates were precipitated with organic-rich sediments. During the driest periods, the lake waters reached salinities sufficient to precipitate beds of nahcolite, halite, and trona. The sediment pore waters were sufficiently saline to precipitate disseminated crystals of nahcolite, shortite, and dawsonite along with a host of other authigenic carbonate and silicate minerals (Milton, 1977).

A noteworthy aspect of the mineralogy is the complete lack of authigenic sulfate minerals. Although sulfate was probably a major anion in the stream waters entering the lakes, the sulfate ion was presumably totally consumed by sulfate-reducing bacteria in the lake and sediment waters according to the following generalized oxidation-reduction reaction:

$$2CH_2O + SO_4^{-2} \rightarrow 2HCO_3^{-1} + H_2S$$

Note that two moles of bicarbonate are formed for each mole of sulfate that is reduced. The resulting hydrogen sulfide could either react with available Fe++ to precipitate as iron sulfide minerals or escape from the sediments as a gas (Dyni, 1998). Other major sources of carbonate include calcium carbonate-secreting algae, hydrolysis of silicate minerals, and direct input from inflowing streams.

The warm alkaline lake waters of the Eocene Green River lakes provided excellent conditions for the abundant growth of blue-green algae (cyanobacteria) that are thought to be the major precursor of the organic matter in the oil shale. During times of freshening waters, the lakes hosted a variety of fishes, rays, bivalves, gastropods, ostracodes, and other aquatic fauna. Areas peripheral to the lakes supported a large and varied assemblage of land plants, insects, amphibians, turtles, lizards, snakes, crocodiles, birds, and numerous mammalian animals (McKenna, 1960; MacGinitie, 1969; and Grande, 1984).

Historical Developments

The occurrence of oil shale in the Green River Formation in Colorado, Utah, and Wyoming has been known for many years. During the early 1900s, it was clearly established that the Green River deposits were a major resource of shale oil (Woodruff and Day, 1914; Winchester, 1916; Gavin, 1924). During this early period, the Green River and other deposits were investigated, including oil shale of the marine Phosphoria Formation of Permian age in Montana (Bowen, 1917; Condit, 1919) and oil shale in Tertiary lake beds near Elko, Nevada (Winchester, 1923).

In 1967, the U.S. Department of Interior began an extensive program to investigate the commercialization of the Green River oil-shale deposits. The dramatic increases in petroleum prices resulting from the OPEC oil embargo of 1973–74 triggered another resurgence of oil-shale activities during the 1970s and into the early 1980s. In 1974 several parcels of public oil-shale lands in Colorado, Utah, and Wyoming were put up for competitive bid under the Federal Prototype Oil Shale

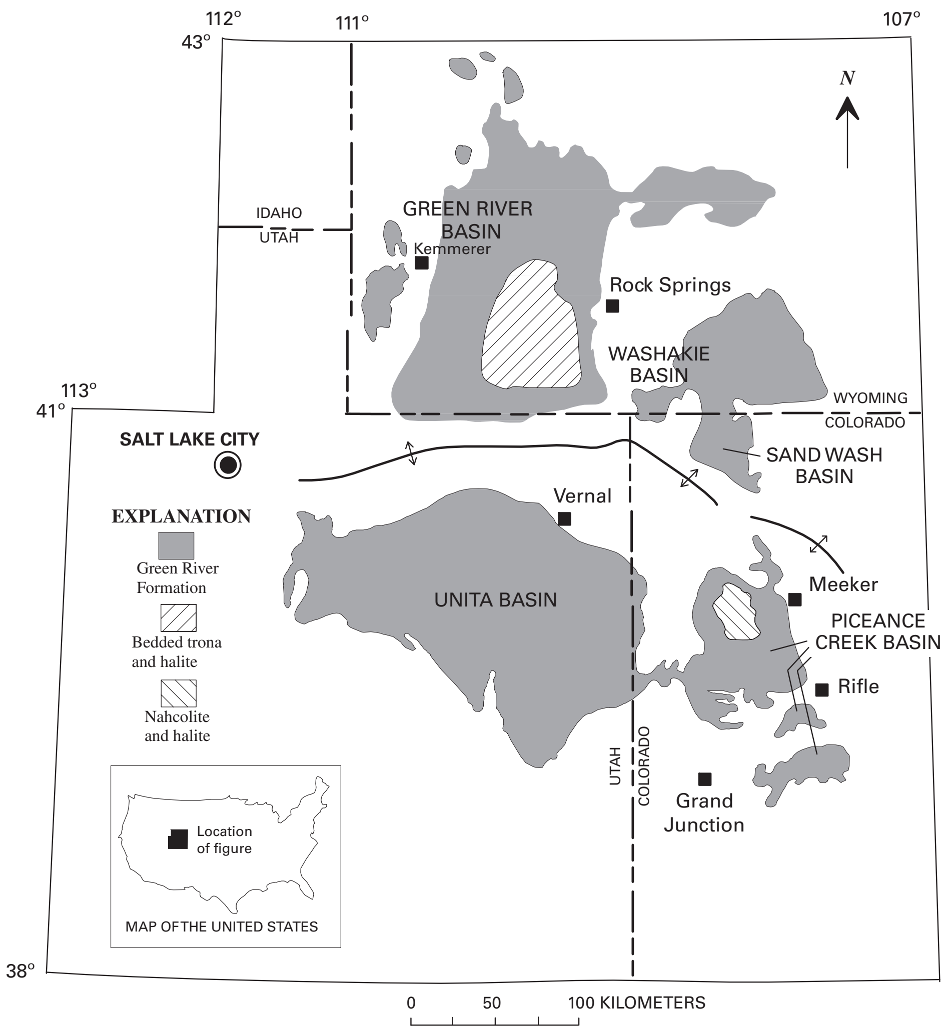


Figure 16. Areas underlain by the Green River Formation in Colorado, Utah, and Wyoming, United States.

