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GEOLOGY AND RESOURCES OF SOME WORLD OIL-SHALE DEPOSITS*

J. R. DYNI**

U.S. Geological Survey
Box 25046, Mail Stop 939
Denver Federal Center, Colorado 80225

Oil-shale deposits are found 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 the Green River oil shale in western United States. It contains an estimated 215 billion tons of in-place shale oil (1.5 trillion U.S. barrels). Total resources of a selected group of oil-shale deposits in 33 countries is estimated at 411 billion tons of in-place shale oil which is equivalent to 2.9 trillion U.S. barrels of shale oil. This figure is very conservative because several deposits mentioned herein have not been explored sufficiently to make accurate estimates and other deposits were not included in this survey.

Introduction

Oil shale is commonly defined as a fine-grained sedimentary rock containing organic matter that will yield substantial amounts of oil and combustible gas upon destructive distillation. Underlying most definitions of oil shale is its potential for the economic recovery of energy including shale oil, combustible gas, heat, and byproducts. A deposit of oil shale having economic potential is usually one that is at or near enough to the surface to be developed by open-cast or conventional underground mining or by *in situ* methods.

Deposits of oil shale are found in many parts of the world. These deposits, which range from Cambrian to Tertiary in age, occur as minor accumulations of little or no economic value to giant deposits that occupy thousands of square kilometers and reach thicknesses of 700 or more meters. 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 significant ways. Oil shales typically contain much larger amounts of

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** e-mail *jdyni@usgs.gov, jdyni@eathlink.net*

inert mineral matter (ca. 60–90 %) than coals which have been defined as containing less than 40 % mineral matter. The organic matter of oil shale, which is the source of liquid and gaseous hydrocarbons, usually has a higher hydrogen to oxygen ratio than that of coal. Generally speaking, 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 the remains of vascular land plants which more commonly comprise much of the organic matter in coal. The origin of some of the organic matter in oil shale is enigmatic 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 carbonate minerals including calcite, dolomite, and siderite, with lesser amounts of aluminosilicate minerals. For other oil shales, the reverse is true – silicate minerals including quartz, feldspar, and clay minerals are dominant whereas carbonate minerals are a minor component. Many deposits of oil shale contain, small but ubiquitous, amounts of sulfide minerals including pyrite, and marcasite. These sulfide minerals suggest that the sediments accumulated in dysaerobic to anoxic waters that preserved the organic matter from burrowing organisms.

Some deposits were altered by tectonic events and volcanism. Structural deformation may impair the mining of an oil-shale deposit, whereas igneous intrusions can thermally degrade the organic matter in oil shale. Such effects may be local, adversely affecting only a part of a deposit, or they may be widespread making most of the deposit unfit for recovery of shale oil.

Although shale oil in today's (2003) world market is not competitive with petroleum, natural gas, or coal, it is still 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 may add byproduct value including alum [$KAl(SO_4)_2 \cdot 12H_2O$], nahcolite ($NaHCO_3$), dawsonite [$Na(Al(OH)_2CO_3$], sulfur, ammonium sulfate, vanadium, zinc, copper, and uranium, and others.

The gross heating value of oil shales on a dry basis ranges from about 500 to 4,000 kcal/kg. 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).

Purpose

The purpose of this report is to discuss the geology and resources of some selected deposits of oil shale in varied geologic settings from different parts of the world. This report also presents new information on selected oil-shale deposits that was not available at the time Russell's book on world oil shales was published (Russell, 1990).

Recoverable Resources

To what extent an oil-shale resource can be commercially developed depends upon many factors. In addition to the geologic history and physical and chemical characteristics of the deposit, other factors must be considered. Infrastructure including of roads, railroads, and power lines, water, and available labor will determine the viability of an oil-shale operation. Oil-shale lands may be in conflict with surface uses. Populated areas (cities and towns), national and state parks, wildlife refuges, and similar entities may limit the lands that can be mined. On the other hand, development of new *in situ* mining methods and processing technologies may allow an oil shale operation to exist closer to restricted areas without causing significant problems of air and water pollution.

The most important factor that will determine the large-scale development of an oil-shale industry is the price of petroleum. Today, few if any, deposits of oil shale can be economically mined and processed for shale oil in competition with petroleum. Nevertheless, some countries with oil-shale resources, but lacking coal and petroleum resources, find it expedient to operate an oil-shale industry. In time, as supplies of petroleum diminish in future years, increased use of shale oil for the production of electric power, transportation fuels, petrochemical chemicals, and other industrial products seems likely.

Determining the Grade of Oil Shale

The grade of oil shale has been determined by many methods and the results are expressed in a variety of units. One method is to determine the heating value of the oil shale with a calorimeter. The results are reported English or metric units, such as British thermal units (Btu) per pound of oil shale, calories per gram (cal/gm), kilocalories per kilogram (kcal/kg), megajoules per kilogram, and others. 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 another oil shale will yield by retorting (destructive distillation).

Another method for determining the grade of an oil shale is to measure its yield in a laboratory retort. This is perhaps the most common type of analysis that is used today 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 improved by the U.S. Bureau of Mines (Stanfield and Frost, 1949) for analyzing oil shale of the Green River Formation in western United States. 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 appraise 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 minus 8-mesh (2.38 mm mesh) screen in a small aluminum retort to 500 °C at a rate of 12 °C 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 separated by centrifuging. The quantities reported are the weight percentages of shale oil (and its specific gravity), water, retorted shale, and "gas plus loss" by difference.

The Fischer assay method has some drawbacks. It 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 – including hydrocarbons, hydrogen, and carbon dioxide – are not normally determined but are reported collectively as "gas plus loss", which is the difference of 100 wt% minus the sum of the weights of oil, water, and spent shale. The kinds and amounts of noncondensible gases in the "gas plus loss" fraction are not determined. Some oil shales may have a greater recoverable energy potential than that reported by the Fischer assay method if the amounts of the components of the "gas plus loss" were known.

The Fischer assay method does not necessarily indicate the maximum amount of oil that can be produced by a given oil shale. Some retorting methods, such as the Tosco II process, are known to yield in excess of 100 % 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 300 to 400 % of the Fischer assay yield. (Schora and others, 1983; Dyni, Anders, and Rex, 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 the number of such analyses is still small. The modified Fischer assay, or close variations of this method, 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 which 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 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 enigmatic but it is likely a mixture of degraded algae 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 oil shales contain a preponderance of organic matter derived from various types of marine and lacustrine algae, with small to abundant admixtures of biologically higher forms of plant debris, depending upon the depositional environment and geographic position of the accumulating organic-rich sediments. Bacterial remains may be volumetrically important in many oil shales; however, their identity in oil shales is difficult to ascertain. Indirect evidence suggests that bacterial processes were important during the deposition and early diagenesis of most oil shales that lead to formation of authigenic sulfide and carbonate minerals.

Most of the organic matter in oil shale is insoluble in ordinary organic solvents. Some the organic matter is bitumen that is soluble in organic solvents. Solid hydrocarbons, including gilsonite, wurtzilite, grahamite, ozokerite, and albertite, are found as veins or pods in some oil shales. These hydrocarbons have somewhat different 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 high enough temperatures, as may be the case if the oil shale was deeply buried, the organic matter can decompose to form oil and gas. Under these circumstances, oil shales can become source rocks for petroleum and natural gas. On the other hand, those oil-shale deposits that have economic potential for its 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 or some type of underground mining.

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

Geothermal maturity of organic matter in an oil shale can also be determined by measuring the reflectance of vitrinite (a common constituent of coal derived from vascular land plants) that may be present. Vitrinite reflectance 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 form oil and gas. However, this method poses several problems with respect to oil shale, because the reflectance of the coaly material may be depressed by lipid-rich organic matter that is present in oil shale.

Another problem could also be that the material that looks like vitrinite in oil shale may, in fact, may not be vitrinite, but organic material of algal origin that looks very similar to vitrinite but does not have the same reflectance response as a true vitrinite. So it is sometimes necessary to determine vitrinite reflectances in coaly rocks that are laterally equivalent to an oil shale but are free of the lipid-rich organic components that can suppress vitrinite reflectance values.

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

Classification of Oil Shale

Oil shale has been an enigmatic type of rock that has received many different names over the past 100 or more years. Some of the more colorful names that have been used include cannel coal, boghead coal, alum shale, stellarite, albertite, kerosene shale, bituminite, gas coal, algal coal, wollongite, schistes bitumineux, torbanite, kukersite, and others. Some of these names are still used for certain types of oil shale because they have been in use for many years.

It has only been in relatively recent years that attempts have been made to classify the many different types of oil shale on a rational basis. Modern classifications of oil shale consider the depositional environment of the deposit, the petrographic character of the organic matter, and identification of the precursor organisms from which the organic matter was derived.

A useful classification of oil shales was developed by Hutton (1987, 1988, and 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 workable scheme for classifying oil shales based primarily on the origin of the organic matter in oil shale. 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) visualizes oil shale as one of three broad groups of organic-rich sedimentary rocks: (1) humic coal and carbonaceous shale, (2) bitumen-impregnated rock (tar sands and petroleum reservoir rocks), and (3) oil shale. He divides oil shales into three grouzps based upon their environment of deposition: (*a*) terrestrial, (*b*) lacustrine, and (*c*) marine (Fig. 1).

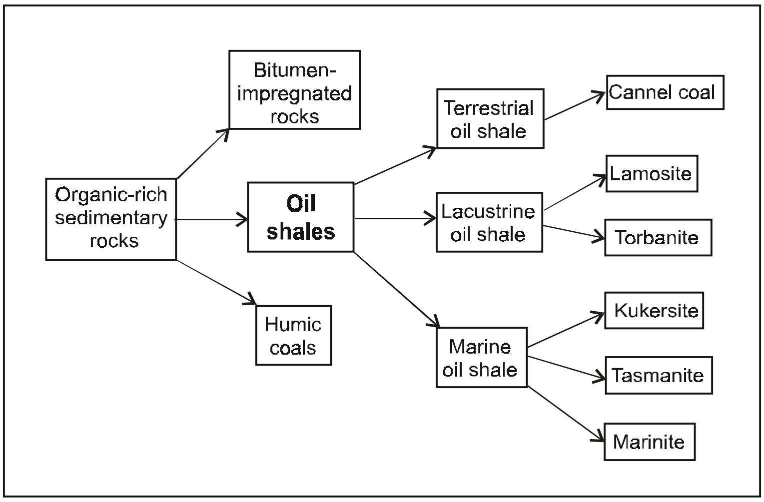


Fig. 1. Classification of oil shales. From Hutton (1987)

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

Several quantitatively important petrographic components of the organic matter in oil shale adapted from coal petrographic terminology include telalginite, lamalginite, and bituminite. Telalginite is organic matter derived from large colonial or thick-walled unicellular algae that possesses recognizable biologic entities, 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 (shades of yellow) under blue/ultraviolet light.

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

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

Cannel coal is brown to black oil shale composed of resins, spores, waxes, cutinaceous and corky materials derived from terrestrial vascular plants as well as 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 brown and grayish-brown to dark-gray to black oil shale in which the chief organic constituent is lamalginite derived from lacustrine planktonic algae. Other minor components include vitrinite, inertinite, telalginite, and bitumen. The Green River oil-shale deposits in western United States and a number of the Tertiary lacustrine deposits in eastern Queensland, Australia, are lamosites.

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

The following three types of oil shale are related to specific kinds of algae from which the organic matter was derived. The names of these types of oil shale have been used for many years and are derived from local geographic features.

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

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

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

Evaluation of Oil-Shale Resources

Relatively little is known about many deposits of oil shale and much exploratory drilling and analytical work still needs to be done. Earlier attempts to determine the size of world oil-shale resources were based on few facts, and estimating the grade and quantity of many of these resources were, at best, a guess. The situation today is not much better, although much information has been published in the past decade or two, notably for deposits in Australia, Canada, Estonia, Israel, and the United States.

Evaluation of oil-shale resources is made difficult because of the wide variety of analytical units that are reported. The grade of a deposit is often expressed in U.S. or Imperial gallons of shale oil per short ton (gpt), liters per metric ton (l/t), barrels, or short tons or metric tons of shale oil, kilocalories per kilogram of oil shale, or gigajoules per unit weight of oil shale. To bring some uniformity into this assessment, oil-shale resources are reported in metric tons of shale oil and in U.S. barrels of shale oil. The grade of oil shale is expressed in liters of shale oil per metric ton (l/t). If the size of the resource is expressed only in volumetric units (barrels, liters, cubic meters, etc.), the density of the shale oil must be known or estimated to convert these values to metric tons. Most oil shales produce shale oil having densities that range from about 0.85 to 0.97 by the modified Fischer assay method. In some cases where the density of the shale oil was unknown, a value of 0.910 is assumed.

