Definition and World Resources of Natural Bitumens

U.S. GEOLOGICAL SURVEY BULLETIN 1944

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Definition and World Resources of Natural Bitumens

By RICHARD F. MEYER and WALLACE DE WITT, JR.

Definitions of the main types of natural bitumens,
with emphasis on natural asphalt, the most significant
quantitatively and economically, and its world distribution

U.S. GEOLOGICAL SURVEY BULLETIN 1944

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply	By	To obtain
Foot (ft)	0.3048	Meter (m)
Mile (mi)	1.609	Kilometer (km)
Square mile (mi^2)	2.59	Square kilometer (km^2)
Centipoise (cP)	.001	Pascal second (Pa·s)
Degrees API (°API)	$\frac{141.5}{131.5+°API}$	Grams per cubic centimeter (g/cm^3)
Barrel per day (bbl/d)	.159	Cubic meter per day (m^3/d)
Short ton per year (ton/yr)	.907	Megagram (metric ton) per year (Mg/a)
Degrees Fahrenheit (°F)	5/9(°F−32)	Degrees Celsius (°C)

API gravity: A standard adopted by the American Petroleum Institute for expressing the specific weight of oils. API gravity = 141.5/specific gravity at 60 °F−131.5. Measured in °API.

Definition and World Resources of Natural Bitumens

By Richard F. Meyer *and* Wallace de Witt, Jr.

Abstract

Natural bitumens, semisolid or solid mixtures of hydrocarbons and as much as 50 percent heterocyclic compounds, are composed largely of carbon and hydrogen but have substituents of nitrogen, oxygen, sulfur, and trace metals, especially iron, nickel, and vanadium. Bitumens are soluble in organic solvents such as toluene or chloroform. The natural bitumens are differentiated from less viscous crude oils on the basis of their absolute viscosity of more than 10,000 centipoises. Natural asphalt, commonly known as oil sand or tar sand, is the only natural bitumen variety of quantitative and economic significance and today serves as a source of road metal and as raw material for synthetic fuels.

Canada's Alberta Province dominates world resources of natural asphalt; it has demonstrated and inferred resources totaling more than 2,500 billion barrels. Resources ranging from 10 billion to 70 billion barrels are in the U.S.S.R., the People's Republic of China, Venezuela, and the United States. Smaller amounts of natural asphalt resources are present in numerous other countries. At present, little use is being made of many of these deposits. However, with the depletion of conventional crude oil, natural asphalt will become more important as a source of hydrocarbons for fuels and petrochemicals.

INTRODUCTION

Bitumen, asphalt, and related substances were used in the Middle East before historical records. Study of archeological sites (Abraham, 1960a; Forbes, 1964; Bilkady, 1984) showed that, as long ago as 4000 B.C., bitumen was used to waterproof reed roofs and boats. Between 3200 B.C. and 2500 B.C., bitumen was used for mortar, pavement, insulation, joints, and water courses. The source of the bitumen was oil seeps and asphalt deposits, some of which were quarried until recently. In historic times, methods were developed to distill oil from the bitumen to recover naphtha and kerosene for illumination, cooking, heating, and military uses.

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DEFINITIONS OF NATURAL BITUMENS AND RELATED SUBSTANCES

Natural Bitumens

Hydrocarbons are molecules composed of hydrogen and carbon atoms and form a continuous series of organic compounds ranging from coal (the heaviest), to crude oil, to methane (the lightest). In nature, hydrocarbons form complex mixtures with nonhydrocarbons; these mixtures are distinguished on the basis of their atomic hydrogen-carbon (H/C) and oxygen-carbon (O/C) ratios, as well as by the amount of included nitrogen, oxygen, sulfur, and trace metals. One such mixture is the natural bitumens.

Physically, these complex mixtures are defined by their solubility in various organic solvents, such as carbon disulfide, and by their fusibility, the fusing or softening point that indicates a gradual transition from a solid to a liquid state, through a considerable range of temperatures. In contrast, many substances, particularly metals having a definite composition, melt quickly, within a narrow range of temperatures (Abraham, 1960b). Various definitions and classifications of natural bitumens, crude oil, petroleum, and coal are given by Abraham (1960a), Carman and Bayes (1961), Bell and Hunt (1963), Wen and others (1978), Hunt (1979), Speight (1980), and Cornelius (1987).

There are no standard definitions for the basic commodities discussed in this bulletin. Terms generally have been adapted to suit particular requirements of geologists, engineers, refiners, or lawyers. The following definitions are from Hunt (1979).

Bitumens.—Native substances of variable color, hardness, and volatility, composed principally of the elements carbon and hydrogen, and sometimes associated with mineral matter. The nonmineral constituents are largely soluble in carbon disulfide.

Coal.—A readily combustible rock containing more than 50 percent by weight, and more than 70 percent by volume, of organic material formed from the compaction or induration of variously altered plant remains. Humic coals form from plant cell or wall material deposited under aerobic conditions, whereas sapropelic coals form from spores, pollen, and algae deposited under anaerobic conditions.

Crude oil.—A petroleum that is removed from the Earth in liquid state or is capable of being so removed.

Kerogen.—The disseminated organic matter of sedimentary rocks that is soluble in nonoxidizing acids, bases, and organic solvents. The organic matter initially deposited with unconsolidated sediments is not kerogen but a precursor that is converted to kerogen during diagenesis. Sapropelic kerogens yield oil and gas on heating, whereas humic kerogens yield mainly gas. Kerogen includes both marine- and land-derived organic matter; the latter is the same as the components of coal.

Petroleum.—A species of bitumen composed principally of hydrocarbons and existing in the gaseous or liquid state in its natural reservoir.

Although petroleum is a species of bitumen, it is convenient to consider it as a separate commodity possessing many of the attributes of bitumen; this practice is followed by most geologists. Refiners (Neumann and Rahimian, 1984) define petroleum as the liquid mixture of hydrocarbons and nonhydrocarbons in a reservoir and define crude oil as the recovered petroleum at the surface; crude oil serves as the feedstock for refineries. In legal terms, Williams and Meyers (1964) defined petroleum as a complex mixture of hydrocarbon compounds, oily and inflammable in character. They defined crude oil, or crude, as liquid petroleum as it comes out of the ground, as distinguished from refined oils manufactured from crude.

The natural bitumens are essentially free of gas; therefore, the species of petroleum considered in this report is crude oil (crude), the term that will be used throughout this bulletin. Distinctions between crude oil and the natural bitumens are arbitrary but useful for categorizing individual deposits. Most of the natural bitumens are the result of the alteration of a crude oil, but some are simply an immature step in the evolution of a mature crude oil. The term "oil" is used in the sense of Speight (1980) for the oily constituent of some natural bitumens, the proportion of which may be used to distinguish natural bitumens from crude oil. Figure 1 shows the relations among coals, crude oil, and natural bitumens.

Natural bitumens are semisolid or solid mixtures of hydrocarbons and as much as 50 percent heterocyclic compounds constituted largely of carbon and hydrogen but having substituents of sulfur, oxygen, nitrogen, and trace metals, especially iron, nickel, and vanadium, in the carbon network (Yen, 1984). In sedimentary rocks, natural bitumen is the soluble (in organic solvents) portion of the disseminated organic matter; kerogen is the insoluble portion. Part or all of the bitumen may be expressed from sedimentary rock (the source bed or rock) through primary migration to form natural bitumen deposits (Tissot and Welte, 1978). The natural bitumen deposits may be subsequently altered to form different varieties of natural bitumens, crude oil, or natural gas. Some crude oil or gas also can evolve in the source rocks and subsequently migrate to form oil or gas reservoirs (pools). The oil or gas thus accumulated may be altered to create reservoir bitumens or, ultimately, natural gas or graphite. Oil shale is rock that contains at least 33 percent ash; its organic matter is normally insoluble but will yield oil upon destructive distillation. Tar is an artificial product of the destructive distillation of coal or wood; therefore, it is excluded from this discussion.