Leasing Program. Two tracts were leased in Colorado (C-a and C-b) and two in Utah (U-a and U-b) to oil companies.

Large underground mining facilities, including vertical shafts, room-and-pillar entries, and modified in-situ retorts, were constructed on Tracts C-a and C-b, but little or no shale oil was produced. During this time, Unocal Oil Company was developing its oil-shale facilities on privately owned land on the south side of the Piceance Creek Basin. The facilities included a room-and-pillar mine with a surface entry, a 10,000 barrel/day (1,460 ton/day) retort, and an upgrading plant. A few miles north of the Unocal property, Exxon Corporation opened a room-and-pillar mine with a surface entry, haulage roads, waste-rock dumpsite, and a water-storage reservoir and dam.

In 1977–78 the U.S. Bureau of Mines opened an experimental mine that included a 723-m-deep shaft with several room-and-pillar entries in the northern part of the Piceance Creek Basin to conduct research on the deeper deposits of oil shale, which are commingled with nahcolite and dawsonite. The site was closed in the late 1980s.

About $80 million were spent on the U-a/U-b tracts in Utah by three energy companies to sink a 313-m-deep vertical shaft and inclined haulage way to a high-grade zone of oil shale and to open several small entries. Other facilities included a mine services building, water- and sewage-treatment plants, and a water-retention dam.

The Seep Ridge project sited south of the U-a/U-b tracts, funded by Geokinetics, Inc. and the U.S. Department of Energy, produced shale oil by a shallow in-situ retorting method. Several thousand barrels of shale oil were produced.

The Unocal oil-shale plant was the last major project to produce shale oil from the Green River Formation. Plant construction began in 1980, and capital investment for constructing the mine, retort, upgrading plant, and other facilities was $650 million. Unocal produced 657,000 tons (about 4.4 million bbls) of shale oil, which were shipped to Chicago for refining into transportation fuels and other products under a program partly subsidized by the U.S. Government. The average rate of production in the last months of operation was about 875 tons (about 5,900 barrels) of shale oil per day; the facility was closed in 1991.

In the past few years, Shell Oil Company began an experimental field project to recover shale oil by a proprietary in-situ technique. Some details about the project have been publicly announced, and the results to date (2006) appear to favor continued research.

Shale-Oil Resources

As the Green River oil-shale deposits in Colorado became better known, estimates of the resource increased from about 20 billion barrels in 1916, to 900 billion barrels in 1961, and to 1.0 trillion barrels (~147 billion tons) in 1989 (Winchester, 1916, p. 140; Donnell, 1961; Pitman and others, 1989). A lithologic section and a summary of the resources by oil-shale zones in the Piceance Creek Basin are shown in figure 17.

The Green River oil-shale resources in Utah and Wyoming are not as well known as those in Colorado. Trudell and others (1983, p. 57) calculated the measured and estimated resources of shale oil in an area of about 5,200 km^2 in eastern Uinta Basin, Utah, to be 214 billion barrels (31 billion tons) of which about one-third is in the rich Mahogany oil-shale zone. Culbertson and others (1980, p. 17) estimated the oil-shale resources in the Green River Formation in the Green River Basin in southwest Wyoming to be 244 billion barrels (~35 billion tons) of shale oil.

Additional resources are also in the Washakie Basin east of the Green River Basin in southwest Wyoming. Trudell and others (1973) reported that several members of the Green River Formation on Kinney Rim on the west side of the Washakie Basin contain sequences of low to moderate grades of oil shale in three core holes. Two sequences of oil shale in the Laney Member, 11 and 42 m thick, average 63 l/t and represent as much as 8.7 million tons of in-situ shale oil per square kilometer. A total estimate of the resource in the Washakie Basin was not reported for lack of subsurface data.

Other Mineral Resources

In addition to fossil energy, the Green River oil-shale deposits in Colorado contain valuable resources of sodium carbonate minerals including nahcolite ($NaHCO_3$) and dawsonite [$NaAl(OH)_2CO_3$]. Both minerals are commingled with high-grade oil shale in the deep northern part of the basin. Dyni (1974) estimated the total nahcolite resource at 29 billion tons. Beard and others (1974) estimated nearly the same amount of nahcolite and 17 billion tons of dawsonite. Both minerals have value for soda ash (Na_2CO_3) and dawsonite also has potential value for its alumina (Al_2O_3) content. The latter mineral is most likely to be recovered as a byproduct of an oil-shale operation. One company is solution mining nahcolite for the manufacture of sodium bicarbonate in the northern part of the Piceance Creek Basin at depths of about 600 m (Day, 1998). Another company stopped solution mining nahcolite in 2004, but now processes soda ash obtained from the Wyoming trona deposits to manufacture sodium bicarbonate.