Byproducts may add considerable value to some oil-shale deposits. Uranium, vanadium, zinc, alumina, phosphate, sodium carbonate minerals, ammonium sulfate, and sulfur are some potential byproducts of oil shales. The spent shale after retorting in some regions is used in the manufacture of cement, notably in Germany and China. The energy obtained by the combustion of the organic matter in oil shale can offset much of the energy required 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 of oil shale 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 for lack of data or accessible publications. Resource data for deeply buried deposits are omitted, such as a large part of the Devonian oil-shale deposits in eastern United States, because they are not likely to be developed in the foreseeable future. Thus, the total resource numbers reported herein should be regarded as very 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 noneconomic occurrences to deposits large enough to be commercially exploitable. The demonstrated oil-shale resources of the Australia total 58 billion tons of which about 3.1 billion tons of oil (24 billion barrels) is recoverable (Crisp and others, 1987, p. 1).

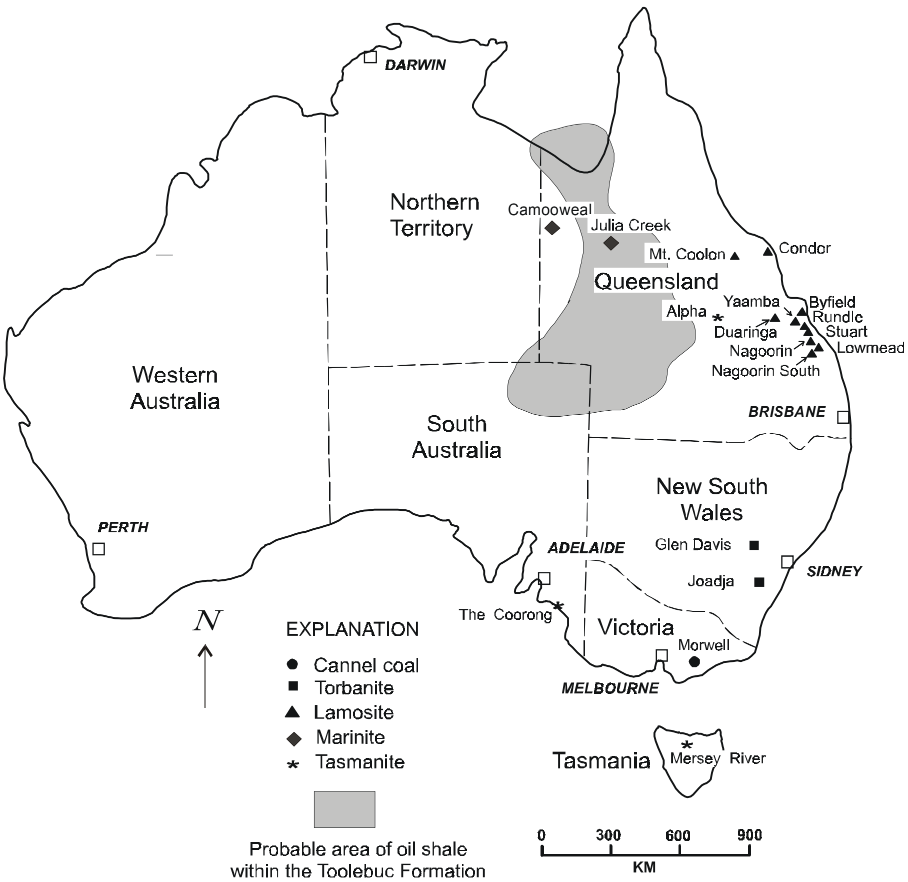


Fig. 2. Occurrences of oil shale in Australia. From Crisp and others (1987, Fig. 1). Area of Toolebuc oil shale from Cook and Sherwood (1989, Fig. 2)

Australia contains a variety of oil-shale deposits that range in age from Cambrian to Tertiary and are diverse in origin. The deposits are located in the eastern one-third of the country in 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 Julia Creek deposit is widespread and near the surface, however, it is low-grade, averaging only about 37 l/t (Ozimic and Saxby, 1983, p. 1).

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 early into the 1900s. The remaining resources of these high-grade deposits are too small to be considered as important oil-shale resources in Australia today (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 was produced in Australia between 1860 and 1960 (Crisp and others, 1987, Fig. 2).

Table 1. **Demonstrated Resources of Oil-Shale Deposits in Australia. From Crisp and others (1987, Table 1)**

Deposit	Age	*In situ* oil, 10^6 tons	Yield, l/t	Area, km^2	Recoverable oil	
					10^6 m^3	10^6 bbls
Queensland						
Alpha	Tertiary	17	200+	10	13	80
Condor	do	17000	65	60	1100	6700
Duaringa	do	10000	82	720	590	3700
Julia Creek	Cretaceous	4000	70	250	270	1700
Lowmead	Tertiary	1800	84	25	120	740
Nagoorin	do	6300	90	24	420	2700
Nagoorin South	do	1300	78	18	74	470
Rundle	do	5000	105	25	420	2700
Stuart	do	5200	94	32	400	2500
Yaamba	do	6100	95	32	440	2800
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		57000			3900	24000

Torbanite

Much of the early production of oil shale was from the torbanite deposits of New South Wales. As many as 16 deposits were exploited between the 1860s and 1960s. During the earlier years of mining, torbanite was used for gas enrichment in Australia and overseas, but paraffin, kerosene, 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 more likely 220 to 250 l/t (Crisp and others, 1987, p. 6). These authors noted that as many as 30 occurrences of torbanite have been recorded in New South Wales of which 16 were commercially exploited.

Two small deposits of torbanite have been investigated in Queensland including 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 1100 m^3 of shale oil was produced from several intermittent operations. Further developments are unlikely unless new resources are found (Crisp and others, 1987, p. 7–8).

Toolebuc Oil Shale (Julia Creek)

Oil shale in the marine Toolebuc Formation of Cretaceous age (i.e., Julia Creek) underlies about 484,000 km^2 in parts of the Eromanga and Carpenteria Basins in eastern Queensland and adjacent states (see Fig. 2). The oil shale ranges from 6.5 to 7.5 meters in thickness but yields on average only about 37 l/t, making it a low-grade oil-shale resource. However, the Toolebuc Formation is estimated to contain 245 billion m^3 of in-place shale oil. Excluding weathered oil shale from the surface to a depth of 50 meters, about 20 % (49 billion m^3 or about 45 billion tons) of the resource between the depths of 50 to 200 meters could be produced by open-pit mining (Ozimic and Saxby, 1983, p. 1). The oil shale also contains potential resources of heavy metals including uranium and vanadium.

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 H/C ratio of the organic matter is about 1.1 ± 0.2 with high aromaticity (>50 %). Only 25 % of the organic matter converts to oil by conventional methods of pyrolysis. (Ozimic and Saxby, 1983).

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 grade is too low for near-term development (Noon, 1984, p. 5).

Eastern Queensland

As a result of the increases in the prices of crude oil resulting from the oil crisis of 1973–74, exploration for oil-shale deposits in Australia was greatly accelerated. Several companies found or confirmed sizable resources of oil shale at Rundle, Condor, Duaringa, Stuart, Byfield, Mt. Coolon, Yaamba, 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).

Eight Tertiary oil-shale deposits in eastern Queensland have been investigated by exploratory core drilling. These include Byfield, Condor, Duaringa, Lowmead, Nagoorin, Nagoorin South, Rundle, Stuart, and Yaamba (Fig. 2). Most of these deposits are lamosites that were deposited in grabens in freshwater lakes commonly in association with coal-forming swamps. The mineral fraction is commonly quartz and clay minerals and lesser siderite, carbonate minerals, pyrite, and others. The deposits range from 1 to 17 billion tons of in-place shale oil, the largest being Condor (17.4 billion tons), Nagoorin (6.3 billion tons), and Rundle (5.0 billion tons) with cutoff grades around 50 l/t (Crisp and others, 1987).

The Stuart oil-shale deposit, estimated to contain 3 billion barrels of in-place shale oil, is under development by the Southern Pacific Petroleum and Central Pacific Minerals companies. As of February 2003, SPP/CPM has produced from an open-cast mine, 1,160,000 tons of oil shale from which 702,000 barrels of shale oil have been produced during 310 total days of operations using the Taciuk retorting process. Current peak shale-oil production runs are about 2,800 barrels of shale oil per day (data provided by Derek Dixon, February 2003).

Brazil

At least nine occurrences of oil shale ranging from Devonian to Tertiary in age have been reported in different parts of Brazil (Padula, 1969). Of these, two deposits have received the most interest: 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 the oil shale of the Permian Irati Formation, a widespread unit in the southern part of the country (Fig. 3).

Fig. 3. Occurrences of oil shale in Brazil. From Padula (1969, Fig. 1)

Paraíba Valley

Two areas in Paraíba Valley totaling 86 km^2 include a total reserve of 840 million bbls as determined by drilling. The total resource is estimated at 2 billion barrels. The zone of interest which is 45 m thick includes several types of oil shale. One type is brown to dark-brown fossiliferous laminated paper shale that contains 8.5 to 13 wt% oil equivalent. A second type is a semipapery oil shale of the same color with an oil yield of 3 to 9 wt% oil equivalent. A third type consists of 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 wide-spread distribution. The Irati Formation crops out from the northeastern part of the state of São Paulo southward for 1,700 km to the southern border of Rio Grande do Sul and into northern Uruguay (Fig. 3).

In the state of Rio Grande do Sul, oil shale occurs in two beds separated by shale and limestone. The beds are thickest in the region of São Gabriel where the upper bed is 9 m thick thinning to the south and east, and the lower bed is 4.5 m thick thinning to the south. The two beds are separated by 12 meters of shale and limestone. 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 São Paulo and part of Santa Catarina, oil shale occurs in as many as 80 beds 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 which 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 wt% shale oil and contains similar resources but the upper bed yields only 2-3 % oil and is not considered suitable for exploitation (Pedula, 1969).

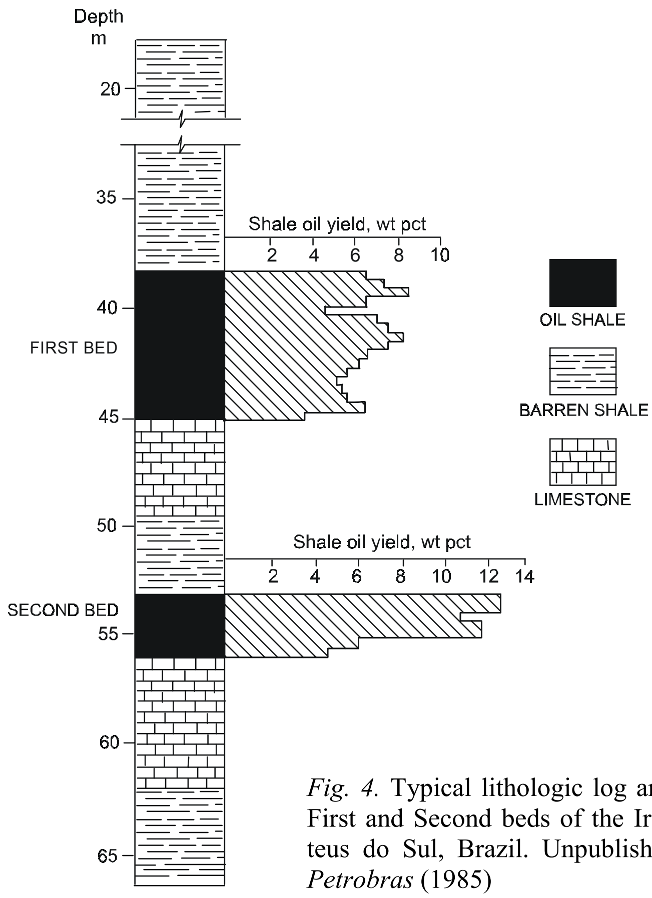


Fig. 4. Typical lithologic log and shale oil yield of the First and Second beds of the Irati oil shale at São Mateus do Sul, Brazil. Unpublished data from L. Carta, *Petrobras* (1985)

The Iratí oil shale is dark-gray, brown, and black, very fine grained, and laminated. Clay minerals comprise 60–70 % of the rock and organic matter much of the remainder with minor contributions of detrital quartz, feldspar, pyrite, and other minerals. Carbonate minerals are sparse. Unlike marine oil shales such as the Devonian oil shales of eastern United States, the Iratí oil shale is not notably enriched in metals. 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. Unpublished data from *Petrobras* (1985)**

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	1480
Oil shale feed stock, l/t	70–125

The origin of the Iratí Formation is controversial. Some researchers have concluded that the organic matter in the Irati oil shale is derived from a predominantly algal/microbial source in a freshwater-brackish lacustrine environment as suggested 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 of the Iratí Formation 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 of Brazil. Early work concentrated on the Paraíba oil shale, but later focused on the Iratí shale. A prototype oil-shale retort and plant (UPI) constructed near Sao Mateus do Sul began operations in 1972 with a design capacity of 1,600 tons of oil shale per day. In 1991 an industrial-size retort, 11 meters in diameter, was put into operation with a design capacity of about 550 tons of shale oil per day. More than 1.5 million tons of shale oil and other products including LPG (liquefied petroleum gas), gas, and sulfur have been produced from startup of the UPI plant through 1998.