Components of Natural Bitumens

The principal components of topped crude oil or natural bitumens can be determined by fractionation with organic solvents (fig. 2). Crude oil is topped if the volatile components are removed to a temperature of 300 °F, above which cracking of large molecules may commence. Extraction with solvents provides a ready means of physically separating the components in a way that reflects their chemical differences. It also provides a way to determine the relative proportions of components, such as the asphaltics and oil, in a natural bitumen sample.

Natural bitumens consist mostly of hydrocarbons (paraffinic, naphthenic, and aromatic) but also include various amounts of nonhydrocarbon heterocyclic compounds, which incorporate nitrogen, oxygen, sulfur, and trace metals as substituents. The preasphaltenes, asphaltenes, and resins constitute the heavy (high molecular weight) constituents of natural bitumens and crude oil and are referred to as the asphaltics (Yen, 1984). Preasphaltenes (carbenes and carboids) (Yen, 1984) are present in very small amounts, usually less than 2 percent, are insoluble in pentane, and are commonly disregarded. Asphaltenes are very large molecules, most often incorporating heteroatoms and trace metals, and are soluble in carbon disulfide but insoluble in normal pentane. Nitrogen, sulfur, and oxygen form hydrocarbon heterocyclic compounds, termed N-S-O compounds, which are strongly polar. These compounds commonly result from the complexing of N-S-O heteroatoms and trace metals in the asphaltene structure.

Resins are also large molecules that are strongly polar; they are soluble in both carbon disulfide and normal pentane (*n*-pentane). The polar compounds (such as the resins and heterocyclic compounds) are significant because of their attraction to water and clay. Because of this attraction, polar compounds adversely affect the rheological properties of petroleum or bitumens that contain large proportions of polar compounds, and they make recovery of

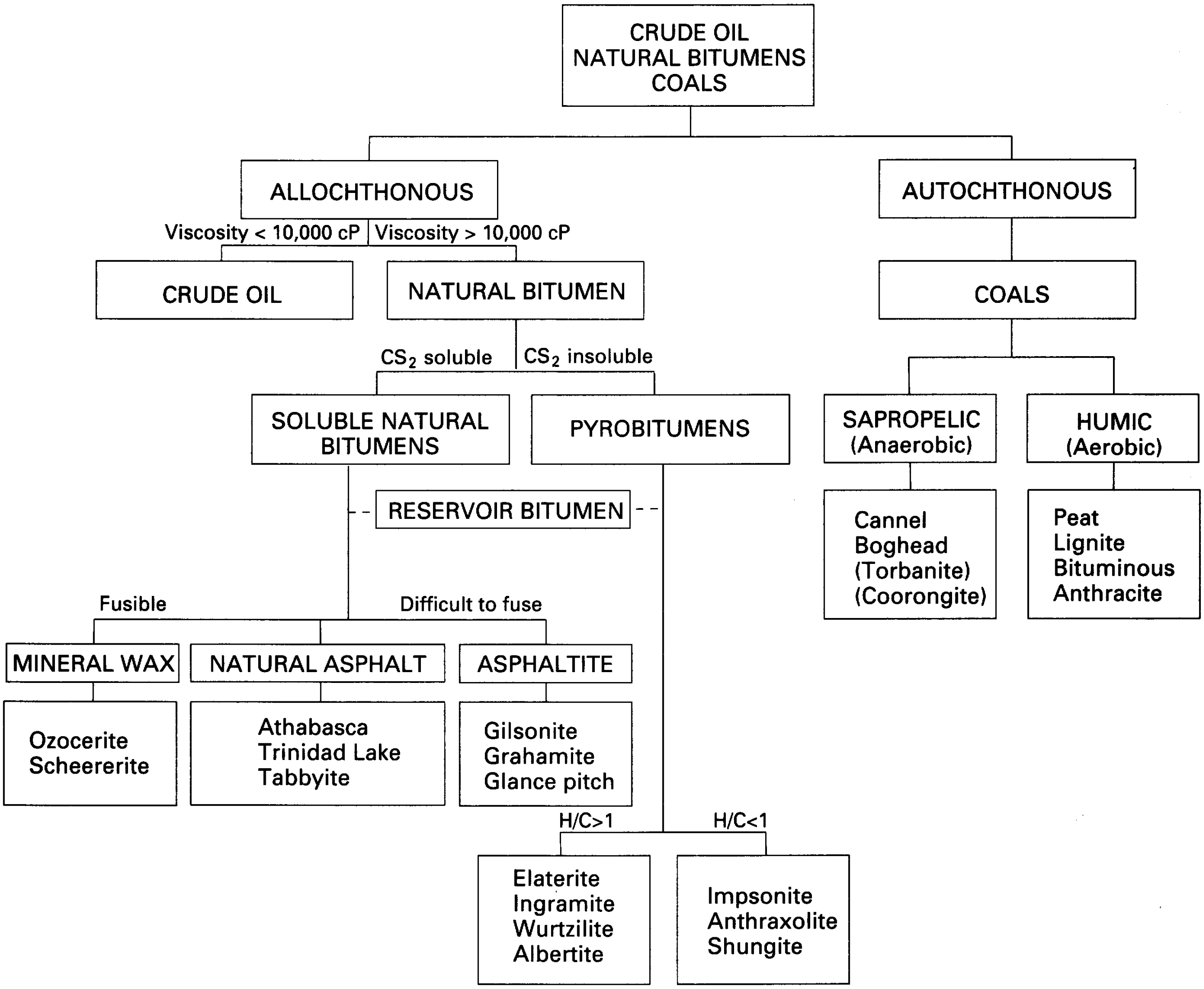

Figure 1. A classification of natural bitumens, crude oil, and coals. H/C, hydrogen-carbon ratio. Modified from Rogers and others, 1974; Hunt, 1979; and Cornelius, 1987.

petroleum or natural bitumens from reservoir rocks difficult. The *n*-pentane-soluble constituents are called the maltenes. The maltenes may be treated with propane; the resins are insoluble in propane, and the remainder of the constituents constitutes the oily fraction.

Types of Natural Bitumens

The natural bitumens are mostly allochthonous and may be divided into two main groups on the basis of their solubility in carbon disulfide. One group, the pyrobitumens, is dark colored, hard, and insoluble in carbon disulfide. The pyrobitumens are divided into two subgroups—those whose H/C is smaller than unity and those whose H/C is larger than unity. The impsonite-anthraxolite-shungite subgroup is metamorphosed and has H/C of about 0.1 to 0.8. The elaterite-wurtzilite-ingramite-albertite subgroup is characterized by H/C as great as 1.6. Elaterite and wurtzilite contain 3–4 weight percent sulfur and have undergone various degrees of vulcanization; the sulfur imparts an elastic constitution. Albertite and ingramite are low in sulfur, have H/C only slightly greater than unity, and appear to be more highly indurated forms of natural asphalt (Hunt, 1979).

The soluble natural bitumens form the other group of bitumens; its members are soluble in carbon disulfide and are composed mostly of hydrocarbons. However, these hydrocarbons frequently are in combination with heterocyclic compounds of nitrogen, sulfur, oxygen, and trace metals, most notably nickel and vanadium. The soluble natural bitumens generally contain various amounts of admixed mineral matter from their host rocks. Soluble bitumens fall into three subgroups defined by their relative fusibility—mineral waxes, natural asphalts, and asphaltites.