The Wilkins Peak Member of the Green River Formation in the Green River Basin in southwestern Wyoming contains not only oil shale but also the world's largest known resource of natural sodium carbonate as trona ($Na_2CO_3.NaHCO_3.2H_2O$). The trona resource is estimated at more than 115 billion tons in 22 beds ranging from 1.2 to 9.8 m in thickness (Wiig and others, 1995). In 1997, trona production from five mines was 16.5 million tons (Harris, 1997). Trona is refined into soda ash (Na_2CO_3) used in the manufacture of bottle and flat glass, baking soda, soap and detergents, waste treatment chemicals, and many other industrial chemicals. One ton of soda ash is obtained from about two tons of trona ore. Wyoming trona supplies about 90 percent of U.S. soda ash needs; in addition, about one-third of the total Wyoming soda ash produced is exported.

In the deeper part of the Piceance Creek Basin, the Green River oil shale contains a potential resource of natural gas, but its economic recovery is questionable (Cole and Daub, 1991). Natural gas is also present in the Green River oil-shale deposits in southwest Wyoming, and probably in the oil shale in Utah, but in unknown quantities. A summary of the oil shale and mineral resources of the Green River Formation in Colorado, Wyoming, and Utah is given in table 8.

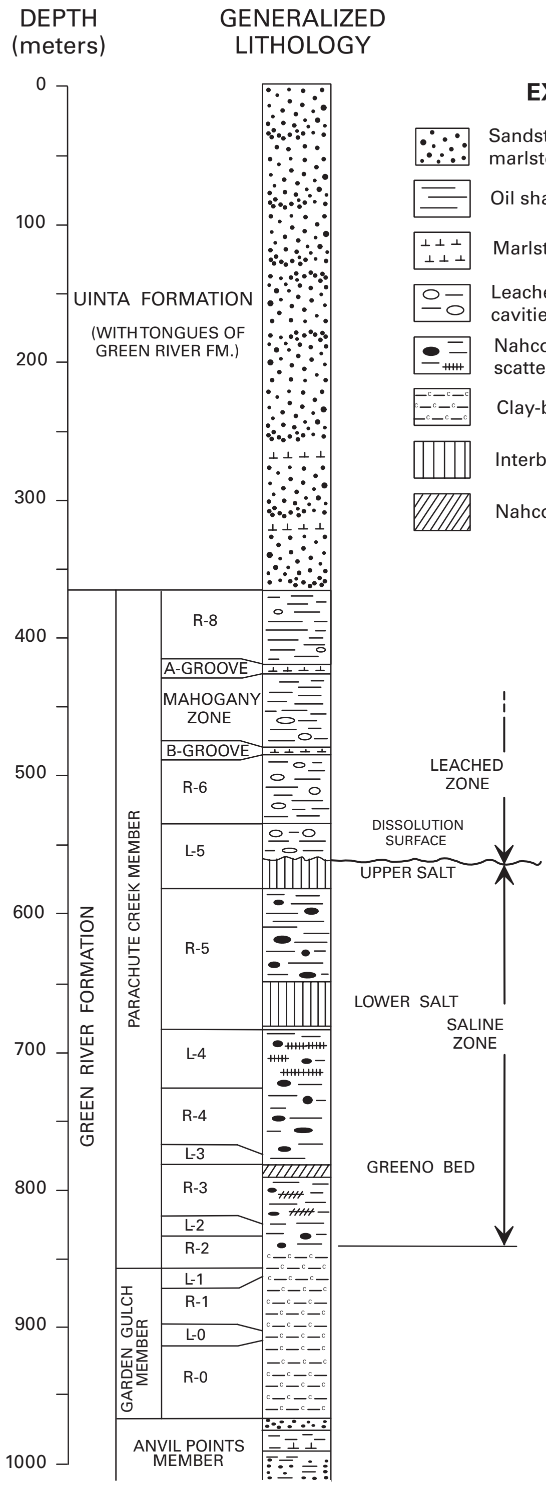
Eastern Devonian–Mississippian Oil Shale

Depositional Environment

Black organic-rich marine shale and associated sediments of Late Devonian and Early Mississippian age underlie about 725,000 km^2 in the eastern United States (fig. 18). These shales have been exploited for many years as a resource of natural gas, but have also been considered as a potential low-grade resource of shale oil and uranium (Roen and Kepferle, 1993; Conant and Swanson, 1961).

Over the years, geologists have applied many local names to these shales and associated rocks, including the Chattanooga, New Albany, Ohio, Sunbury, Antrim, and others. A group of papers detailing the stratigraphy, structure, and gas potential of these rocks in eastern United States have been published by the U.S. Geological Survey (Roen and Kepferle, 1993).

The black shales were deposited during Late Devonian and Early Mississippian time in a large epeiric sea that covered much of middle and eastern United States east of the Mississippi River (fig. 18). The area included the broad, shallow,



SHALE OIL RESOURCES

Zone	Shale oil (10^9 tons)	Shale oil (10^9 bbls)
R-8	(ND)	(ND)
Mahogany	25.25	172.94
R-6	23.23	159.09
L-5	7.65	52.42
R-5	26.09	178.72
L-4	8.88	60.85
R-4	15.74	107.78
L-3	2.73	18.72
R-3	8.52	58.38
L-2	2.93	20.08
R-2	7.75	53.07
L-1	1.56	10.70
R-1	16.84	115.35
Total	147.17	1008.10

Figure 17. Generalized stratigraphic section of the Green River Formation and associated rocks in the north-central part of the Piceance Creek Basin, northwestern Colorado, United States. Adapted from Cole and Daub (1991, their fig. 2). The shale-oil resource data, converted from U.S. barrels to metric tons, are from Pitman and others (1989).