Canada

Canada's oil-shale deposits range from Ordovician to Cretaceous in age. These include deposits of lacustrine and marine origin. As many as 19 deposits have been identified in Canada (Macauley, 1981; Davies and Nassichuk, 1988) (Fig. 5). 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. The Albert oil shale yields 100 l/t of shale oil on average and has potential for recovery of oil as well as 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) that can be doubled by hydroretorting. The Cretaceous Boyne and Favel marinites form volumetrically 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 economic interest.

Outcrops of lower Carboniferous lacustrine oil shale on Grinnell Peninsula, Devon Island, in the Canadian Arctic Archipelago are as much as 100 meters 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-place shale oil remain poorly known.

The oil-shale deposits of Canada are summarized in Table 3 below.

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 (Fig. 6). 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. Here, one bore hole penetrated more than 500 meters of oil shale. However, complex folding and faulting has obscured the true thickness of the oil shale, which may be much less.

Table 3. **Oil Shale Deposits in Canada**

No. on Fig. 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	May be equivalent to Collingwood Shale	Ordovician	Marinite		Unknown
4	North shore of Lake Erie, Elgin and Norfold Counties, Ontario	Marcellus Formation	Devonian	Marinite		Probably minor
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	Lower Missis-sippian	Torbanite?		Unknown
13	Stellarton Basin, Pictou County, Nova Scotia	Pictou Group	Pennsylvanian	Torbanite and lamosite	< 5–35 (in 60 beds)	25–140

No. on Fig. 5	Deposit	Geologic unit	Age	Oil shale type	Thickness, meters	Grade, liters/ton
14	Queen Charlotte Islands, British Columbia	Kunga Formation	Jurassic	Marinite	≤35	≤35
15	Cariboo district, British Columbia	?	Lower Jurassic	Marinite?		Minor oil yields
16	Manitoba Escarpment, Manitoba and Saskatchewan	Boyne and Favel Formations	Cretaceous	Marinite	40 & 30, respectively	20-60
17	Anderson Plain, Northwest Territories	Smoking Hills Formation	Upper Cretaceous	Marinite	30	>40
18	Mackenzie Delta, Northwest and Yukon Territories	Boundary Creek Formation	Upper Cretaceous	Marinite		Unknown
*	Grinnell Peninsula, Devon Island, Canadian Arctic	Emma Fiord Formation	Early Cretaceous	Lacustrine: lamosite?	>100	11–406

* Not shown on Fig. 5. See Davies and Nassichuk (1988, Fig. 1) for location.

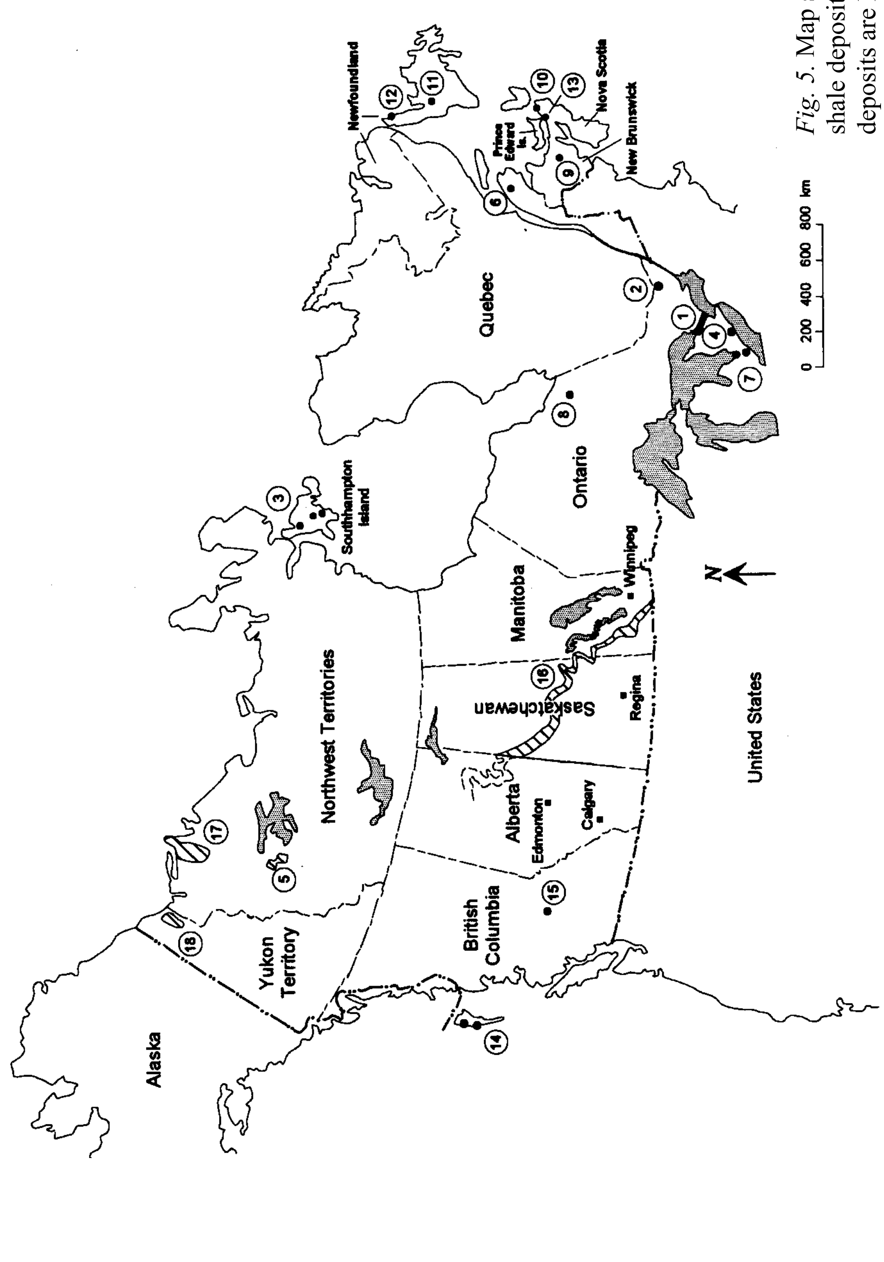


Fig. 5. Map showing locations of oil-shale deposits in Canada. Numbered deposits are keyed to Table 3 in text. Adapted from Macauley (1981)

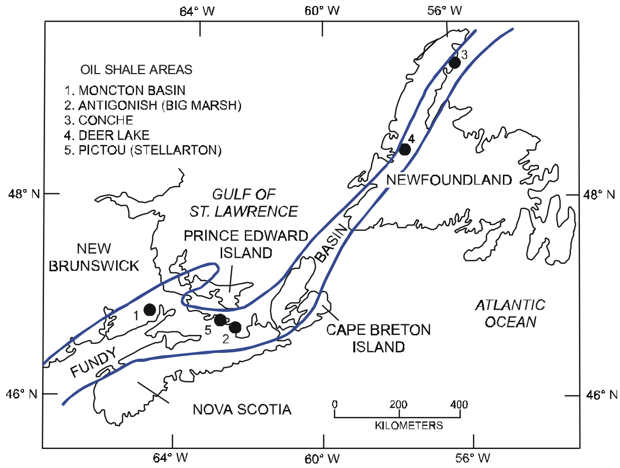


Fig. 6. Oil-shale deposits in the Maritime Provinces of Canada. Adapted from Kalkreuth and Macauley (1987, Fig. 1)

The richest part of the sequence, the Albert Mines zone, measures about 120 meters in thickness in one borehole; this may be double the true thickness because of structural complexity. The shale oil yield ranges from less than 25 to more than 150 l/t. The average specific gravity of the shale oil 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 resource for the entire oil-shale sequence is estimated at 270 million barrels (Macauley and others, 1984), or about 37 million tons of shale oil.

The oil shales consist of interbedded dolomitic marlstone, laminated marlstone, and clayey marlstone. The mineral matrix includes dolomite, local calcite, and minor siderite. Silicic components include quartz, feldspar, some analcime, abundant illite, and minor amounts of smectite. The occurrence of dolomite and analcime as well as presence of an evaporite facies of halite which overlies the oil-shale sequence suggest that the oil shales were deposited in an alkaline saline lake.

The first commercial development occurred when a single vein of albertite, a solid hydrocarbon cutting across the oil-shale deposits, was mined from 1863 to 1874. During that time 140,000 tons of albertite were shipped to the U.S. where it was sold for $18/ton. The vein was mined to a depth of 335 meters. A 41-ton sample of albertite sent to England in the early 1900s yielded 420 l/t and 450 m^3 of gas/ton. In 1942 the Canadian Department of Mines and Resources initiated a core-drilling program to test the oil-shale deposit. A total of 79 boreholes were drilled and a resource of 91 million tons of oil shale to a depth of 122 meters that averaged 44.2 l/t was delineated. An additional 10 bore holes 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).

China

China's principal resources of oil shale are those at Fushun and Maoming. The first commercial production of shale oil in China began at Fushun in 1930 with the construction of Refinery No. 1. Fushun Refinery No. 2 began production in 1954. Production of shale oil began at Maoming in 1963. The three refineries switched from shale oil to cheaper crude oil, but a new plant for retorting oil shale was constructed at Fushun and began production in 1992. At Fushun, 60 Fushun-type retorts, having a capacity of 100 tons of oil shale per day, produce 60,000 tons of shale oil per year (Chilin, 1995).

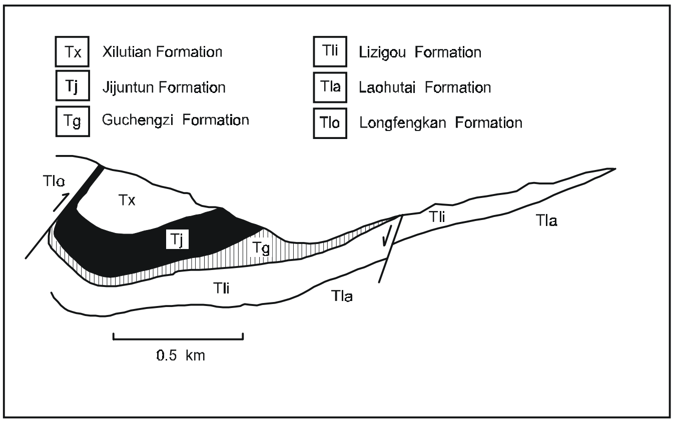
Fushun

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. The coal and oil shale are found 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 comprise 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, six coal beds are present. The formation also contains a cannel coal 1 to 15 m thick that is used for decorative carving. The coal also contains red to yellow gem-quality amber.