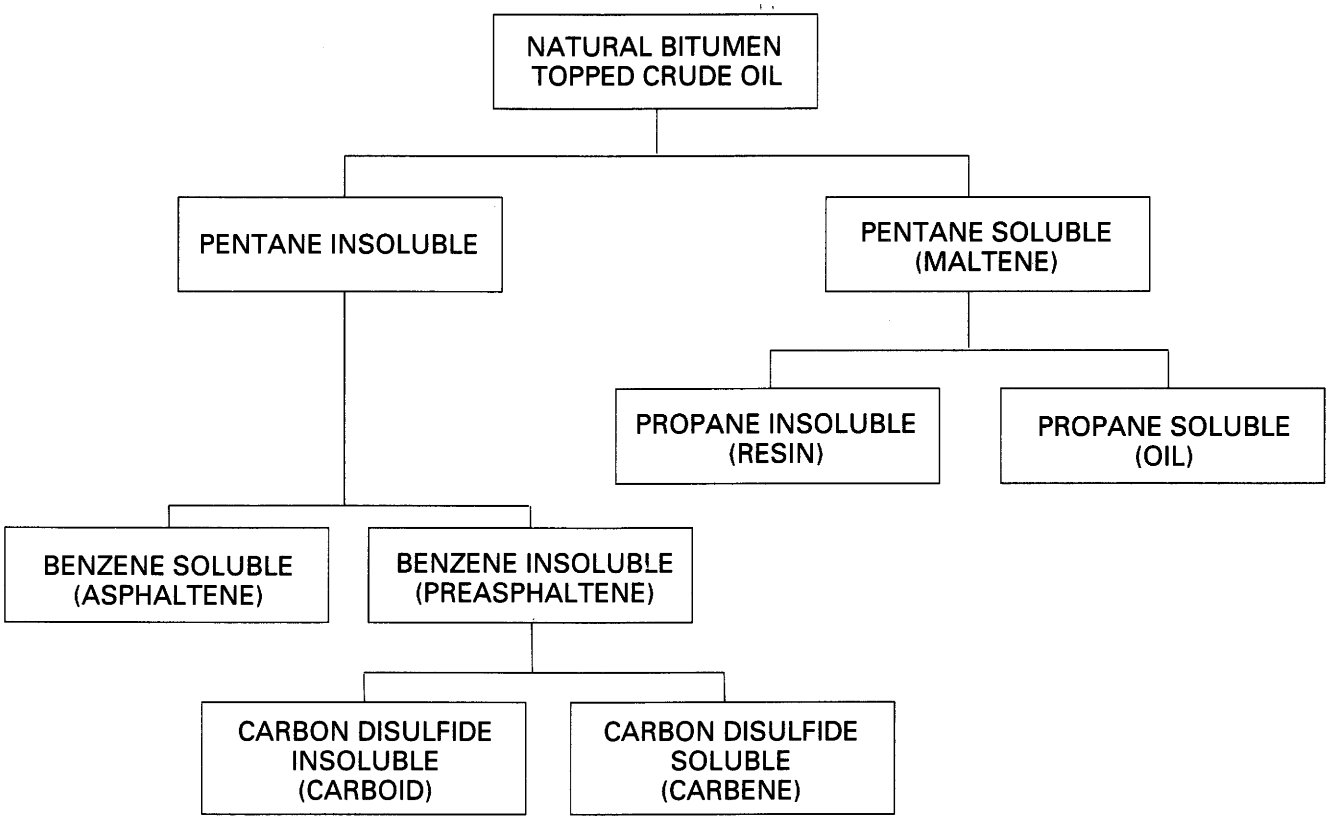

Figure 2. Solvent fractionation of natural bitumens and topped crude oil. Modified from Yen, 1984.

The mineral waxes are similar to the pyrobitumens that have H/C greater than unity (fig. 1). However, they differ from the pyrobitumens and from the other soluble natural bitumens chemically because the waxes are mostly normal paraffins and cycloparaffins, whereas pyrobitumens consist substantially of asphaltics, and the other natural bitumens are composed almost entirely of aromatic hydrocarbons and asphaltics, to the virtual exclusion of paraffins. Ozocerite, the most common mineral wax, is easily fusible, has H/C of about 1.5, and is made up almost entirely of paraffins.

The natural asphalts are black, easily soluble, fuse at 50–160 °F, frequently contain admixed mineral matter, and are usually composed in part of nitrogen-sulfur-oxygen heterocyclic compounds and trace metals. Characteristically, natural asphalt occurs in lenticular deposits at or near the Earth's surface. Deposits of natural asphalt, with or without admixed mineral matter, may be very small areally or may underlie many square miles. Conversely, the other natural bitumens generally occur in dikes a few feet or tens of feet in thickness and as much as several miles in length. Because only natural asphalt is of quantitative importance or of economic significance, the general term natural bitumen is frequently, although incorrectly, used as a synonym for natural asphalt. Rogers and others (1974) concluded that the term natural asphalt may be used when a bitumen's origin from crude oil by nonthermal degradation is evident. Connan and van der Wiede (1978) used natural asphalt to signify altered, but not immature, crude oil.

The asphaltites are very dark colored solids that will fuse, but only at temperatures above about 230 °F, and are almost completely soluble.

Reservoir bitumens (figs. 1 and 3) are black, solid, graphitic or asphaltic particles or coatings within the pores of oil- or gas-bearing reservoir rocks, having been derived from the petroleum contained therein. Such bitumens are frequently seen in cores and well cuttings and are described by Rogers and others (1974) from Paleozoic carbonate reservoir rocks lying unconformably below the Cretaceous sandstones of the western Canada basin. The reservoir bitumens are derived from the reservoir oil by two different processes, thermal alteration and deasphalting; the derivation from two processes leads to variations in solubility in carbon disulfide. They are distinguished from other bituminous substances by being predominantly composed only of hydrogen and carbon. The insoluble reservoir bitumens mostly have H/C of less than 1 and densities of about 1.15–1.40, whereas the soluble forms have H/C of about 1.2–1.5 and densities of 1.02–1.14. Figure 3 shows that the reservoir bitumens form a distinct grouping, based on their H/C, which are lower than the ratios of all the natural bitumens except impsonite and anthraxolite, and their (N+S)/O, which are considerably higher than those of the latter two pyrobitumens.