Table 8. Summary of the energy and mineral resources of the Green River Formation in Colorado, Utah, and Wyoming, United States. Data from Donnell (1980), Culbertson and others (1980), Trudell and others (1983), Dyni (1974, 1997), Beard and others (1974), Cole and Daub (1991), Pitman and Johnson (1978), Pitman and others (1989), Wiig and others (1995), and unpublished data from the U.S. Bureau of Mines (1981).

[km^2, square kilometers; l/t, liters per ton; m^3, cubic meters]

Basin	Area (km^2)	Federal lands (percent)	Resources Grade (l/t)	Resources Shale oil (10^9 tons)
Shale-oil resources				
Piceance Creek Basin, Colorado	4,600	79[1]	≥63	147
			≥104	(85)[2]
			≥125	(49)[2]
Uinta Basin, Utah	~ 2,150	77	≥42	31
Green River Basin, Wyoming	~ 1,200	62	≥63	35.4
	~(475)[2]		125	(1.9)[2]
Total	7,900			213
Other resources				
Green River Basin, Wyoming				
Trona	~ 2,800	57		115
Piceance Creek Basin, Colorado				
Dawsonite	~ 1,300			26
Nahcolite	660			29
Natural gas	>230			130x10^9 m^3

[1]The percentage of Federal lands in the Piceance Creek Basin has been reduced by several percent from this figure owing to the transfer of a group of oil-shale placer claims to private ownership.

[2]Data included in the total figure for the basin.

Interior Platform on the west that grades eastward into the Appalachian Basin. The depth to the base of the Devonian–Mississippian black shales ranges from surface exposures on the Interior Platform to more than 2,700 m along the depositional axis of the Appalachian Basin (de Witt and others, 1993, their pl. 1).

The Late Devonian sea was relatively shallow with minimal current and wave action, much like the environment in which the Alum Shale of Sweden was deposited in Europe. A large part of the organic matter in the black shale is amorphous bituminite, although a few structured fossil organisms such as *Tasmanites*, *Botryococcus*, *Foerstia*, and others have been recognized. Conodonts and linguloid brachiopods are sparingly distributed through some beds. Although much of the organic matter is amorphous and of uncertain origin, it is generally believed that much of it was derived from planktonic algae.

In the distal parts of the Devonian sea, the organic matter accumulated very slowly along with very fine-grained clayey sediments in poorly oxygenated waters free of burrowing organisms. Conant and Swanson (1961, p. 54) estimated that 30 cm of the upper part of the Chattanooga Shale deposited on the Interior Platform in Tennessee could represent as much as 150,000 years of sedimentation.

The black shales thicken eastward into the Appalachian Basin owing to increasing amounts of clastic sediments that were shed into the Devonian sea from the Appalachian highland lying to the east of the basin. Pyrite and marcasite are abundant authigenic minerals, but carbonate minerals are only a minor fraction of the mineral matter.

Resources

The oil-shale resource is in that part of the Interior Platform where the black shales are the richest and closest to the surface. Although long known to produce oil upon retorting, the organic matter in the Devonian–Mississippian black shale yields only about half as much as the organic matter of the Green River oil shale, which is thought to be attributable to