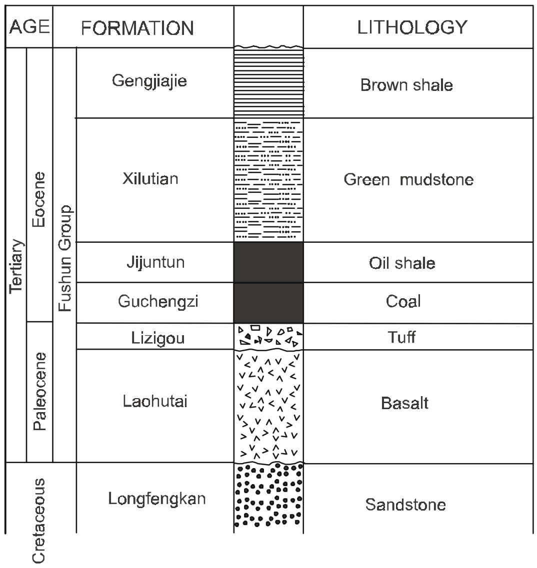
Overlying the Guchengzi Formation is the Eocene Jijuntun Formation that consists of oil shale of lacustrine origin. The oil shale is in gradational contact with the underlying coal of the Guchengzi Formation and with the overlying lacustrine green mudstone of the Xilutian Formation (Fig. 7). The Jijuntun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

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

The yield of the oil shale ranges from <4.7 to 16 % by weight of the rock. The mined shale averages 7–8 % (~78–89 l/m). In the vicinity of the mine, oil shale resources are estimated at 260 million tons of which 235 million tons (90 %) are thought to be mineable. The total resource of oil shale is estimated at 3,600 million tons.



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



Generalized stratigraphic section of the Fushun area. (No scale)

Fig. 7. Stratigraphic section and geologic cross section of the Fushun oil-shale deposit, Liaoning Province, China. From Johnson (1990, Figs 4 and 6)

The West Open Pit mine is in a tightly folded syncline 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. Two additional underground mines lie just east of the open pit mine. The floor of the 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 brings sandstone of the Cretaceous Longfengkan Formation in contact with the Jijuntun oil shale (Fig. 7).

The first significant mining of coal at Fushun began about 1901. Coal production increased, first under the Russians and later 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 10-15 years of mining coal at Fushun, oil shale was discarded with the overburden as waste rock. Production of oil shale began in 1926 under the Japanese and peaked in the early 1970s with about 60 million tons of oil shale (~2 million tons of shale oil) produced annually then dropped to about 8 million tons in 1978. This reduction was partly due to increased discovery and production of cheaper petroleum within China, which reduced the need for shale oil. Baker and Hook (1979) have published additional details on oil shale processing at Fushun.

Maoming

The Maoming deposit of Tertiary age is 50 km long, 10 km wide, and 20–25 m thick. Total reserves of oil shale are 5 billion tons. The Jintang mine has a reserve of 860 million tons of oil shale. The Fischer assay yield of the oil shale is 4–12 % and averages 6.5 %. The ore is yellow brown and the bulk density is about 1.85. The oil shale contains 72.1 % ash, 10.8 % moisture, 1.2 % sulfur, with a heating value of 1745 kcal/kg (dry basis). About 3.5 million tons of oil shale are mined yearly (Guo-Quan, 1988).

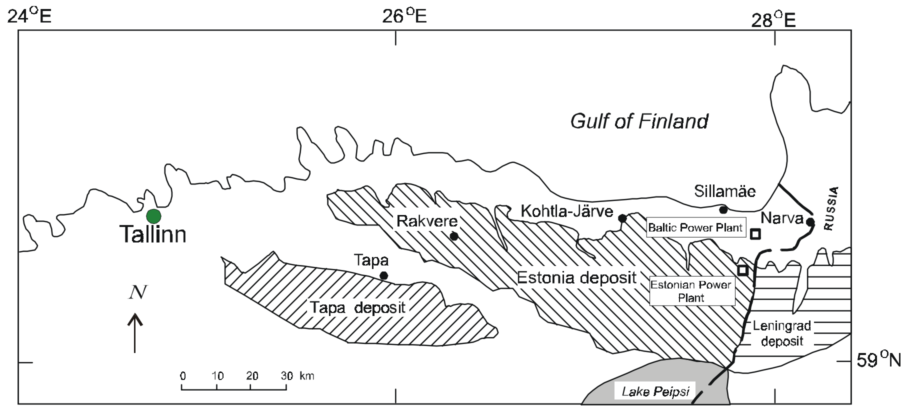
The minus 8 mm fines (heating value of 1158 kcal/kg) which has a moisture content of 16.3 % cannot be currently utilized and is being tested for burning in a fluidized-bed boiler. Cement is manufactured with a content of about 15–25 % of the oil-shale ash.

Estonia

Although the Ordovician kukersite oil-shale deposits of Estonia have been known since the 1700s, active exploration of these deposits did not begin until W.W.I as a result of fuel shortages brought about by the war. Full-scale mining began in 1918. Oil-shale production in that year was 17,000 tons by open-pit mining. By 1940, the annual production of oil shale reached 1.7 million tons. However, it was not until after W.W.II, during the Soviet era, that production climbed dramatically, peaking in 1980 when 31.4 million tons of oil shale were mined by 11 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 (Öpik, 1998). Of this amount 81 % was used to fuel electric power plants, 16 % was processed into petrochemicals, and the remaining few percent was used to manufacture cement as well as a few 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).

Kukersitic oil shale occupies more than 50,000 km^2 in northern Estonia and eastward into Russia to near St. Petersburg. In Estonia there are two kukersite deposits; the Estonia deposit and the somewhat younger Tapa deposit (Fig. 8). The Leningrad deposit in Russia is an eastward extension of the Estonia deposit.



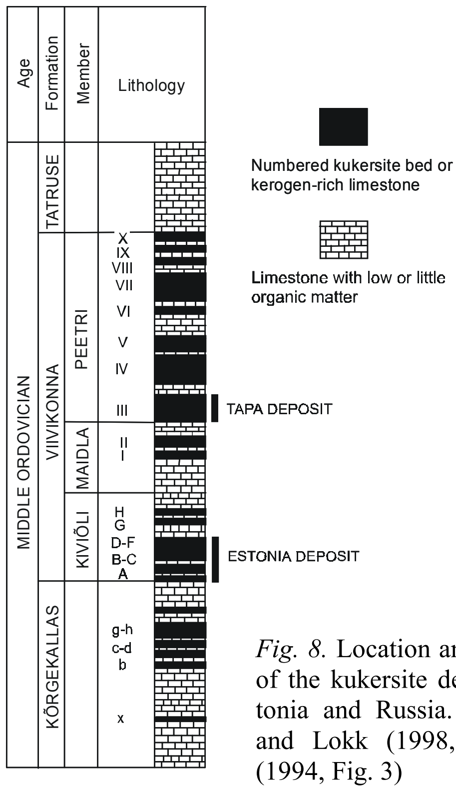


Fig. 8. Location and stratigraphic section of the kukersite deposits in northern Estonia and Russia. Adapted from Kattai and Lokk (1998, Fig. 1) and Bauert (1994, Fig. 3)

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

Rock-Eval analyses of the richest-grade kukersite 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 of kukersite in seven open-pit mines ranges from 2,440 to 3,020 kcal/kg (Reinsalu, 1998a, Table 5). Most of organic matter in kukersite 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 kukersite and interbedded limestones includes dominantly low-Mg calcite (>50 %), dolomite (<10–15 %), and siliciclastic minerals including quartz, feldspars, illite, chlorite, and pyrite (<10–15 %). 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) suggests 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 suggest oxygenated waters and the widespread lateral continuity of even thin beds of kukersite suggest negligible bottom currents.

Kattai and Lokk (1998, p. 109) estimate 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 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 defines 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_2 (Fig. 8) is 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 drilled in the Estonia field exceeds 10,000. The Estonia kukersite has been relatively thoroughly explored while the Tapa deposit is currently in the prospecting stage.

Another older oil-shale deposit, the marine Dictyonema shale of early Ordovician age underlies most of the northern part of Estonia. Until recently, little has been published about this unit because it was covertly mined for its uranium during the Soviet era. The unit ranges from less than 0.5 meter to more than 5 meters in thickness (Fig. 9). A total of 22.5 tons of elemental uranium was produced from 271,575 tons of mined shale. The history of the plant at Sillamäe, Estonia, where uranium ware produced from the Dictyonema shale and later from other sources is outlined in several articles (Lippmaa and Maremäe, 1999, 2000, 2001).

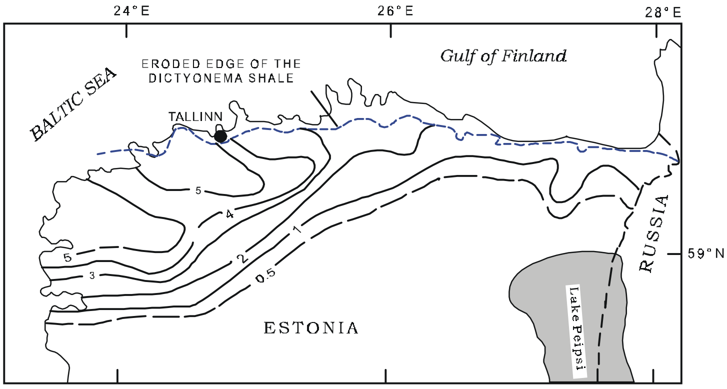


Fig. 9. Isopach map of the Ordovician Dictyonema shale in northern Estonia. From Loog and others (1996, Fig. 1)

The future of oil shale mining in Estonia faces a number of problems including competition from natural gas, petroleum, and coal. The present opencast mines in the Estonian oil-shale deposits will eventually need to convert to more expensive underground operations as the deeper oil shale is mined. Serious environmental problems of air and ground water pollution from burning oil shale and leaching of trace metals and organic compounds from spoil piles left from many years of mining and processing the kukersite and the Dictyonema oil shales are under study and remediable work is underway. The geology, mining, and reclamation of the Estonia deposit is reviewed in detail by Kattai, Saadre, and Savitski (2002) and in this volume.

Israel

Twenty marinites of late Cretaceous age have been identified in Israel (Minster, 1994). The locations of the deposits are shown on Fig. 10. About 12 billion tons of oil-shale reserves have been identified. The average heating value of Israeli oil shale is 1150 kcal/kg of rock with an average oil yield of 6 wt%. The oil shales range from 35 to 80 meters in thickness (V. Fainberg cited by Kogerman, 1996, p. 263) or 5 to 200 meters according to PAMA Ltd. (see Table 4). The organic content of Israeli oil shales is relatively low, ranging from 6 to 17 wt% with an oil yield of only 60–71 l/t. The moisture content is high (~20 %) as well as the carbonate content (45–70 % calcite). The sulfur content is also high (5–7 wt%) (Minster, 1994). Some of the deposits can be mined by open-pit methods. A commercially exploitable bed of phosphate rock, 8 to 15 meters thick, underlies the oil shale in the Misor Rotem open-cast mine.

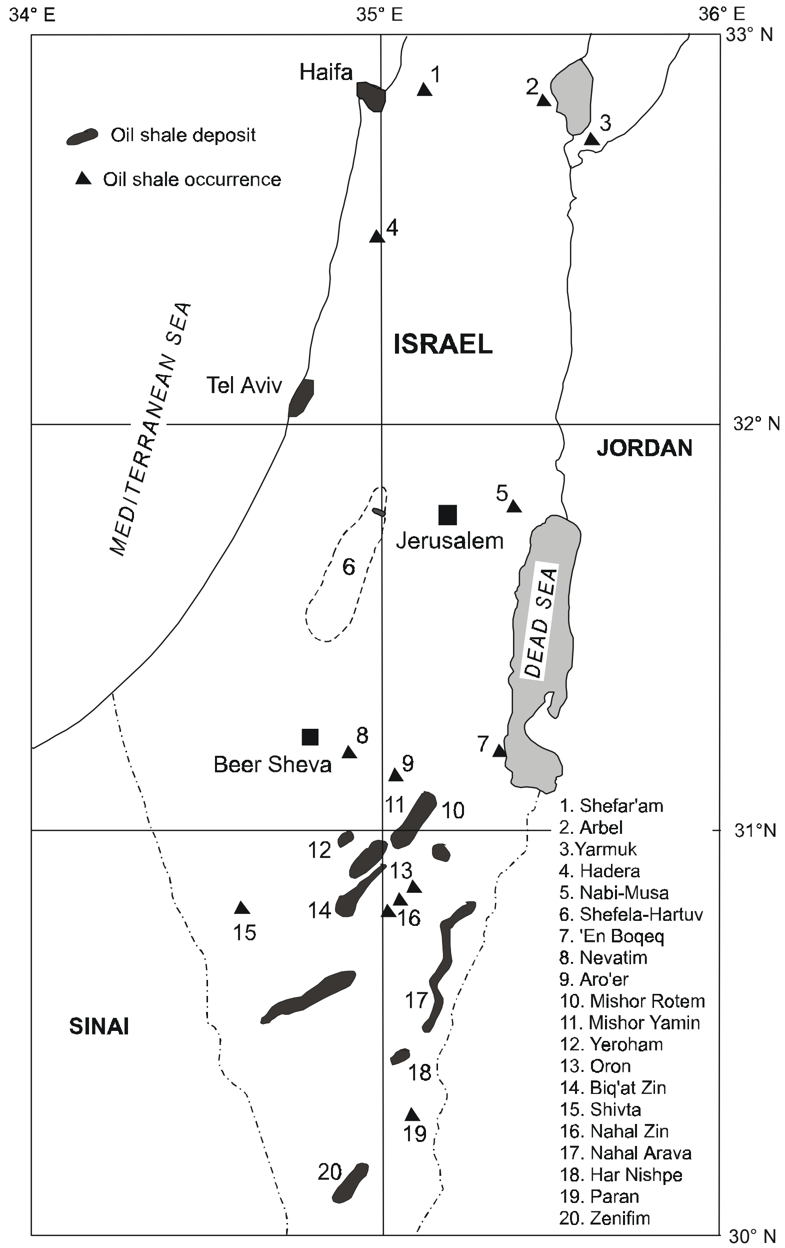


Fig. 10. Occurrences of oil shale in Israel. From Minster (1994, Fig. 1)

Utilizing oil shale from the Rotem-Yamin deposit (deposits *10–11* on Fig. 10), about 55 tons of oil shale per 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. Its heating value ranges from 650 to 1200 kcal/kg.