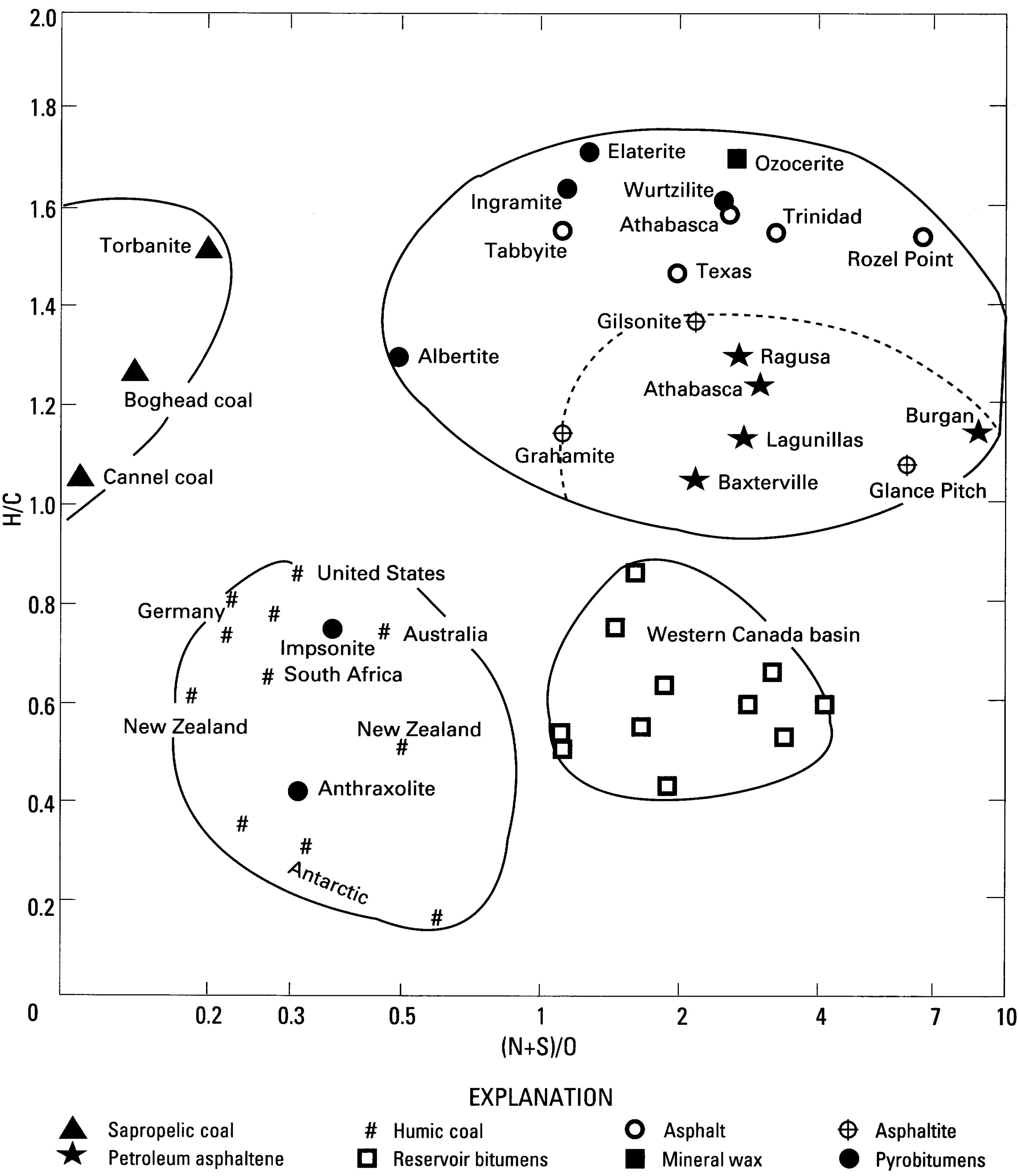

Figure 3. Atomic ratios of coals and natural bitumens. H/C, hydrogen-carbon ratio; (N+S)/O, (nitrogen+sulfur)-oxygen ratio. From Hunt 1979.

Crude Oil

Crude oil is allochthonous (fig. 1) and is composed mainly of hydrocarbons. It is distinguished from natural bitumens by its viscosity of less than 10,000 centipoises (cP) (fig. 4). Petroleum is divided into conventional, heavy, and extra heavy oil on the basis of API gravity. Conventional oil is lighter than 20 °API. The gravity of heavy oil is

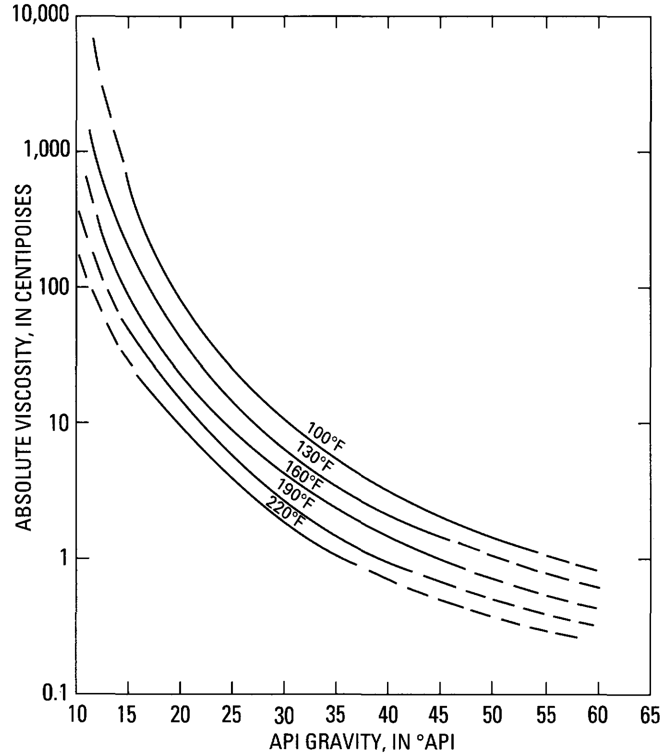

Figure 4. Correlation of absolute viscosity and API gravity for gas-free crude oil at various reservoir temperatures. Modified from Beal, 1946.

between 10 and 20 °API. Extra heavy oil has a gravity less than 10 °API; that is, a specific gravity greater than 1. These definitions differ from those of the World Petroleum Congress (WPC) (Martinez and others, 1987) only in that the congress sets the upper limit of heavy oil at 22.3 °API (specific gravity of 0.920). The heaviness of a crude oil is a function of increasing size of the hydrocarbon and asphaltic molecules, especially the asphaltenes, that make up the crude oil. The number of hydrogen atoms decreases, and the number of carbon and heteroatoms increases.

Heavy oil and natural bitumens owe their character to their deficiency of light paraffinic and naphthenic molecules, the most volatile components of an oil, and their resultant aromaticity. Heavy oil and natural bitumens (except the mineral waxes) consist of 50 percent or more aromatic hydrocarbons and N-S-O compounds (Cornelius, 1987). This composition may result from immaturity of an oil or from degradation of a mature oil. Alteration of oil by water washing or biodegradation results in loss of light hydrocarbons, especially paraffins. Alteration by deasphalting through contact with natural gas leads to heavy oil and natural bitumens. Thermal alteration results in production of methane and pyrobitumens or equivalent reservoir bitumen. The class "aromatic asphaltic oil" (Tissot and Welte, 1978) is the quantitatively most important of all classes of oil and includes the extra heavy and heavy oil of Venezuela and the U.S.S.R. and the natural bitumens of Alberta, Canada, the U.S.S.R., and the United States.

Coal

Coal is mostly autochonous, readily combustible, and composed of at least 50 weight percent and 70 volume percent organic matter. The sapropelic coals evolved anaerobically from algae, spores, and pollen, whereas the humic coals formed aerobically from plant cell and wall material. Coals expel volatile hydrocarbons with increasing thermal maturity and ultimately are composed only of fixed carbon and inorganic ash. On the basis of their ratios of hydrogen to carbon, sapropelic coals (fig. 3) are comparable to the asphalts, asphaltites, and petroleum asphaltenes but differ in having higher oxygen contents (Hunt, 1979). The humic coals have H/C similar to those of the reservoir bitumens of the western Canada basin. The bitumens, however, differ in having higher oxygen contents than humic coals. Humic coals are similar to impsonite and anthraxolite but have higher devolatilization temperatures.