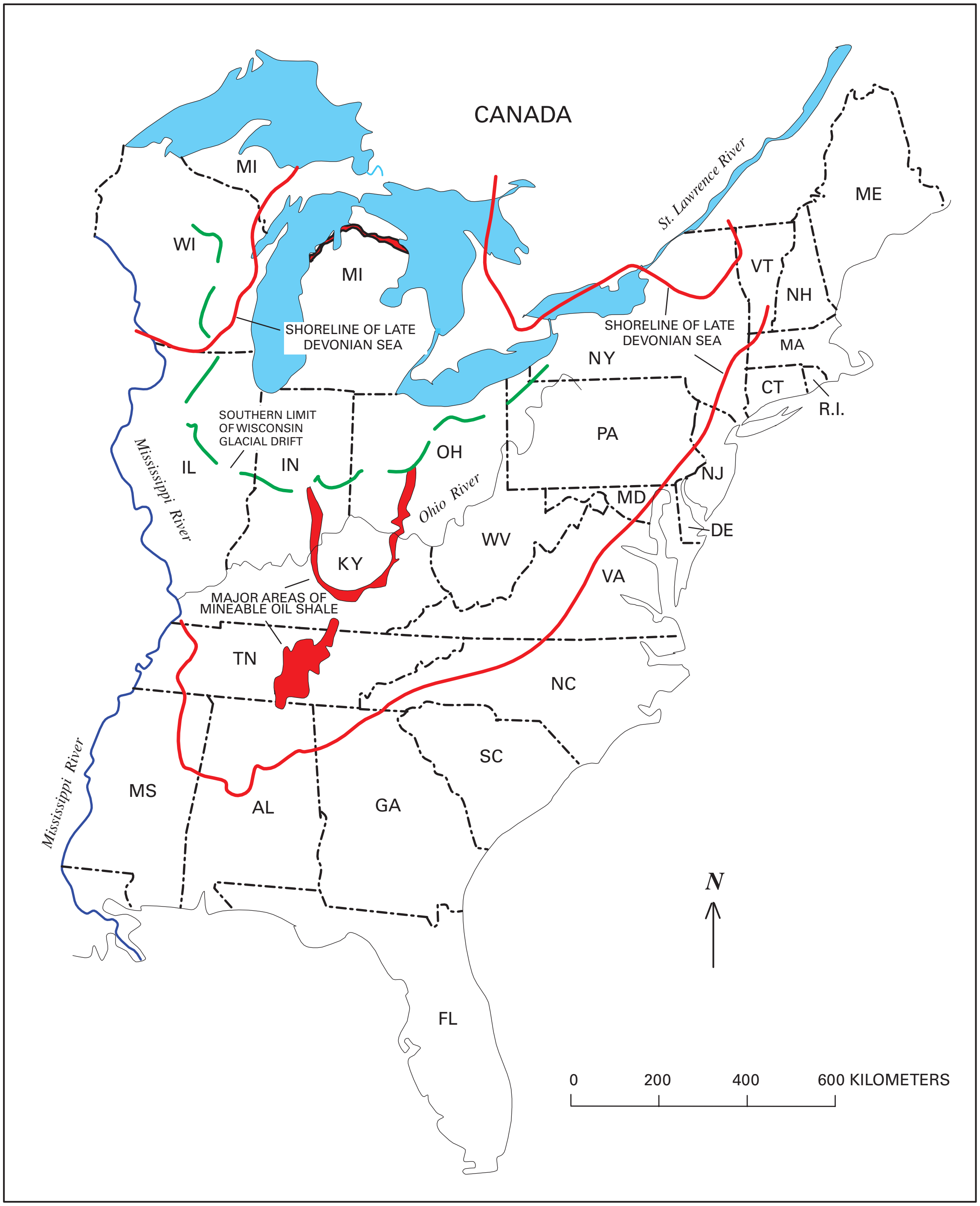


Figure 18. Paleogeographic map showing shoreline of the Late Devonian sea in eastern United States and major areas of surface-mineable Devonian oil shale. After Conant and Swanson (1961, their fig. 13) and Matthews and others (1980, their fig. 5).

differences in the type of organic matter (or type of organic carbon) in each of the oil shales. The Devonian–Mississippian oil shale has a higher ratio of aromatic to aliphatic organic carbon than Green River oil shale, and is shown by material balance Fischer assays to yield much less shale oil and a higher percentage of carbon residue (Miknis, 1990).

Hydroretorting Devonian–Mississippian oil shale can increase the oil yield by more than 200 percent of the value determined by Fischer assay. In contrast, the conversion of organic matter to oil by hydroretorting is much less for Green River oil shale, about 130 to 140 percent of the Fischer assay value. Other marine oil shales also respond favorably to hydroretorting, with yields as much as, or more than, 300 percent of the Fischer assay (Dyni, and others, 1990).

Matthews and others (1980) evaluated the Devonian–Mississippian oil shales in areas of the Interior Platform where the shales are rich enough in organic matter and close enough to the surface to be mineable by open pit. Results of investigations in Alabama, Illinois, Indiana, Kentucky, Ohio, Michigan, eastern Missouri, Tennessee, and West Virginia indicated that 98 percent of the near-surface mineable resources are in Kentucky, Ohio, Indiana, and Tennessee (Matthews, 1983).

The criteria for the evaluation of the Devonian–Mississippian oil-shale resource used by Matthews and others (1980) were:

1. Organic carbon content: ≥10 weight percent
2. Overburden: ≤200 m
3. Stripping ratio: ≤2.5:1
4. Thickness of shale bed: ≥3 m
5. Open-pit mining and hydroretorting

On the basis of these criteria, the total Devonian–Mississippian shale oil resources were estimated to be 423 billion barrels (61 billion tons); resources by State are summarized in table 9.

Table 9. Estimated resources of near-surface oil shale in eastern United States by hydroretorting. Data derived from Matthews and others (1980, their table 3).

[km^2, square kilometer; hectare=2.47 acres]

State	Area (km^2)	Shale oil tons (10^9)	Shale oil tons/hectare
Ohio	2,540	20.2	79,000
Kentucky	6,860	27.4	40,000
Tennessee	3,990	6.3	15,500
Indiana	1,550	5.8	37,000
Michigan	410	0.7	17,500
Alabama	780	0.6	7,500
Total	16,130	61.0	

Summary of World Resources of Shale Oil

Resources of shale oil for selected deposits worldwide are listed in alphabetical order by country in table 10. Individual deposits for some countries are listed under subheadings, commonly by States or Provinces.

Because of widespread use in the reporting of petroleum and shale-oil resources, quantities are expressed in terms of U.S. barrels in table 10; resources are also reported in metric tons of shale oil. Sources of information (author and date of reference) are given for most of the deposits. The data are too sparse for most deposits to differentiate between resources and reserves of oil shale.

The grade of the oil-shale resource is not indicated in the table. However, it can be assumed that most of the deposits listed will yield, by Fischer assay, at least 40 or more liters of shale oil per ton of oil shale.