Table 4. **Characteristics of Ten Deposits of Oil Shale in Israel. Data from unpublished and undated (2000?) PAMA Ltd. brochure titled 'Energy from Oil Shale in Israel'**

Deposit	Overburden thickness, meters	Oil shale thickness, meters	Percent organic matter in oil shale	Oil shale resources, tons × 10^6
Nabi Musa	0–30	25–40	14–18	200
Hartuv	25–50	150–200	14–15.5	1100
Ein Boqueq	30–100	40–60	15.0	200
Mishor Rotem	20–150	20–150	11–17	2260
Mishor Yamin	20–170	20–120	10–18.5	5200
Yeroham	70–130	10–50	16.0	200
Oron	0–80	10–60	15–21	700
Zin	5–50	5–30	12–16	1500
Zenifim	30–50	10–60	8.0	1000
Sde Boker	50–150	15–70	15–18	3000

Jordan*

Jordan has few resources of oil and gas and no commercial deposits of coal. However, there are about 26 known occurrences of oil shale in Jordan, some of which are large and relatively high-grade (Jaber and others, 1997; Hamarneh, 1998, p. 2). The eight most important of these are 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 kilometers east of the Dead Sea. The El Lajjun, Sultani, and the Juref ed Darawish have been the most extensively explored by boreholes and many samples have been analyzed.

Table 5 summarizes some of the geologic parameters of the eight deposits.

* 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.

Table 5. **Resource Data for Eight Deposits of Oil Shale in Jordan.**
From Jaber and others (1997, Table 1) and Hamarneh, (1998); some data are rounded

Deposit	Number of boreholes	Area, km^2	Overburden, meters	Thickness of oil shale, meters	Shale oil, wt pct	Oil shale, 10^9 tons	Shale oil, $\times 10^6$ tons
El Lajjun	173	20	30	29	10.5	1.3	126
Sultani	60	24	70	32	7.5	1.0	74
Juref ed Darawish	50	1500	70	31	?	8.6	510
Attarat Umm Ghudran	41	670	50	36	11	11	1245
Wadi Maghar	21	19	40	40	6.8	31.6	2150
Wadi Thamad	12	150	140–200	70–200	10.5	11.4	1140
Khan ez Zabib		?	70	40	6.9	?	
Siwaga					7.0		
TOTAL		2385				64.9+	5246+

The Jordanian oil-shale deposits are marinites of late Cretaceous (Maastrichtian) to early Tertiary in age. A number of deposits are found in grabens and some may prove to be parts of larger deposits, such as the Wadi Maghar deposit which is now considered to be the northern extension of the Attarat Umm Ghudran deposit. The deposits listed in the above table are at shallow depths, in essentially horizontal beds. As much as 90 % of the oil shale is amenable to opencast mining (Hamarneh, 1998, p. 5). The overburden consists of unconsolidated gravel and silt containing some stringers of marl and limestone and, in some areas, basalt. Overall, the Jordanian oil shales thicken northward toward the Yarmouk deposit near the northern border of Jordan where it apparently extends into Syria (Fig. 11). The Yarmouk deposit may prove to be an exceptionally large deposit. It underlies several hundred square kilometers and reaches 400 meters in thickness (T. Minster, 1999, personal communication).

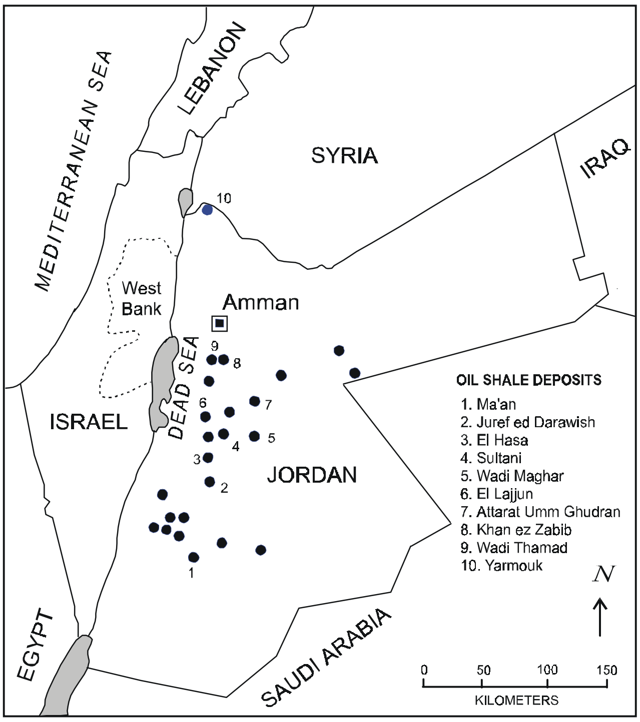


Fig. 11. Oil-shale occurrences in Jordan. Adapted from Jaber and others (1997, Fig. 1) and Hamarneh (1998, Figure on p. 4)

The oil shales in central Jordan occur within 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 Jordanian oil shale is low (2–5.5 wt%) whereas comparable deposits of oil shale in Israel have a much higher moisture content of 10–24 % (T. Minster, personal communication, 1999). Calcite, quartz, kaolinite, and apatite make up the major mineral components of the El Lajjun oil shale with small amounts of dolomite, feldspar, pyrite, illlite, geothite, and gypsum. The sulfur content of Jordanian oil shale ranges from 0.3 to 4.3 %. The sulfur content of shale oil from the Juref ed Darawish and the Sultani deposits is very high, 8 and 10 %, respectively. Of interest is the relatively high trace metal content of the oil shales from the Juref ed Darawish, Sultani, and El Lajjun deposits, notably Cu (68–115 ppm), Ni (102–167), Zn (190–649 ppm), Cr (226–431 ppm), and V (101–268 ppm) (Hamarneh, 1998, p8). Phosphate, rock that underlies the El Hasa deposit (deposit 3 on Fig. 11), is mined by open cast. About 5 million tons of oil shale is removed and wasted with the overburden (T. Minster, 1999, personal communication).

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 that provides fresh water to Amman and other towns in central Jordan is too small to meet the demands of an oil-shale industry. Another deeper aquifer in the Kurnub Formation 1000 meters below the surface may be able to provide an adequate supply of water. Further assessment of the potential ground water supplies of Jordan for an oil-shale industry is needed.

Syria

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

Morocco

Oil-shale deposits have been identified at ten localities in Morocco (Fig. 12). All of the deposits are late Cretaceous in age and are marinites, not unlike those of Egypt, Israel, and Jordan. The two most important deposits that have been explored are the Timahdit and the Tarfaya deposits. As many as 157 boreholes totaling 34,632 meters, 800 meters of mine entries, and about 69,000 analyses have been made (Bouchta, 1984). The moisture content of the Timahdit and Tarfaya oil shales is 8 and 20 %, respectively) and the shale oils contain about 6–8 %. In the 1980s several energy companies from North America and Europe have conducted exploratory drilling, and experimental mining and processing of Moroccan oil shale, but no shale oil production has resulted from this work.

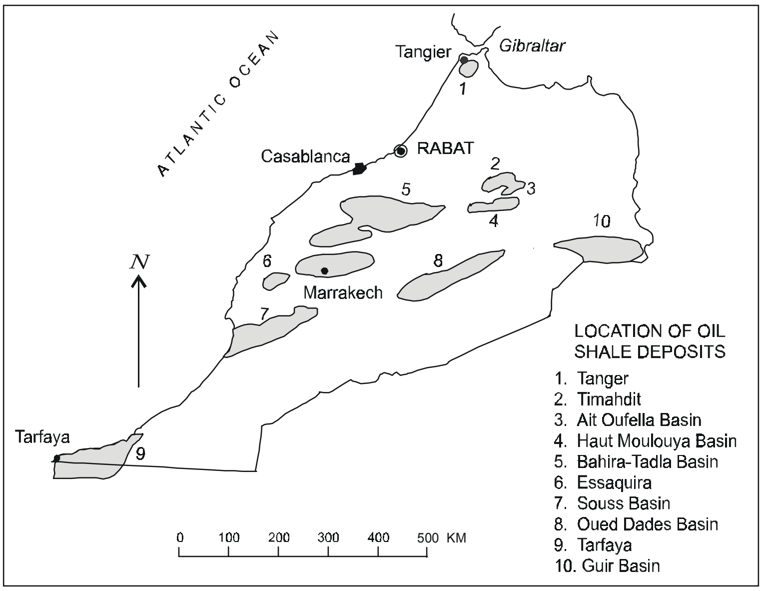


Fig. 12. Locations of oil-shale deposits in Morocco. From Bouchta (1984, Fig. 1)

Russia

More than 80 deposits of oil shale have been identified in Russia. The kukersite oil shale in the Leningrad District is burned as fuel in the Slantsy electric power plant near St. Petersburg.

In addition to the Leningrad deposit, the best deposits for exploitation are those in the Volga-Petchyorsk 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 meters in thickness but are high in sulfur (4–6 %, 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) lists resources of thirteen deposits of oil shale for 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. Additional details of the Russian deposits in English are given by Russell (1990, p. 470–527).

Sweden

The alum shale formation is a unit of black organic-rich marinite about 20-60 meters 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 or more meters in repeated sequences owing to multiple thrust faults (Fig. 13).

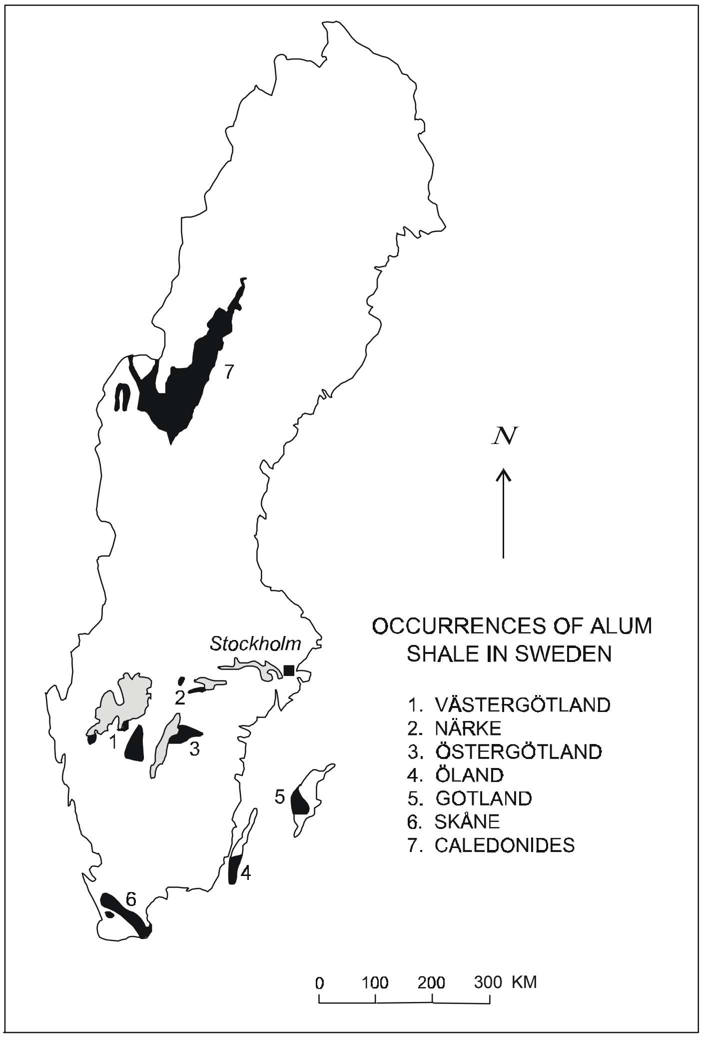


Fig. 13. Map showing occurrences of alum shale in Sweden. From Andersson and others (1985, Fig. 3)

Correlative black shales occur 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 shales of early (Tremadoc) Ordovician age (Andersson and others, 1985, Figs 3 and 4). The alum shale represents very slow deposition in shallow, near-anoxic waters that were little disturbed by wave and bottom current action.