CLASSIFICATION SYSTEMS OF NATURAL BITUMENS

Today, except for natural asphalt and petroleum, which are commercially important substances, natural bitumens are mostly of interest to organic geochemists. Connan and van der Weide (1978) recognized that physical attributes of the deposits of bitumens revealed little of their origin because the asphaltic character may be due either to immaturity or alteration of the bitumen. Because most asphaltic deposits result from degradation, indicated by severe depletion of the normal paraffin hydrocarbons, Connan and van der Weide (1978) refer to altered crude oils as natural asphalt. Curiale (1986) discounted bitumen classifications based on solubility, fusibility, and H/C in favor of molecular and bulk maturation data. He contrasted immature bitumens, which have migrated short distances from presumably rich source rocks, with altered oils, which were generated by and migrated from mature source rocks. Once formed, all solid bitumens may be subject to the same modification processes.

A difficulty with purely geochemical classification techniques is that they require methods and analytical abilities beyond the expertise of most geologists. Their advantages lie in the great amount of additional information that geochemical methods may provide relative to a substance's origin and maturity to aid in the search for additional deposits of bitumens or petroleum or both. However, classifications based upon physical attributes, such as solubility in organic solvents, fusibility, hardness, and color, together with viscosity and density measurements, provide the simplest means of acquiring comparable worldwide resource information.

Table 1. Physical and chemical limits of natural bitumen and petroleum (from Khalimov and others, 1983)

Class	Oil (percent)	Asphaltics (percent)	Viscosity (cP)	Density (specific gravity)
High viscosity oil [Heavy oil]	75	<25	50–2,000	0.935–0.965
Maltha [Extra heavy oil]	40–75	25–60	2,000–20,000	0.965–1.030
Asphalt [Natural bitumen]	25–40	60–75	20,000–1,000,000	1.030–1.100
Asphaltite	<25	>75	>1,000	1.050–1.200
Kerite [Pyrobitumen]	[1]3–5	90	([2])	1.070–1.350
Anthraxolite [Pyrobitumen]	([3])	100	([4])	1.300–2.000
Ozocerite [Mineral wax]	([5])	<50	([6])	0.850–0.970

[1]Rarely as high as 10.
[2]Hard, partly soluble in chloroform.
[3]Not available.
[4]Hard, insoluble in chloroform.
[5]If pure, 100 percent; if impure, 50 percent.
[6]Semihard paraffinic structure.

Definitions applied to natural bitumens vary in different places, frequently for legal purposes. The Energy Resources Conservation Board (ERCB) of Alberta, Canada, uses subjective definitions and makes special adjustments for market variations (ERCB, 1984). Although heavy oil is separated from conventional oil at 900 kg/m^3 (a specific gravity of about 0.900 or about 25 °API), the ERCB uses no physical or chemical parameter to distinguish heavy oil from bitumen.

The U.S. Department of Commerce uses 25 °API as the criterion for identifying heavy oil (*in* Lundberg Survey, Incorporated, 1989). This standard probably derives from Hawkins (1967, p. 5), who defined heavy oil as follows: "Heavy oil and low-gravity oil are used interchangeably and include all crude oils with a measured API gravity of 25° or less. However, only oil which is mobile at reservoir conditions is included in the study. Recovery of oil by primary methods was considered evidence of oil mobility." The U.S. Department of Energy (Ruth M. Davis, written commun., 1980) defined tar sand as "any consolidated or unconsolidated rock (other than coal, oil shale, or gilsonite) that contains a hydrocarbonaceous material with a gas-free viscosity greater than 10,000 centipoises at reservoir temperature."

In the U.S.S.R., a more complex terminology for describing natural bitumens has evolved, but the fundamental basis for subdivision (percent of oil and of asphaltics, viscosity, and density) is very useful. The classes of bitumens and a summary of their physico-chemical characteristics (table 1) are adapted from Khalimov and others (1983). In their classification, "high-viscosity oil" is most closely comparable to heavy oil (Lisovsky and others, 1984) and "maltha" to extra heavy oil. However, Khalimov and others (1983) refer to maltha as viscous bitumen, as distinct from the other natural bitumens and from heavy oil. Kerite and anthraxolite seem to correspond most closely with the pyrobitumens, whereas ozocerite is clearly a mineral wax. Gol'dberg and I͡Udin (1979) and Gol'dberg (1981) further proposed that bitumens be broken into two categories: naphthides and naphthoids. Naphthides include petroleum, gas condensate, natural gas, and their natural derivatives. Naphthoids are the pyrogenic or tectonogenic analogs of naphthides; that is, the flammable products of destructive distillation induced by contact metamorphism. Although the term naphthoid is encountered in tables of classification, it is found infrequently in the literature. U.S.S.R. classification is based upon three genetic series: hypergenous (oxidizing), phase-migrational, and thermal metamorphic. (1) Deposits of the oxidizing series result from reactions with water at or near the Earth's surface; the reactions include water washing, bacterial degradation, and natural deasphalting. (2) Phase-migrational deposits result from differentiation of the fluids during migration by precipitation or deasphalting. Fluids differentiated during upward migration result in the early deposition of the molecules of highest molecular weight and give rise to vein deposits (Gol'dberg, 1981). (3) The thermal-metamorphic series may result from contact metamorphism or the pyrolysis of rocks fairly rich in organic matter.

Bitumens of the same class may occur in all three series in the U.S.S.R. system, depending upon perceptions of the bitumens' origin. Apparently, the degree of thermal maturity and the structural style of a basin are used by U.S.S.R. geologists as a guide to the class and series of a natural bitumen, rather than the thermal maturity and alteration of the bitumen indicating the maturity of a basin

Table 2. Comparison of petroleum and natural bitumen classification systems

Source	Oil (percent)	Asphaltics (percent)	Viscosity at reservoir temperature (cP)	Gravity (°API)
Heavy oil				
UNITAR[1]			<10,000	10.0–20.0
WPC[2]			<10,000	10.0–22.3
U.S.S.R.[3]	>75	<25	50–2,000	15.1–19.8
People's Republic of China			[4]50–100	17.0–22.0
			[5]<10,000	17.0–22.0
Extra heavy oil				
UNITAR			<10,000	<10.0
WPC			<10,000	<10.0
U.S.S.R.[6]	40–75	25–60	2,000–20,000	5.9–15.1
People's Republic of China			[5]10,000–50,000	<17.0
Natural bitumen				
UNITAR			>10,000	
WPC			>10,000	
U.S.S.R.[7]	5–40	60–75	20,000–1,000,000	−2.9–5.9
People's Republic of China			[5]>50,000	<13.0

[1]United Nations Institute for Training and Research/United Nations Development Programme Information Centre for Heavy Crude and Tar Sands.

[2]World Petroleum Congress.

[3]High viscosity oil in U.S.S.R. terminology.

[4]At reservoir temperature.

[5]Gas free.

[6]Maltha in U.S.S.R. terminology.

[7]Asphalt in U.S.S.R. terminology.

in terms of organic source material and its alteration, sedimentary rocks, structural evolution, and degree of metamorphism. The nature of the bitumen's original source material, whether organic matter, petroleum, or another natural bitumen, is intrinsic to U.S.S.R. classification schemes.

Natural asphalt is known from a number of places in Venezuela, but Venezuela is best known for its enormous deposits of extra heavy oil in the Orinoco Oil Belt. In Venezuela, the United Nations Institute for Training and Research/United Nations Development Programme Information Centre for Heavy Crude and Tar Sands (UNITAR) definitions generally are followed.

In the People's Republic of China, heavy oil and natural bitumen, as defined by Liu (1989), represent a special case. China's nonmarine oil is relatively low in asphaltene, sulfur, and trace metal content but high in resin. Thus, it has both high viscosity and high API gravity (Liu, 1989; Xu and Niu, 1989).