For some countries, shale-oil resources of individual deposits are listed. Resources for individual deposits are shown in parentheses when they are included in the total resource figure for a country. Resource figures shown in boldface are from data reported in the literature; the associated figure in normal type was calculated for table 10.

The reliability of resource data, as indicated in the foregoing sections of this report, ranges from excellent to poor. Data for some deposits that have been explored extensively by core drilling are good, such as the Green River oil shale in Colorado, the kukersite deposit in Estonia, and some of the Tertiary deposits in eastern Queensland, Australia, are especially good in comparison to others.

A few large deposits of oil shale, such as the Toolebuc oil shale of Queensland, Australia, are too low-grade to be utilized in the near future. However, improved methods of mining and processing could change their economic status. The largest and richest known deposit by far is the Green River oil shale in western United States. In Colorado alone, the total resource reaches one trillion barrels, of which one-quarter to perhaps as much as one-third may be recoverable with mining and processing techniques available today.

Some countries having good-quality oil shale but lacking petroleum and (or) coal resources will continue to mine oil shale for transportation fuels, petrochemicals, fuel for electric power plants, building materials, and other byproducts. However, their oil-shale industries face imposing challenges from cheaper resources of crude petroleum and coal, as well as from air and water pollution problems.

Production of oil shale from several countries, for which some data are available, are shown in figure 19. World oil-shale production peaked in 1980 when 47 million tons were mined, much of it in Estonia where it was used mainly for fuel in several large electric power plants.

Table 10. In-situ shale-oil resources of some world oil-shale deposits.

Country, region, and deposit[1]	Age[2]	In-place shale-oil resources[3] (10⁶ bbls)	In-place shale-oil resources[3] (10⁶ tons)	Date of estimation[4]	Source of information
Argentina		**400**	57	1962	
Armenia					
Aramus	T	**305**	44	1994	Pierce & others (1994)[5]
Australia					
New South Wales	P	**40**	6	1987	Crisp & others (1987)
Queensland					
Alpha	P	**80**	1	1987	Matheson (1987)[6]
Byfield	T	**249**	36	1999	Wright (1999, written commun.)[6]
Condor	T	**9,700**	1,388	do	do
Duaringa (upper unit)	T	**4,100**	587	do	do
Herbert Creek Basin	T	**1,530**	219	do	do
Julia Creek	K	**1,700**	243	do	do
Lowmead	T	**740**	106	do	do
Mt. Coolon	T	**72**	10	do	do
Nagoorin Basin	T	**3,170**	454	do	do
Rundle	T	**2,600**	372	do	do
Stuart	T	**3,000**	429	do	do
Yaamba	T	**4,100**	587	do	Wright (1999, written commun.)[7]
South Australia					
Leigh Creek	TR	**600**	86	1999	Wright (1999, written commun.)[6]
Tasmania					
Mersey River	P	**48**	7	1987	Crisp & others (1987)
Austria		**8**	1	1974	
Belarus					
Pripyat Basin	D	6,988	**1,000**		
Brazil					
Iratí Formation	P	**80,000**	11,448	1994	Afonso & others (1994)
Paraíba Valley	T	**2,000**	286	1969	Padula (1969)
Bulgaria		**125**	18	1962	
Canada					
Manitoba-Saskatchewan					
Favel-Boyne Formations	K	**1,250**	191	1981	Macauley (1981, 1984a, 1986)[8]
Nova Scotia					
Stellarton Basin	P-ℙ	1,174	**168**	1989	Smith & others (1989)[8]
Antigonish Basin		531	**76**	1990	Smith & Naylor (1990)
New Brunswick					
Albert Mines	M	**269**	38	1988	Ball & Macauley (1988)
Dover	M	**14**	2	do	do
Rosevale	M	**3**	0.4	do	do
Newfoundland					
Deer Lake Basin	M	?	?	1984	Hyde (1984)[9]

Table 10. In-situ shale-oil resources of some world oil-shale deposits—*Continued.*

Country, region, and deposit[1]	Age[2]	In-place shale-oil resources[3] (10^6 bbls)	In-place shale-oil resources[3] (10^6 tons)	Date of estimation[4]	Source of information
Nunavut					
Sverdrup Basin	M	?	?	1988	Davies & Nassichuk (1988)[10]
Ontario					
Collingwood Shale	O	**12,000**	1,717	1986	Macauley (1986)
Kettle Point Fm	D	?	?	1986	do
Chile		**21**	3	1936	
China		**16,000**	2,290	1985	Du & Nuttall (1985)[11]
Moaming	T	(2,271)	**(325)**	1988	Guo-Quan (1988)
Fushun	T	(127)	**(18)**	1990	Johnson (1990)
Congo, Republic of		**100,000**	14,310	1958	
Egypt					
Safaga-Quseir area	K	**4,500**	644	1984	Troger (1984)
Abu Tartur area	K	**1,200**	172	1984	Troger (1984)
Estonia					
Estonia deposit	O	3,900	**594**	1998	Kattai & Lokk (1998)[12]
Dictyonema Shale	O	12,386	**1,900**		
France		**7,000**	1,002	1978	
Germany		**2,000**	286	1965	
Hungary		56	**8**	1995	Papay (1998)[13]
Iraq					May be very large;
Yarmouk	K	?	?	1999	See Jordan
Israel		**4,000**	550	1982	Minster & Shirav (1982)[14]
Italy		**10,000**	1,431	1979	
Sicily		**63,000**	9,015	1978	
Jordan					
Attarat Umm Ghudran	K	8,103	**1,243**	1997	Jaber & others (1997)[15]
El Lajjun	K	821	**126**	1997	do
Juref ed Darawish	K	3,325	**510**	1997	do
Sultani	K	482	**74**	1997	do
Wadi Maghar	K	14,009	**2,149**	1997	do
Wadi Thamad	K	7,432	**1,140**	1997	do
Yarmouk	K		(Large)	1999	Minster (1999)[16]
Kazakhstan					
Kenderlyk field		2,837	**400**	1996	Yefimov (1996)[17]
Luxembourg	J	**675**	97	1993	Robl and others (1993)
Madagascar		**32**	5	1974	
Mongolia					
Khoot	J	294	**42**	2001	Avid and Purevsuren (2001)
Morocco					
Timahdit	K	**11,236**	1,719	1984	Bouchta (1984)[18]
Tarfaya Zone R	K	**42,145**	6,448	1984	do