The Cambrian alum shales of Sweden have been known for over 350 years as a source of potassium aluminum sulfate that could be extracted from the shale for use 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 shales were 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 W.W.II, alum shale was retorted for its oil but production ceased in 1966 owing to the availability of cheaper supplies of petroleum. During this period, about 50 million tons of shale was mined at Kinnekulle in Västergötland and at Närke (Fig. 13).

The alum shale is remarkable for its high content of metals including uranium, vanadium, nickel, and molybdenum. Small amounts of vanadium were produced during W.W.II a pilot plant built at Kvarntorp produced more than 62 tons of uranium between 1950–1961. Later, higher-grade ore was found at Ranstad in Västergötland where an open-pit mine and mill were established. About 50 tons of uranium per year were produced between 1965–1969. 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).

Table 6. **Summary of Fossil Energy Potential of the Alum Shale in Sweden for Shale Containing More Than 10 % Organic Matter. From Andersson and others (1985, Table 2)**

Area	Shale, 10^6 tons	Organic matter		Shale oil		Energy in gas and coke, 10^{12} MJ
		Wt%	Tons, 10^6	Wt%	Tons, 10^6	
Närke	1700	20	340	5	85	8800
Östergötland	12000	14	1600	3.5	400	41900
Västergötland	14000	~13	1840	0–3.4	220	53300
Öland	6000	12	700	2.7	170	18000
Skåne	15000	11	1600	0	0	58600
Jämtland (Caledonides)	26000	12	3200	0	0	117200
TOTAL	74700		9280		875	297800

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 a significant potential resource of fossil and atomic 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 %. The organic matter is most abundant in the upper part of the shale sequence (Fig. 14). Oil yields are not in proportion to the organic content of the shale from one area to another because of variations in the geothermal history of the areas occupied by the alum shale. For example, at Skåne and Jämtland (Fig. 13) the alum shale is overmature and oil yields are nil, although the organic content of the shale is 11–12 %. In areas less affected by geothermal alteration, oil yields range from 2 to 6 % by Fischer assay. Hydroretorting can increase the Fischer assay yields by 300–400 % (Andersson and others, 1985, Fig. 24).

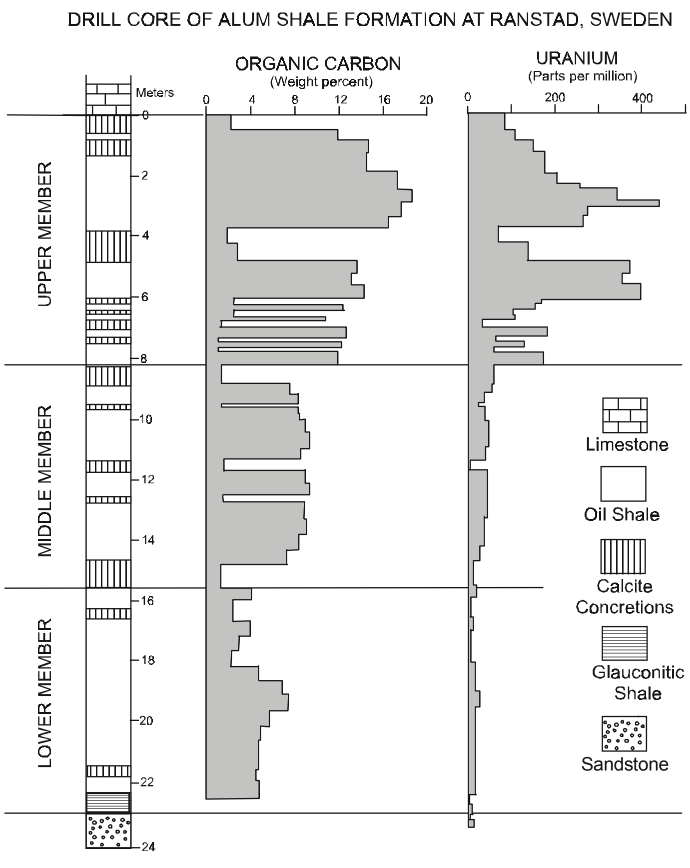


Fig. 14. Lithology and plots of the abundances of organic carbon and uranium in a drill core from the alum shale at Ranstad, Sweden. From Andersson and others (1985, Fig. 9)

The uranium resources of the alum shale of Sweden, although low grade, are enormous. In the Ranstad area of Västergötland the uranium content of a 3.6-meter-thick zone in the upper part of the formation reaches 306 ppm. Uranium concentrations reach 2000–5000 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, 8–9 meters thick, contains an estimated resource of 1.7 million tons of uranium metal (Andersson and others, 1985, Table 4). Figure 14 shows a lithologic log of a core hole drilled at Ranstad with plots of Fischer assay and uranium analyses.

Thailand

Lacustrine deposits of oil shale of Tertiary age are present near Mae Sot, Tak Province, and at Li, Lampoon Province. The Mae Sot deposit has been explored by many core holes drilled by the Thai Department of Mineral Resources. 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. The deposit contains an estimated 18.7 billion tons of oil shale which will yield an estimated 6.4 billion barrels (916 million tons) of shale oil. The gross heating value of the Mae Sot oil shale ranges from 287 to 3700 kcal/kg. The moisture content is 1 to 13 % and the sulfur content is about 1 %. The deposit at Li is probably also a lamosite but the reserves are small. It is estimated at 15 million tons of oil shale yielding 12–41 gallons (50–171 l/t) of oil per ton (Vanichseni and others, 1988, p. 515–516).

United States

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

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. 15). These basins are separated by the Uinta Mountain Uplift and its eastward extension, the Axial Basin Anticline. The Green River lake system was in existence for more than 10 million years during a time of a warm temperate to subtropical climate. During parts of their history, the lake basins were closed and the waters became highly saline.

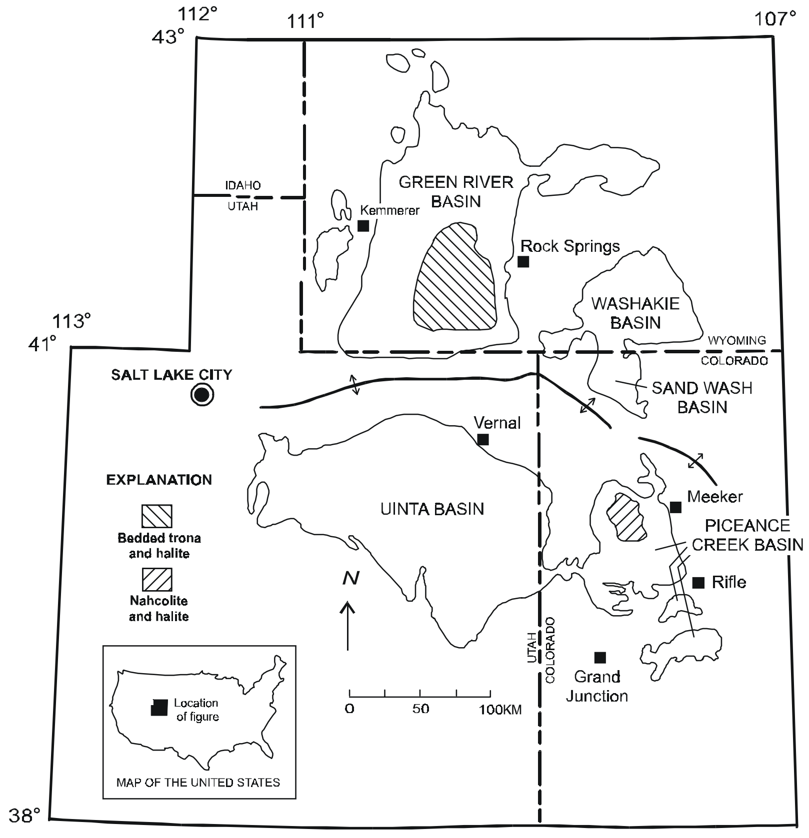


Fig. 15. Area underlain by the Green River Formation in Colorado, Utah, and Wyoming, USA

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 in size and the lake waters became increasingly saline and alkaline. The lake-water content of soluble sodium carbonates and chloride increased while 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 waters were also 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. Sulfate was probably a major anion in the stream waters entering the lakes. Presumably, the sulfate ion was 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 species include 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 is 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, ostracods, 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 aggressive program to investigate the commercialization the Green River oil-shale deposits. The dramatic increases in petroleum prices resulting from the OPEC oil embargo of 1973, 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 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 (1460 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-meter-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.

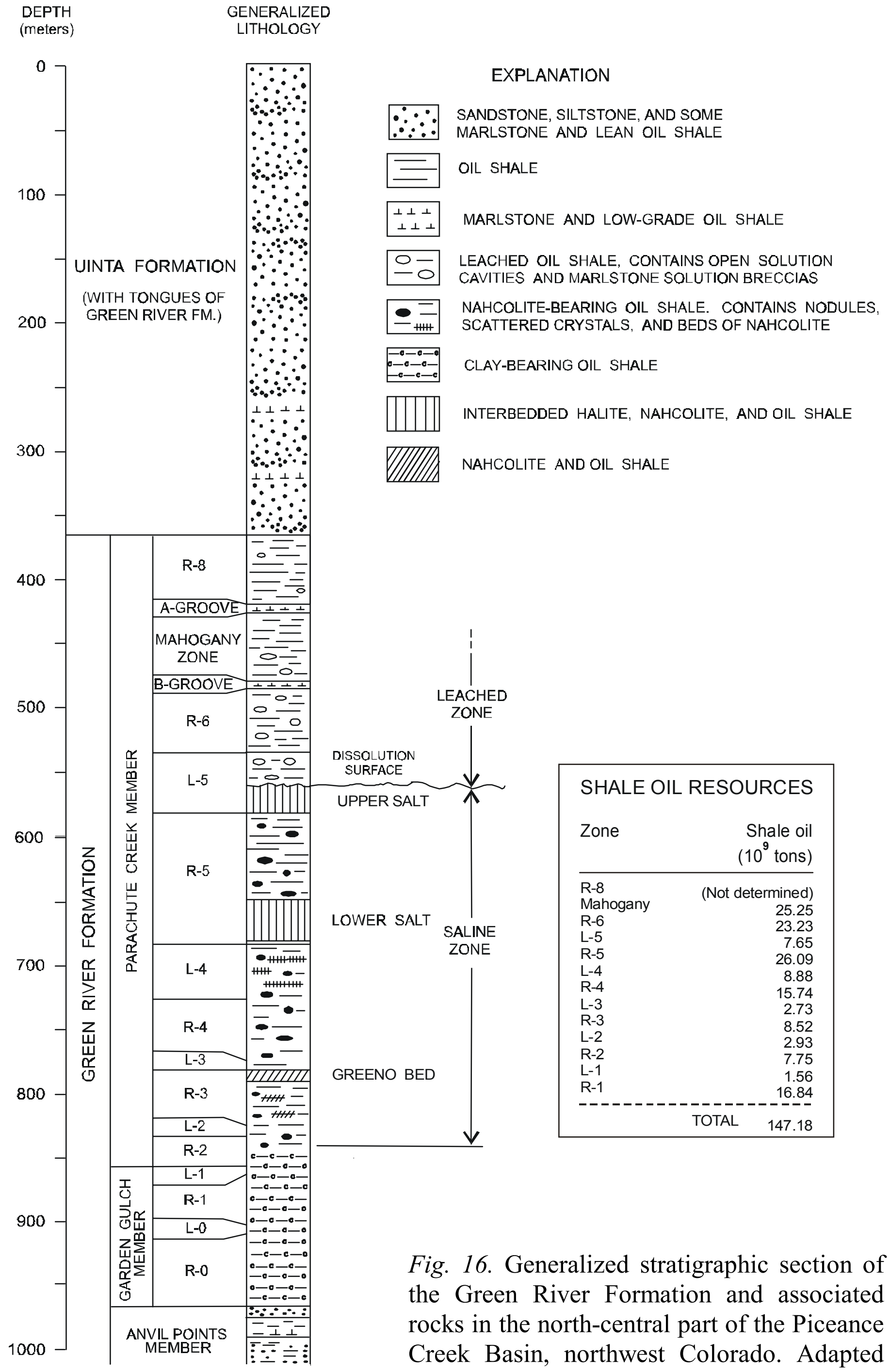
On the U-a/U-b tracts in Utah, about $80,000,000 was spent by three energy companies to sink a 313-meter-deep vertical shaft and inclined haulage way to a high-grade zone of oil shale and to open several small entries. Other facilities included a mine services building, water and sewage treatment plants, and a retention dam.