Table 2 compares the preceding classifications. Data sources are UNITAR (Cornelius, 1987), WPC (Martinez and others, 1987), U.S.S.R. (see table 1), and the People's Republic of China (Liu, 1989). The UNITAR and WPC definitions are clear and unequivocal. U.S.S.R. heavy oil is limited by about 15 °API but fits within the UNITAR and WPC gravity and viscosity limits and approximates the chemical composition of comparable Venezuelan heavy oil. Chinese heavy oil fits within the UNITAR and WPC viscosity limits but has higher gravity boundaries. U.S.S.R. maltha (extra heavy oil) closely matches in chemical composition the Venezuelan heavy and extra heavy oil within the same gravity range; however, the viscosity and gravity limits are different from those of UNITAR and WPC. Chinese extra heavy oil is both higher in gravity and more viscous than the UNITAR and WPC limits. Natural bitumen is defined by UNITAR and WPC as any oil heavier than 10,000 cP. The U.S.S.R. definition imposes a lower range of viscosities, the lower limit of which is twice as high as that of UNITAR and WPC but also includes a gravity range; gravity is not a part of UNITAR and WPC definitions. The Chinese definition is anomalous in that the gravity is as high as 13 °API, but the viscosity is more than 50,000 cP. The UNITAR and U.S.S.R. definitions are similar, but the Chinese definitions differ greatly from other definitions because of the different chemical character of the nonmarine oils. Of significance is the absolute need for stating the definitions being used in any particular instance. In resource compilations, for example, the assignment of maltha is important not merely for the numbers involved but for implications as to its ease of recoverability, transportation, and upgrading and its intended end use.

DIFFERENTIATING NATURAL BITUMENS AND CRUDE OIL

The dividing line between crude oil and natural bitumens is of interest scientifically and in the estimation of resource recoverability. The boundary is of critical importance with respect to regulation and its economic impacts. The United Nations Information Centre for Heavy Crude and Tar Sands (Martinez, 1984) and the 12th World Petroleum Congress (Martinez and others, 1987) chose a viscosity of 10,000 cP, as shown graphically in figure 1, to separate natural bitumen from the less viscous oils. Danyluk and others (1984) recognized that such a demarcation is not precise because the two otherwise essentially indistinguishable materials, heavy oil and natural bitumen, may be alternatively defined, depending upon the reservoir temperature. They recommended standard viscosity measurement techniques and suggested that the demarcation zone lies between 5,000 and 15,000 cP. Gibson (1984) described five viscosity measurement methods and urged that one, such as that based on the commonly used rotational viscometer, be selected for a worldwide standard.

Briggs and others (1988) defined heavy oil as that more viscous than 100 cP, their rationale being that production rates for pumped cold oil will be less than 10 barrels per day (bbl/d) if the oil's viscosity exceeds 100 cP. They did not distinguish between heavy oil and bitumen but considered all deposits that normally occur at depths of 1,000 to 4,000 ft and that can be exploited in situ to be heavy oil. Cornelius (1987) drew the line between heavy and conventional crude at 300 cP because he expected oil to flow in the reservoir at that viscosity or less.

If possible, the limits of natural bitumen and heavy oil should be based upon physical and chemical attributes that can be easily measured and will reflect the requirements for recovery. Viscosity is the principal factor involved with recovery, and, although it can be measured with precision, it is fundamentally dependent upon temperature. Although customarily calculated at reservoir temperature, the viscosity at surface temperature is also critically important in transporting the material following its extraction. Viscosity data are not routinely available for most deposits, but density information is reported for oils and bitumens in nearly all reservoirs. Furthermore, density is not very sensitive to temperature variations. A correlation between viscosity and density is thus very desirable.

Physical attributes such as density and viscosity generally reflect the chemical composition of a natural bitumen or petroleum. Natural bitumen and heavy and extra heavy crude oil contain a large proportion—as much as 50 weight percent—of asphaltenes, resins, and heterocompounds. These high proportions lead to high molecular weights and content of constituents such as sulfur and trace metals, which are undesirable impurities in the refining process. In a reservoir, natural bitumen and the heavier oils have very low ratios of gas to oil, being essentially gas free (dead oil), and so any entrained gas will not appreciably affect the viscosity. In addition, their density is close to the specific gravity of water, so that whether viscosity is reported as absolute in centipoises or kinematic in centistokes (centipoises times density) is not a serious consideration in assessing the reservoir behavior of the bitumen.

The correlations between density and viscosity at different temperatures are given in figure 4. The correlations are maintained even as the viscosity decreases as a result of increased temperature. Oil at reservoir temperatures of 100–130 °F will have an absolute viscosity of 100 cP at about 18–20 °API. Oils having a gravity of 10 °API, or a specific gravity of 1 (that of water), will have a viscosity of about 10,000 cP at 130 °F and will be even more viscous at lower temperatures. This relation places 10 °API oils in the category of natural asphalt. Figure 4 clearly suggests the temperature increments required to produce oil (that is, to reduce viscosity to at least 100 cP, so that oil will flow).

Precise boundaries do not exist between crude oil and natural bitumens. The various species within the natural bitumens can be defined by both physical and chemical parameters. The most important demarcation, between natural asphalt and crude oil, occurs at a viscosity of about 10,000 cP. The need to use enhanced recovery methods, usually heat, begins at a viscosity of about 100 cP, or about 18 °API, the boundary between heavy and conventional oil (Briggs and others, 1988; Lisovsky and others, 1984). The effectiveness of known in situ recovery methods declines at about 10,000 cP. At most localities, natural bitumens, including natural asphalt, must be mined and upgraded to pipeline quality for transportation and refining.

We recommend that the natural bitumens be defined on the basis of their solubility, fusibility, hardness, color, density, and viscosity and that they be distinguished from crude oil by having an absolute (dynamic) viscosity in excess of 10,000 cP.

USAGE OF NATURAL BITUMENS

Except for natural asphalt, natural bitumens (fig. 1) are only of local economic interest. Because the other natural bitumens are minor in quantity and commercial importance, the term "natural bitumen" is generally considered to be synonymous with natural asphalt. The term "natural asphalt" displaces the etymologically incorrect terms oil sand and tar sand, which are not always sand and never tar, although they may contain oil. However, because of past usage, the terms "oil sand" and "tar sand" will undoubtedly continue in use indefinitely.

The chief interest in natural asphalt is as a source of synthetic oil. Natural asphalt has been virtually displaced as a construction material by commercial asphalt processed from crude oil, usually heavy, in refineries, where quality can be closely controlled. However, natural asphalt is mined locally for construction purposes in Albania, Indonesia, Trinidad and Tobago, Turkey, and the U.S.S.R.

Natural asphalt has been mined for paving, mastic, and other uses, but the natural material has now been almost wholly displaced by asphalt manufactured from heavy oil and refinery residua. Some mines, quarries, and deposits are still in operation, but at a low level of activity. Miller (1938), Redfield (1949), and Armanet (1962) reviewed production activity for all the natural bitumens, and the U.S. Bureau of Mines (Coumbe and Avery, 1956) reported on the use of natural asphalt and related bitumens for 1953, the latest year for which statistics were available, when the market was essentially one of manufactured asphalt. In 1953, the production of gilsonite was still being reported. In 1986, native asphalt was being produced by three companies in Texas and Utah, and gilsonite was being mined by two firms in Colorado and Utah (Johnson, 1986). No later production reports are available.