Table 10. In-situ shale-oil resources of some world oil-shale deposits—*Continued.*

Country, region, and deposit[1]	Age[2]	In-place shale-oil resources[3] (10^6 bbls)	In-place shale-oil resources[3] (10^6 tons)	Date of estimation[4]	Source of information
Myanmar (Burma)		**2,000**	286	1924	
New Zealand		**19**	3	1976	
Poland		**48**	7	1974	
Russia					
St. Petersburg kukersite	O	25,157	**3,600**		
Timano-Petchorsk Basin	J	3,494	**500**		
Vychegodsk Basin	J	19,580	**2,800**		
Central Basin	?	70	**10**		
Volga Basin	?	31,447	**4,500**		
Turgai & Nizheiljisk deposit	?	210	**30**		
Olenyok Basin	Є	167,715	**24,000**		
Other deposits	—	210	**30**		
South Africa		**130**	19	1937	
Spain		**280**	40	1958	
Sweden					
Narke	Є	594	**85**	1985	Andersson & others (1985)
Ostergotland	Є	2,795	**400**	1985	do
Vastergotland	Є	1,537	**220**	1985	do
Oland	Є	1,188	**170**	1985	do
Thailand Deposit & (Province)					
Mae Sot (Tak)	T	**6,400**	916	1988	Vanichseni & others (1988)
Li (Lampoon)	T	**1**		1988	do
Turkmenistan & Uzbekistan					
Amudarja Basin[19]	P	7,687	**1,100**		
Turkey Deposit & (Province)					
Bahcecik (Izmit)	T	35	**5**	1993	Güleç & Önen (1993)[20]
Beypazari (Ankara)	T	398	**57**	1995	Sener & others (1995)
Burhaniye (Bahkesir)	T	28	**4**	1993	Güleç & Önen (1993)
Golpazari (Bilecik)	T	126	**18**	1993	do
Goynuk (Bolu)	T	804	**115**	1995	Sener & others (1995)
Hatildag (Bolu)	T	203	**29**	1995	do
Seyitomer (Kutahya)	T	349	**50**	1995	do
Ulukisla (Nigde)	T	42	**6**	1993	Güleç & Önen (1993)
Ukraine Boltysh deposit		4,193	**600**	1988	Tsherepovski
United Kingdom		**3,500**	501	1975	

Table 10. In-situ shale-oil resources of some world oil-shale deposits—*Continued.*

Country, region, and deposit[1]	Age[2]	In-place shale-oil resources[3] (10^6 bbls)	In-place shale-oil resources[3] (10^6 tons)	Date of estimation[4]	Source of information
United States					
Eastern Devonian shale	D	**189,000**	27,000	1980	Matthews & others (1980)[21]
Green River Fm	T	**1,466,000**	213,000	1999	This report
Phosphoria Fm	P	**250,000**	35,775	1980	Smith (1980)
Heath Fm	M	**180,000**	25,758	1980	do
Elko Fm	T	**228**	33	1983	Moore & others (1983)
Uzbekistan					
Kyzylkum Basin		8,386	**1,200**		
Total (rounded)		**2,826,000**	**409,000**		

[1]The resources in the above table are listed by country in alphabetical order. For some countries, the deposits are listed under State or Province.

[2]The age of the deposit, when known, is indicated by the following symbols: Ꞓ, Cambrian; O, Ordovician; D, Devonian; M, Mississippian (Early Carboniferous); ℙ, Pennsylvanian (Late Carboniferous); P, Permian; TR, Triassic; J, Jurassic; K, Cretaceous; and T, Tertiary.

[3]The resources of shale oil are given in U.S. barrels and metric tons. Resource numbers in boldface type are from the references cited; the associated number in nonboldface type was calculated for this table. In several cases, resource numbers in parentheses are included in the total resource number for the country. To determine tons of resources from volumetric data, it is necessary to know the specific gravity of the shale oil. In some cases, this value was given in the source reference; if not, a specific gravity of 0.910 was assumed.

[4]The "date of estimation" is the publication date of the source reference. If a reference is not listed for a deposit, the resource data are from Russell (1990). A few deposits for which no resource numbers are given are still listed in the table because they are believed to be of significant size.