Another project sited south of the U-a/U-b tract funded by 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 last major project in the Green River Formation. Plant construction began in 1980 and ultimately closed in 1991. Capital investment costs for constructing the mine, retort, upgrading plant, and other facilities was $650 million. Unocal produced 657,000 tons of shale oil, which were shipped to Chicago for refining into transportation fuels and other products under a program subsidized by the U.S. Government. The average rate of production in the last months of operation was about 875 tons of shale oil per day.

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 to 1.0 trillion barrels (~131 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 Fig. 16.

Estimates of the Green River oil-shale resources in Utah and Wyoming are not as well known as those in Colorado. Trudell and others (1983) estimated measured and estimated resources of shale oil in an area of about 5,200 km^2 in eastern Uinta Basin, Utah, at 31 billion barrels (4.4 billion tons). Culbertson and others (1980) estimated the oil-shale resources in the Green River Formation in the Green River Basin in southwest Wyoming to be 35 billion tons of shale oil.



SHALE OIL RESOURCES

Zone	Shale oil (10^9 tons)
R-8	(Not determined)
Mahogany	25.25
R-6	23.23
L-5	7.65
R-5	26.09
L-4	8.88
R-4	15.74
L-3	2.73
R-3	8.52
L-2	2.93
R-2	7.75
L-1	1.56
R-1	16.84
TOTAL	147.18

Fig. 16. Generalized stratigraphic section of the Green River Formation and associated rocks in the north-central part of the Piceance Creek Basin, northwest Colorado. Adapted from Cole and Daub (1991, Fig. 2). The shale-oil resource data, recast from U.S. barrels to metric tons, are from Pitman and others (1989)

Additional resources are also found in the Washakie Basin east of the Green River Basin in southwest Wyoming. Here, 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 meters thick, average 63 l/t and represent as much as 8.7 million tons of in-place shale oil per square kilometer. A total estimate of the resource in 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 deeper 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 mostly likely to be recovered as a by-product of an oil-shale operation. Two companies are presently solution mining about several hundred thousand tons of nahcolite per year in the northern part of the Piceance Creek Basin at depths of about 600 meters (Day, 1998).

The Wilkins Peak Member of the Green River Formation in the Green River Basin in southwest Wyoming contains not only oil shale but also the world's largest known resource of natural sodium carbonate as trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). The trona resource is estimated at more than 115 billion tons in 22 beds ranging from 1.2 to 9.8 meters 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) which is 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 % of U.S. soda ash needs. About one-third of the Wyoming soda ash is exported.

In the deeper part of the Piceance Creek Basin, the Green River oil shale contains a significant 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 7.

Table 7. **Summary of the Energy and Mineral Resources of the Green River Formation in Colorado, Utah, and Wyoming. 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)**

Basin	Area, km^2	Federal lands, pct	Resources	
			Grade, l/t	Reserves, 10^9 tons
Oil-shale resources				
Piceance Creek Basin, Colorado		79*		
	4600		≥63	171
			(≥104)	(85)
			(≥125)	(49)
Uinta Basin, Utah		77		
Mahogany Zone	~2150		≥42	8
Green River Basin, Wyoming		62		
	~1200		≥63	35.4
	(~475)		(125)	(1.9)
TOTAL	7900			215
Other resources				
Green River Basin, Wyoming				
Trona	~2800	57		115
Piceance Creek Basin, Colorado				
Dawsonite	~1300			26
Nahcolite	660			29
Natural gas	>230			130×10^9 m^3

*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.

Eastern Devonian Oil Shale

Depositional Environment. Black organic-rich marine shale and associated sediments of late Devonian and early Mississippian age underlie roughly 725,000 km^2 in eastern United States (Fig. 17). 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).

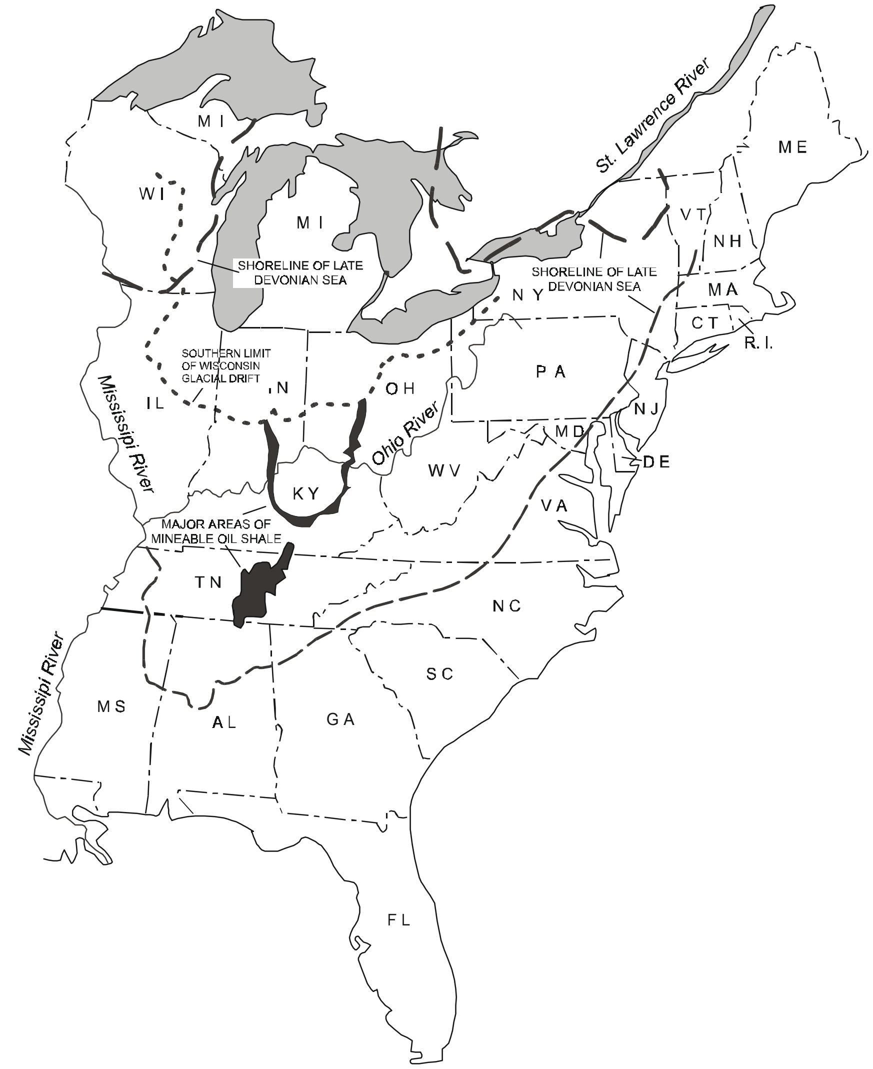


Fig. 17. Paleogeographic map showing shoreline of the late Devonian sea in eastern United States and major areas of surface-mineable Devonian oil shale. After Conant and Swanson (1961, Fig. 13) and Matthews and others (1980, Fig. 5)

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 (see Fig. 17). The area included the broad, shallow, Interior Platform on the west that grades eastward into the Appalachian Basin. The depth to the base of the Devonian black shales ranges from surface exposures on the Interior Platform to more than 2,700 meters along the depositional axis of the Appalachian Basin (de Witt and others, 1993, Pl. 1).

The Late Devonian sea was relatively shallow with minimal current and wave activity, much like the depositional environment in which the alum shale of Sweden was deposited in Europe. A large part of the organic matter in the Devonian black shale is amorphous material although a few structured fossil organisms such as *Tasmanites*, *Botyrococcus*, and *Foerstia*, and others have been recognized. Conodonts and linguloid brachiopods are sparingly distributed through some beds. Although much of the organic matter is amorphous (bituminite) 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 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 upper Chattanooga shale deposited on the Interior Platform in Tennessee could represent as much as 150,000 years of sedimentation on a compacted basis.

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 accessories, 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.

The Devonian black shale has long been known to produce oil upon retorting, but the organic matter yields only about half as much as the organic matter in the Green River oil shale. The difference in yields is attributable to the type of organic matter (or type of organic carbon) found in each oil shale.

The Devonian oil shale has a higher ratio of aromatic to aliphatic carbon than Green River oil shale. Material balance Fischer assays show that the organic carbon of Devonian oil-shale yields much less shale oil and a higher percentage of carbon residue than the organic matter in Green River oil shale (Miknis, 1990).

Hydroretorting Devonian oil shale can increase the oil yield by more than 200 % of 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 % of Fischer assay. Other marine oil shales have also found to respond favorably to hydroretorting with yields up to 300, or more, percent of Fischer assay (Dyni, Anders, and Rex, 1990).

Matthews and others (1980) evaluated the Devonian oil shales in areas of the Interior Platform where the shales are rich enough in organic matter and close enough to the surface where they are mineable by open pit. The states investigated were Alabama, Illinois, Indiana, Kentucky, Ohio, Michigan, eastern Missouri, Tennessee, and West Virginia. About 98 % of the near-surface mineable resource is in Kentucky, Ohio, Indiana, and Tennessee (Matthews, 1983).

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

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

On this basis, the total resource was estimated to be 423 billion barrels (61 billion tons).

The resources are summarized by states in Table 8.

Table 8. **Estimated Resources of Near-Surface Oil Shale in Eastern United States by Hydroretorting. Data derived from Matthews and others (1980, Table 3)**

State	Area, km^2	Shale oil	
		Tons, 10^9	Tons, per hectare
Ohio	2540	20.2	79000
Kentucky	6860	27.4	40000
Tennessee	3990	6.3	15500
Indiana	1550	5.8	37000
Michigan	410	0.7	17500
Alabama	780	0.6	7500
TOTAL	16130	61.0	

Turkey

Lacustrine oil-shale deposits of Paleocene to Eocene and 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 occurrence of authigenic zeolites suggests deposition in hypersaline lacustrine waters in closed basins.

Data on the shale oil resources are sparse because only a few of these 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 until further studies are made, resource estimates for these deposits will remain uncertain. The total resources of shale oil for eight deposits are estimated at 284 million tons (Table 9).

Table 9. **Oil-Shale Deposits of Turkey.**
Data from Güleç and Önen (1993) and Sener and others (1995)

Deposit and Province	Calorific value	Average oil yield	Total sulfur	Oil-shale resource	Shale oil resource
		Wt%		10^6 tons	
Bahçecik (Izmit)	418–1875 Kcal/kg			100	5
Beypazari (Ankara)	3.40 MJ/kg	5.4	1.4	1058	57
Burhaniye (Balikesir)	0–1768 Kcal/kg			80	4
Gölpazari (Bilecik)	0–1265 Kcal/kg			356	18
Göynük (Bolu)	3.25 MJ/kg	4.6	0.9	2500	115
Hatildag (Bolu)	3.24 MJ/kg	5.3	1.3	547	29
Seyitömer (Kütahya)	3.55 MJ/kg	5.0	0.9	1000	50
Ulukisla (Nigde)	630–2790 Kcal/kg			130	6
			TOTAL	5771	284

Note: For those deposits lacking average oil yields, an estimated yield of 5 wt% was assumed. For deposits where two tonnages were given in the references, the larger number was used.

Summary of World Resources of Shale Oil

Resources of shale oil for selected deposits from around the world are listed in Table 10. The deposits are listed in alphabetical order by country. Several deposits for some countries are listed under subheadings, commonly by states or provinces.

Because of the widespread use of U.S. barrels for reporting petroleum and shale oil resources, this quantity is used in Table 10. The shale-oil resources are also reported in tons of shale oil. The date and author of the source of the resource information is given for most of the deposits. No attempt was made to differentiate between resources and reserves of oil shale because the data are too sparse for most deposits.