Minor mining of ozocerite and pyrobitumens (kerite, anthraxolite, and shungite) continues in the U.S.S.R., in addition to small amounts of natural asphalt produced for road building (Beskrovnyi and others, 1985). Asphaltites and some asphalt are mined in Turkey (Heavy Oiler, 1989). Attempts are being made to use the asphaltic limestone on Buton Island, Indonesia, as road material (Corne and Soehartono, 1989).

In 1962, according to Armanet (1962), the important bitumen mines were the mines of Gard (Avejan and Saint-Jean-de-Maruejols), Auvergne (Puy-de-Dome), and Ain and Haute-Savoie (Seyssel, Bourbogne, and Gardebois and Montrottier) in France; Vorwohle in Germany; Caxito in Angola; Maestu in Spain; Abruzzi and Ragusa in Italy; Val de Travers in Switzerland; Latakia in Syria; Uvalde in Texas, U.S.A.; and Pitch Lake, in Trinidad and Tobago. Other significant mines include Bombay Island, India (Fox, 1922), Selenitza, Albania (Miller, 1938), Leyte Island, the Republic of the Philippines (Palacio, 1957), and Buton Island, Indonesia (Warga Dalem and Padmosubroto, 1988; Corne and Soehartono, 1989).

NATURAL ASPHALT RESOURCES

Natural Asphalt Deposits

A list of world resources of natural asphalt (table 3) is derived from Meyer and Duford (1989), with the exception of U.S.S.R. asphalt, the source for which is Gol'dberg (1981). The quantities listed are only the amounts from deposits that contain at least 1 million barrels of natural asphalt in situ; these deposits are considered to be sufficiently large to have at least the potential to serve as a source for synthetic oil. This choice of size is based primarily on economics, not technology. Most probably, deposits even as large as 100 million barrels of natural asphalt in situ will not be exploited for oil in the foreseeable future.

Table 3. World natural asphalt resources (in million barrels)

Area	Demonstrated	Inferred
NORTH AMERICA		
United States	22,823	33,709
Canada	1,685,725	831,100
Total	1,708,548	864,809
SOUTH AMERICA		
Trinidad	60	
Venezuela	50,400	
Total	50,460	
EUROPE		
Albania	371	
Italy	1,260	
Romania	25	
U.S.S.R.	18,837	
Total	20,493	
ASIA		
People's Republic of China	10,050	
U.S.S.R.	66,213	
Total	76,263	
AFRICA		
Madagascar	35	31
Nigeria	1,000	
Zaire	30	—
Total	1,065	31
MIDDLE EAST		
Syria	13	
Total	13	
SOUTHEAST ASIA		
Indonesia	10	
Republic of the Philippines	1	1
Total	11	1
WORLD TOTAL	1,856,853	864,841

Giant deposits, for convenience, may be considered to be those containing at least 1 billion (1,000 million) barrels of natural asphalt in situ. Natural asphalt in Alberta, Canada, in the western Canada basin (1,686 billion barrels demonstrated and 831 billion barrels inferred) completely dominates the world's natural asphalt resource. The deposits contain about 91 percent of the demonstrated and 96 percent of the inferred natural asphalt resources of the world. These resources are found in Lower Cretaceous sandstones in the Athabasca, Cold Lake, and Peace River deposits and in Upper Devonian limestones of the Carbonate Triangle area.

In the United States, there are eight giant natural asphalt deposits:

1. Arctic Coastal Plain basin, Alaska, Kuparuk deposit, Paleocene and Upper Cretaceous Ugnu sandstones (Werner, 1987), 11 billion barrels inferred;
2. Cherokee basin, Kansas and Missouri, sandstones of the Middle Pennsylvanian Bluejacket and Warner Sandstone Members of the Krebs Formation, 2.7 billion barrels, measured and inferred;
3. Gulf Coast basin, Texas, San Miguel deposit, sandstones of the Upper Cretaceous San Miguel Formation, 2 billion barrels demonstrated and inferred;
4. Illinois basin, Kentucky, Upper Mississippian Big Clifty Sandstone Member of the Golconda Formation, 2.1 billion barrels demonstrated and inferred;
5. Paradox basin, Utah, Tar Sand Triangle deposit, Lower Permian White Rim Sandstone Member of the Cutler Formation, 2.9 billion barrels demonstrated and inferred, and Circle Cliffs deposit, sandstones of the Middle Triassic Moenkopi Formation, 1.7 billion barrels demonstrated and inferred;
6. Santa Maria basin, California, Foxen deposit, sandstones of the Pliocene Foxen Formation, 1.9 billion barrels inferred, and Casmalia field, diatomaceous mudstone of the Miocene and Pliocene Sisquoc Formation, 1.5 billion barrels demonstrated;
7. Uinta basin, Utah, P.R. Spring deposit, sandstones of the Paleocene and Eocene Green River Formation, 4.3 billion barrels demonstrated and inferred, and Sunnyside deposit, sandstones of the Paleocene and Eocene Green River Formation, 6.1 billion barrels demonstrated and inferred;
8. Black Warrior basin, Alabama, Upper Mississippian Hartselle Sandstone, 7.8 billion barrels inferred.

These deposits represent nearly 80 percent of the total U.S. demonstrated and inferred resource, the other 20 percent being distributed among numerous deposits of less than 1 billion barrels each.

In South America, only the natural asphalt deposits of Venezuela appear to qualify as giant. Mendez (1988) gave a total for Venezuela of 50.4 billion barrels, most of which occurs in eight deposits along the southwestern flank of the eastern Venezuela basin. Whether any of the individual deposits is as large as 1 billion barrels of asphalt in situ is not known; the best known deposit, Guanoco (Bermudez) Pitch Lake, evidently is not that large (Abraham, 1960a).

Giant natural asphalt deposits in Europe are confined to Italy and the U.S.S.R.. In Italy, Miocene calcarenites of the Ragusa area on the Ragusa Platform appear to contain as much as 1.3 billion barrels demonstrated.

Herein, the U.S.S.R. is divided into an eastern portion, whose resources are assigned to Asia, and a western portion, whose resources are assigned to Europe. For the U.S.S.R. as a whole, the resource level is drastically reduced from that given in Meyer and Duford (1989), which was taken from Meyerhoff and Meyer (1987). For the European portion, the reduction is more than 100 billion barrels, and for the Asian portion, more than 570 billion barrels. Savinkin (1989, p. 11) stated that "the current best estimate of bitumen [natural asphalt] resources [in the U.S.S.R.] is up to 60 billion tons [378 billion barrels]." The estimate given here for the U.S.S.R. as a whole is 85.1 billion barrels (Gol'dberg, 1981); this estimate excludes nearly 105 billion barrels of maltha, which fits the category of extra heavy oil and is comparable to oils in the Venezuelan Orinoco Oil Belt. Savinkin (1989) probably included maltha in his total, and maltha was included in the estimate of Meyerhoff and Meyer (1987). The sizes of individual deposits are not known.

The largest occurrences of natural asphalt in European U.S.S.R. are in Lower Mississippian clastic and carbonate and Upper Devonian carbonate rocks of the Timan-Pechora province and in Lower Permian carbonate rocks of the Volga-Urals province, most importantly the Melekess basin-South Tatar arch district. In the Volga-Urals province, however, by far the greatest quantity of oil is maltha, herein excluded from natural asphalt resources. The total amount of natural asphalt for European U.S.S.R. is 18.8 billion barrels.

In Asia, the sizes of individual deposits are unknown, but collections of natural asphalt deposits in close proximity constitute giant deposits in Asian U.S.S.R. and the People's Republic of China. Two such collections of deposits contain 70 percent of the 66.2 billion barrels of natural asphalt that have been identified in Asian U.S.S.R.—the Central Anabar and the Olenek-Udzha areas, on the Siberian platform in the Lena-Tungusska province. The natural asphalt is concentrated in rocks of Late Proterozoic, Cambrian, Permian, and Early Jurassic age.