[5]The resource was estimated by assuming seven beds of oil shale totaling 14 m in thickness, which underlie 22 square kilometers and have an average oil-shale bulk density of 2.364 gm/cc.

[6]Shale-oil specific gravity (SG) of 0.910 was assumed. Resource data from Matheson (1987) augmented by a personal communication from Dr. Bruce Wright to Professor J.L. Qian dated March 29, 1999.

[7]McFarlane (1984) gives the Yaamba deposit as 2.92 billion in-situ barrels of shale oil.

[8]Shale oil SG of 0.910 was assumed.

[9]The west side of the basin is largely unexplored and may contain oil-shale deposits.

[10]Alginite-rich oil shale is found in the Lower Carboniferous Emma Fiord Formation at several localities in the Sverdrup Basin. On Ellemere Island the shale is geothermally overmature, but on Devon Island, the oil shale is immature to marginally mature.

[11]China's total oil-shale resources are given by Du and Nuttall (1985, p. 211).

[12]A shale-oil yield of 10 wt pct and a shale oil SG of 0.968 were used to calculate barrels of resources (Yefimov and others, 1997, p. 600). Kogerman (1997, p. 629) gives the range of oil yields of Estonian kukersite as 12–18 wt pct.

[13]Assumed a shale-oil yield of 8 wt pct and a shale-oil SG of 0.910.

[14]Fainberg and Hetsroni (1996) estimate Israel's oil-shale reserves at 12 billion tons, which equates to 600 million tons of shale oil.

[15]Shale-oil SG of 0.968 was assumed.

[16]The oil-shale deposit underlies several hundred square kilometers and reaches 400 m in thickness (Minster, 1999, written commun.).

[17]Shale-oil SG of 0.900 was assumed.

[18]Shale-oil SG of 0.970 was assumed. Occidental Oil Company made the estimate of the Timahdit resource and Bouchta estimated the Tarfaya resource; details of both estimates are in Bouchta (1984).

[19]Amudarja Basin extends across border between Turkmenistan and Uzbekistan.

[20]Güleç and Önen (1993) reported 5,196 million tons of oil shale in seven deposits but no shale-oil numbers. Graham and others (1993) estimate the Goynuk resource at 9 billion tons of oil shale. Sener and others (1995) reported 1,865 million tons of oil shale in four Turkish deposits.

[21]The Devonian oil-shale resource estimated by Matthews and others (1980) is based on hydroretorting analyses. To make these results compatible with the rest of the resource data in this table, which are based mostly on Fischer assay analyses, the resource numbers given by Matthews and others (1980) were reduced by 64 percent.

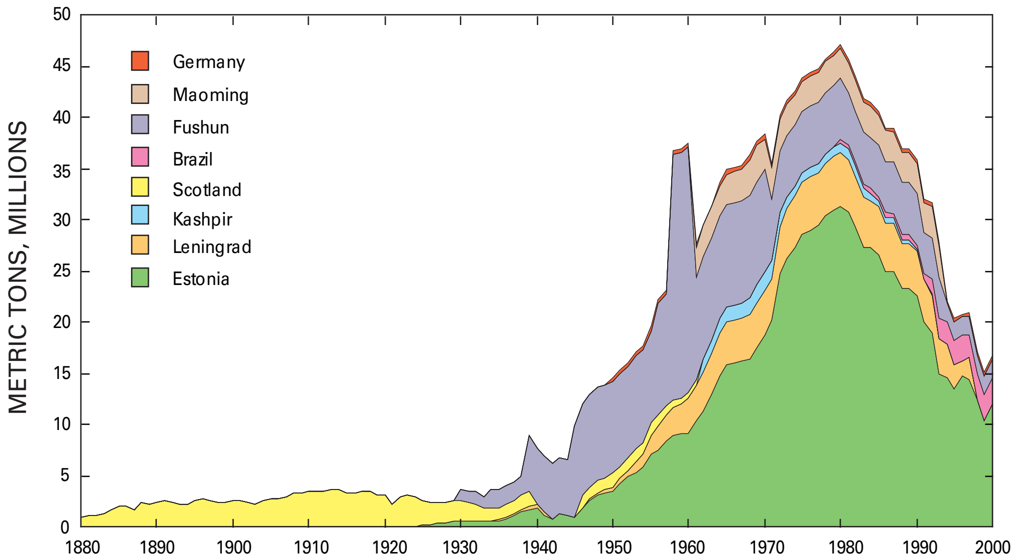


Figure 19. Production of oil shale in millions of metric tons from Estonia (Estonia deposit), Russia (Leningrad and Kashpir deposits), United Kingdom (Scotland, Lothians), Brazil (Iratí Formation), China (Maoming and Fushun deposits), and Germany (Dotternhausen) from 1880 to 2000.

The total resource of oil shale of 409 billion tons (2.9 trillion U.S. barrels) listed in table 10 should be considered a minimum figure, because numerous deposits are still largely unexplored or were not included in this study. Further exploration will undoubtedly add many more billions of tons of in-situ shale oil to this total.

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Manuscript approved for publication December 28, 2005
Published in the Central Region, Denver, Colorado
Graphics by author
Photocomposition by Sharon Powers
Edited by Tom Judkins