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 this table.

The reliability of the resource data for many of the deposits listed in Table 10 ranges from excellent to poor. Data for some deposits 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, which have been explored extensively by core drilling.

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 foreseeable future. However, improved methods of mining and processing could change this picture. 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 of the deposit 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 petroleum and coal as well as being a significant source of air and water pollution.

The total world resource of oil shale of 411 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 research will undoubtedly add many more billions of tons of in-place shale oil to this total as new information becomes available.

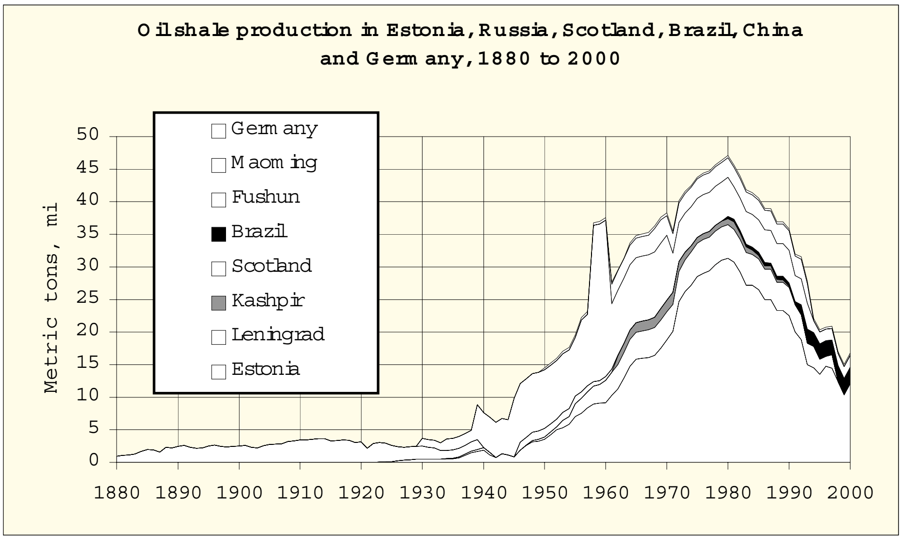


Fig. 18. Production of oil shale from selected world oil-shale deposits from 1880 to 2000

Table 10. **Shale-Oil Resources of Some World Oil-Shale Deposits**

Country, region, and deposit	Age	In-place shale oil resources, × 10^6 bbls	In-place shale oil resources, × 10^6 tons	Date of estimation	Source of information and footnotes [ ]
Argentina		**400**	57	1962	
Armenia					
Aramus	T	**305**	44	1994	Pierce & others (1994) [1]
Australia					
New South Wales	Pm	**40**	6	1987	Crisp & others (1987)
Queensland					
Alpha	Pm	**80**	1	1987	Matheson (1987) [2]
Byfield	T	**249**	36	1999	Wright (1999) [2]
Condor	T	**9700**	1388	do	Wright (1999) [2]
Duaringa (upper unit)	T	**4100**	587	do	Wright (1999) [2]
Herbert Creek Basin	T	**1530**	219	do	Wright (1999) [2]
Julia Creek	K	**1700**	243	do	Wright (1999) [2]
Lowmead	T	**740**	106	do	Wright (1999) [2]
Mt. Coolon	T	**72**	10	do	Wright (1999) [2]
Nagoorin Basin	T	**3170**	454	do	Wright (1999) [2]
Rundle	T	**2600**	372	do	Wright (1999) [2]
Stuart	T	**3000**	429	do	Wright (1999) [2]
Yaamba	T	**4100**	587	do	Wright (1999) [3]
South Australia					
Leigh Creek	Tr	**600**	86	1999	Wright (1999) [2]
Tasmania					
Mersey River	Pm	**48**	7	1987	Crisp & others (1987)
Austria		**8**	1	1974	
Brazil					
Irati Formation	Pm	**80000**	11448	1994	Afonso & others (1994)
Paraíba Valley	T	**2000**	286	1969	Padula (1969)

Table 10. Shale-Oil Resources of Some World Oil-Shale Deposits (continuation)

Country, region, and deposit	Agev	In-place shale oil resources, $\times 10^6$ bbls	In-place shale oil resources, $\times 10^6$ tons	Date of estimation	Source of information and footnotes [ ]
Bulgaria		**125**	18	1962	
Burma		**2000**	286	1924	
Canada					
Manitoba-Saskatchewan					
Favel-Boyne Formations	K	**1250**	191	1981	Macauley (1981,1984a, 1986) [4]
Nova Scotia					
Stellarton Basin	P-Pm	1174	**168**	1989	Smith & others (1989) [5]
Antigonish Basin		531	**76**	1990	Smith & Naylor (1990)
*New **Brunswick***					
Albert Mines	M	**269**	38	1988	Ball & Macauley (1988) [6]
Dover	M	**14**	2	do	Ball & Macauley (1988) [6]
Rosevale	M	**3**	0.4	do	Ball & Macauley (1988) [6]
Newfoundland					
Deer Lake Basin	M			1984	Hyde (1984) [7]
Northwest Territories					
Sverdrup Basin	M			1988	Davies & Nassichuk (1988) [8]
Ontario					
Collingwood Shale	O	**12000**	1717	1986	Macauley (1986)
Kettle Point Fm	D			1986	Macauley (1986)
Chile		**21**	3	1936	
China		**16000**	2290	1985	Du & Nuttall (1985) [9]
Maoming	T	(2271)	(325)	1988	Guo-Quan (1988)
Fushun	T	(127)	(18)	1990	Johnson (1990)
Egypt					
Safaga-Quseir area	K	**4500**	644	1984	Troger (1984)
Abu Tartur area	K	**1200**	172	1984	Troger (1984)

Country, region, and deposit	Age	In-place shale oil resources, × 10^6 bbls	In-place shale oil resources, × 10^6 tons	Date of estimation	Source of information and footnotes [ ]
Estonia					
Estonia deposit	O	3900	**594**	1998	Kattai & Lokk (1998) [10]
Dictyonema shale	O	12386	1900		
France		**7000**	1002	1978	
Germany		**2000**	286	1965	
Hungary		56	**8**	1995	Pápay (1998) [11]
Iraq					May be very large
Yarmouk	K				See Jordan
Israel		**4000**	550	1982	Minster & Shirav (1982) [12]
Italy		**10000**	1431	1979	
Sicily		**63000**	9015	1978	
Jordan					
El Lajjun	K	821	**126**	1997	Jaber & others (1997) [13]
Sultani	K	482	**74**	1997	Jaber & others (1997) [13]
Juref ed Darawish	K	3325	**510**	1997	Jaber & others (1997) [13]
Wadi Maghar	K	14009	**2149**	1997	Jaber & others (1997) [13]
Attarat Umm Ghudran	K	8103	**1243**	1997	Jaber & others (1997) [13]
Wadi Thamad	K	7432	**1140**	1997	Jaber & others (1997) [13]
Yarmouk	K		(Large)	1999	Minster (1999) [14]
Kazakhstan					
Kenderlyk field		2,837	**400**	1996	Yefimov (1996) [15]
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	**11236**	1719	1984	Bouchta (1984) [16]
Tarfaya, Zone R	K	**42145**	6448	1984	Bouchta (1984) [16]

Table 10. Shale-Oil Resources of Some World Oil-Shale Deposits (end)

Country, region, and deposit	Age	In-place shale oil resources, × 10^6 bbls	In-place shale oil resources, ×10^6 tons	Date of estimation	Source of information and footnotes [ ]
New Zealand		**19**	3	1976	
Poland		**48**	7	1974	
Russia					
St. Petersburg kukersite	O	25157	**3600**		
Pripyat basin	D	6988	**1000**		
Timano-Petchorsk basin	J	3494	**500**		
Vychegodsk basin	J	195967	**2800**		
Central basin	?	70	**10**		
Volga basin	?	31447	**4500**		
Turgai & Nizhneiljisk deposit	?	210	**30**		
Kyzylkum basin	Pm	8386	**1200**		
Amudarja basin	Pm	7687	**1100**		
Olenyok basin	C	167715	**24000**		
Other deposits	–	210	**30**		
South Africa		**130**	19	1937	
Spain		**280**	40	1958	
Sweden					
Närke	C	594	**85**	1985	Andersson & others (1985)
Östergötland	C	2795	**400**	1985	Andersson & others (1985)
Västergötland	C	1537	**220**	1985	Andersson & others (1985)
Öland	C	1188	**170**	1985	Andersson & others (1985)
Thailand					
Tak Province					
Mae Sot	T	**6400**	916	1988	Vanichseni & others (1988)
Lampoon Province					
Li	T	**1**		1988	Vanichseni & others (1988)

Country, region, and deposit	Age	In-place shale oil resources, × 10^6 bbls	In-place shale oil resources, × 10^6 tons	Date of estimation	Source of information and footnotes [ ]
Turkey					
Deposit & (Province)					
Bahçecik (Izmit)	T	35	**5**	1993	Güleç & Önen (1993) [17]
Beypazari (Ankara)	T	398	**57**	1995	Sener & others (1995)
Burhaniye (Bahkesir)	T	28	**4**	1993	Güleç & Önen (1993)
Gölpazari (Bilecik)	T	126	**18**	1993	Güleç & Önen (1993)
Göynük (Bolu)	T	804	**115**	1995	Sener & others (1995)
Hatildag (Bolu)	T	203	**29**	1995	Sener & others (1995)
Seyitömer (Kütahya)	T	349	**50**	1995	Sener & others (1995)
Ulukisla (Nigde)	T	42	**6**	1993	Güleç & Önen (1993)
Ukraine					
Boltysh deposit					
United Kingdom		**3500**	501	1975	
Scotland					
United States					
Eastern Devonian shale	D	**189000**	27000	1980	Matthews & others (1980) [18]
Green River Fm	T	**1499000**	215000	1999	This report
Phosphoria Fm	Pm	**250000**	35775	1980	Smith (1980)
Heath Fm	M	**180000**	25758	1980	Smith (1980)
Elko Fm	T	**228**	33	1983	Moore & others (1983)
Zaire		**100000**	14310	1958	
TOTAL		**2859090**	**410600**		

Table notes:

The resources in the above table are listed by country in alphabetical order. For some countries, the deposits are listed under state or province.

The age of the deposit, when known, is given using the following symbols: C, Cambrian; O, Ordovician; D, Devonian; M, Mississippian (early Carboniferous); Pennsylvanian (late Carboniferous); Tr, Triassic; J, Jurassic; Pm, Permian; K, Cretaceous; and T, Tertiary.

The resources of shale oil are given in U.S. (42-gallon) barrels and metric tons. The resource numbers in boldface type are from the references cited and the associated number in normal type was calculated for this table.

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.

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.

The following footnotes are keyed to the numbers in parentheses in the "Source of Information" column.

1. The resource was estimated by assuming 7 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.
2. 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 29 March 1999.
3. McFarlane (1984) gives the Yaamba deposit as 2.92 billion in-place barrels of shale oil.
4. Shale oil SG of 0.910 was assumed.
5. Shale oil SG of 0.910 was assumed.
6. Shale oil SG of 0.910 was assumed.
7. The west side of the basin is largely unexplored and may contain oil-shale deposits.
8. 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 overmature, but on Devon Island, the oil shale is immature to marginally mature.
9. China's total oil-shale resources are given by Du and Nuttall in Lu (1984).
10. 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.
11. Assumed a shale-oil yield of 8 wt pct and a shale-oil SG of 0.910.
12. Fainberg and Hetsroni (1996) estimate Israel's oil-shale reserves at 12 billion tons, which equates to 600 million tons of shale oil.
13. Shale oil SG of 0.968 was assumed.
14. The oil-shale deposit underlies several hundred square kilometers and reaches 400 meters in thickness (T. Minster, 1999, personal communication).
15. Shale oil SG of 0.900 was assumed.
16. Shale oil SG of 0.970 was assumed. The estimate of the Timahdit resource was made by Occidental Oil Company and the Tarfaya resource was estimated by Bouchta; details of both estimates are in Bouchta (1984).
17. Güleç and Önen (1993) reported 5196 million tons of oil shale in 7 deposits but no shale-oil numbers. Graham and others (1993) estimate the Göynük resource at 9 billion tons of oil shale. Sener and others (1995) reported 1865 million tons of oil shale in 4 Turkish deposits.
18. 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.

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