At least two areas in the People's Republic of China have very large collections of natural asphalt deposits. These two areas contain total resources of as much as 5 billion barrels each in lower Paleozoic rocks on the Yangzi platform of the Yellow Sea province and in the Junggar, Tarim, and other western China basins.

In Africa, the most notable occurrence is the 1-billion-barrel deposit in the Benin embayment (Dahomey basin) in Nigeria. The natural asphalt occurs in Upper Cretaceous sandstones. One or more giant deposits probably occur in Angola, but necessary volumetric data are not available in the resource literature.

Although many seeps and natural asphalt quarries are located in the Middle East, none of these is of giant size.

Resource Evaluation

Any evaluation of resources necessitates consideration of the individual deposits, their size, and grade. Some natural asphalt deposits are essentially pure; they contain

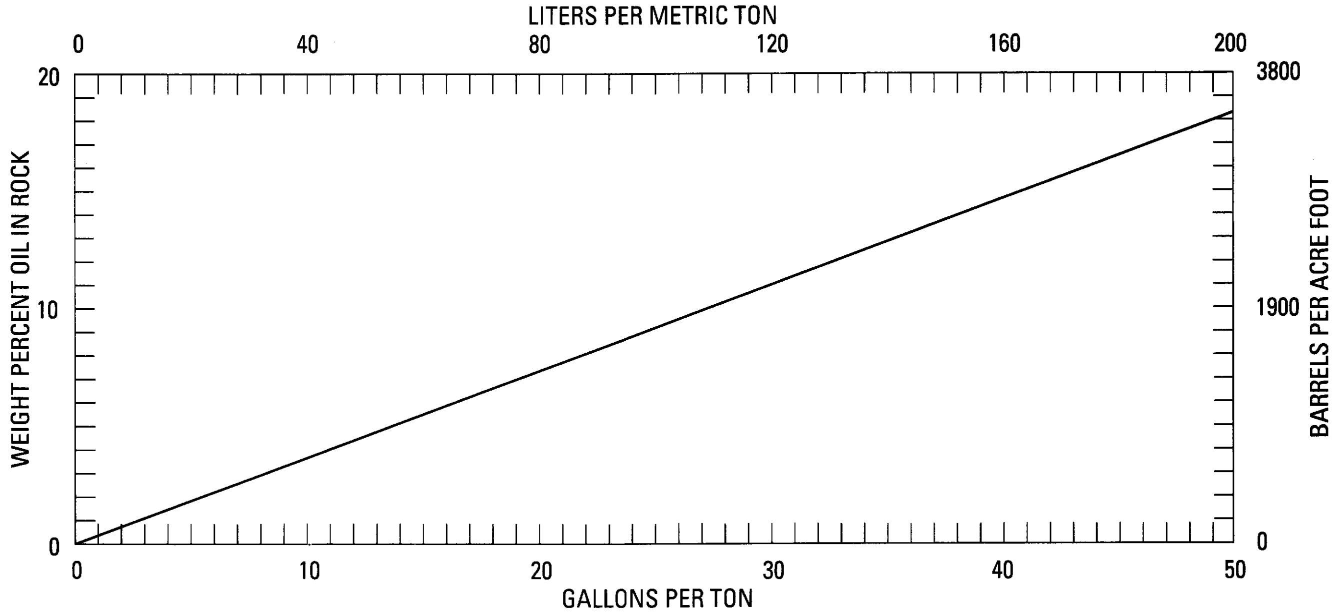

Figure 5. Grade conversion chart for natural asphalt deposits. From Earley, 1987.

very small amounts of mineral matter such as sand, silt, or clay. In these deposits, the grade is close to 100 weight percent natural asphalt. Other deposits are composed of natural asphalt in a matrix of sand, sandstone, or limestone; this composition makes their grade (that is, the weight percent natural asphalt) critically important in determining economic exploitability.

Earley (1987) examined the effects of the amount of overburden (stripping ratio) and grade upon economic recoverability of a natural asphalt deposit. He used the discounted cash flow rate of return (DCFROR) as a measure of profitability and therefore a measure of incentive to exploit a deposit. Earley (1987) found that, by using drag lines to remove overburden, the stripping ratio (the ratio of waste rock to ore) had little effect on the DCFROR to an overburden thickness of about 300 ft. With greater thicknesses of overburden, the cost of stripping rapidly increases. Because 300 ft is too shallow to attempt thermal recovery with steam, a zone of presently unrecoverable ore between about 300 and 600 ft is left for recovery by a new technology, such as shaft and tunnel.

Figure 5 is a conversion chart for the common ways in which grade is expressed. Figure 6 gives the sensitivity of DCFROR to grade for three different natural asphalt processing plant sizes. For plants processing more than 15,000 bbl/d, grade does not appreciably affect profitability, but an obvious loss in profitability occurs below 10,000 bbl/d at lower grades. A grade of about 7 weight percent natural asphalt is close to the lower limit of exploitability; a grade of 12 weight percent or greater is desirable.

Average in situ recovery of natural asphalt from rock asphalt deposits may be expected to be about 15 weight percent of asphalt in situ, by using thermal methods. By

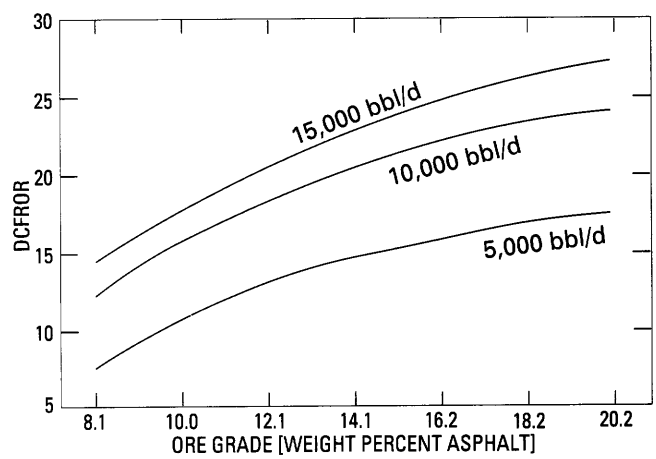

Figure 6. Sensitivity of discounted cash flow rate of return to natural asphalt grade for three different processing plant sizes. DCFROR, discounted cash flow rate of return; bbl/d, barrels per day. From Earley, 1987.

using mining methods, asphalt recovery may be as high as 95 percent. Thus, a deposit of 1 billion barrels of natural asphalt in situ may yield from 150 million to 950 million barrels of raw natural asphalt, before processing losses. A perspective may be obtained from the efforts to exploit natural asphalt as a source of synthetic oil in the western Canada basin. There, 1987 annual production was about 126 million barrels or 345,000 bbl/d (ERCB, 1987). Approximately two-thirds of this production was from two surface-mining operations (Athabasca deposit), and the remainder from three major commercial in situ projects (Cold Lake) and numerous smaller or experimental projects. Cumulative production to the end of 1986 totaled 755 million barrels from the two Athabasca deposit surface-mining operations, 88 million barrels from the Cold Lake in situ projects, and 2.5 million barrels from the Peace River in situ project. These three deposits constitute 4,465 million barrels of original reserves (proved reserves plus cumulative production). Because the reserves are based on the amount of bitumen recoverable with existing wells and facilities, the figures represent only a small portion of the in situ natural asphalt resources (table 3) (Meyer and Duford, 1989).

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