GEOLOGY OF NATURAL BITUMEN AND HEAVY OIL RESOURCES

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Summary

Tar sand (also known as oil sand and bituminous sand) is a sand deposit that is impregnated with dense, viscous petroleum-like material called bitumen. Heavy oil reservoirs and tar sand deposits are widely distributed throughout the world in a variety of countries. Although the heavy oil reservoirs can be seen as reservoirs that are very similar in geological character to petroleum reservoirs, tar sand deposits can differ considerably from conventional crude oil, and heavy oil reservoirs. Thus, the various tar sand deposits have been described as belonging to two types:

- Materials that are found in stratigraphic traps.
- Deposits that are located in structural traps.

There are, inevitably, gradations, and combinations of these two types of deposits and a broad pattern of deposit entrapment are believed to exist. In general terms, the entrapment characteristics for the very large tar sand deposits all involve a combination of stratigraphic and structural traps. Entrapment characteristics for the very large tar sands all involve a combination of stratigraphic-structural traps. There are no very large tar sand accumulations having more than four billion barrels (4×10^9 bbl) in place either in purely structural or in purely stratigraphic traps. In a regional sense, structure is an important aspect since all of the very large deposits occur on gently sloping homoclines.

The tar sand deposits of the world have been described as belonging to two types. These are:

- In situ deposits resulting from breaching and exposure of an existing geologic trap.
- Migrated deposits resulting from accumulation of migrating material at outcrop.

However, there are inevitable gradations and combinations of these two types of deposits. The deposits have been laid down over a variety of geologic periods, and in different entrapments and a broad pattern of deposit entrapment is believed to exist since all deposits occur along the rim of major sedimentary basins, and near the edge of pre-Cambrian shields. The deposits either transgress an ancient relief at the edge of the shield (e.g. those in Canada) or lie directly on the ancient basement (e.g. as in Venezuela, West Africa, and Madagascar).

A feature of major significance in at least five of the major areas is the presence of a regional cap (usually a widespread transgressive marine shale). Formations of this type occur in the Colorado Group in Western Canada, in the Freites formation in eastern Venezuela, or in the Jurassic formation in Melville Island) overlying the formation. The cap plays an essential role in restraining vertical fluid escape from the basin thereby forcing any fluids laterally into the paleo-delta itself.

1. Distribution and Structure of the Reservoir–Deposit

Heavy oil reservoirs and tar sand deposits are widely distributed throughout the world in a variety of countries. Although the heavy oil reservoirs can be seen as reservoirs that are very similar in geological character to petroleum reservoirs, tar sand deposits can differ considerably from conventional crude oil, and heavy oil reservoirs.

Petroleum accumulations are usually found in structural highs where reservoir rocks of suitable porosity and permeability are covered by a dense, relatively impermeable cap rock, such as an evaporate or a shale. A reservoir rock sealed by a cap rock in the position of a geological high, such as an anticline, is known as a structural petroleum trap. Other types of traps, such as sand lenses, reefs, and pinch-outs of more permeable and porous rock units are also known and occur in various fields. In all these situations, the changes in permeability and porosity determine the location of petroleum and/or a gas accumulation. The essential feature of a geologic trap is that the boundary between the cap rock or other sealing agent and the reservoir rock generally is convex upward, but the exact form of the boundary varies widely. The simplest forms are the flat-lying convex lens, the anticline, and the dome, each of which has a convex surface at the top of the formation (geologic structure).

Many crude oil and gas accumulations are trapped in anticlines or domes, structures that are generally more easily detected than some other types of traps. Some traps are formed by the reservoir rock being cut off at its upper end by a fault that places sealing rock against the fractured end. Alternatively, the upper end may have been eroded during a period of non-conformity, resulting in the subsequent covering of the eroded top of the reservoir rock by a sealing rock.

There are also examples in which the reservoir rock wedges out at its upper end as an original depositional feature due to lateral variation in deposition or abuts against an old land surface (stratigraphic trap). Traps associated with salt intrusions are of various kinds; limestone reefs can also serve as reservoir rocks, and give rise to overlying traps of anticline form as a result of differential compaction. Last, examples are also known in which the reservoir rock extends to the surface of the earth but oil and gas are sealed in it by clogging of the pores by bitumen or by natural cements. Many reservoirs display more than one of the factors contributing to the entrapment of hydrocarbons.

The distinction between a structural trap and a stratigraphic trap is often not clear. For example: an anticline trap may be related to an underlying buried limestone reef. Beds of sandstone may wedge out against an anticline because of depositional variations or intermittent erosion intervals. Salt domes, formed by flow of salt at substantial depths, also have created numerous traps that are both a structural trap and a stratigraphic trap.

Thus, the various tar sand deposits have been described as belonging to two types:

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- Deposits that are located in structural traps.

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The tar sand deposits of the world have been described as belonging to two types. These are:

- In situ deposits resulting from breaching and exposure of an existing geologic trap.
- Migrated deposits resulting from accumulation of migrating material at outcrop. However, there are inevitable gradations and combinations of these two types of deposits. The deposits have been laid down over a variety of geologic periods and in different entrapments and a broad pattern of deposit entrapment is believed to exist since all deposits occur along the rim of major sedimentary basins, and near the edge of pre-Cambrian shields. The deposits either transgress an ancient relief at the edge of the shield (e.g. those in Canada) or lie directly on the ancient basement (e.g. as in Venezuela, West Africa, and Madagascar).

A feature of major significance in at least five of the major areas is the presence of a regional cap (usually a widespread transgressive marine shale). Formations of this type occur in the Colorado Group in Western Canada, in the Freites formation in eastern Venezuela, or in the Jurassic formation in Melville Island) overlying the formation. The cap plays an essential role in restraining vertical fluid escape from the basin thereby forcing any fluids laterally into the paleo-delta itself. Thus, the subsurface fluids were channeled into narrow outlets at the edge of the basin.

In Canada, the town of McMurray, about 240 miles north north east of Edmonton, Alberta lies at the eastern margin of the largest accumulation in the world that is, in effect, three major accumulations within the Lower Cretaceous deposits. The

McMurray-Wabasca reservoirs are found toward the base of the formation and are characteristically cross-bedded coarse grit, and gritty sandstone that are unconsolidated or cemented by tar; fine-to-medium grained sandstone and silt occur higher in the sequence. Bluesky-Gething and Grand Rapids reservoirs are composed of sub-angular quartz and well-rounded chart grains. The sandstone of both of these deposits is frequently glauconitic and has a calcareous matrix. In addition, the McMurray-Wabasca tar sand deposit dips at between 5 feet and 25 feet per mile (1.5 meters and 8 meters per mile) to the southwest. The Bluesky-Gething sands overlie several unconformities between the Mississippian and the Jurassic deposits.

In terms of specific geological and geochemic aspects of the formation, the majority of the work has, again, been carried out on the Athabasca deposit. Attention has repeatedly been focused on the variation in physical properties of crude oil produced in multiple-zone fields or in some instances within a single reservoir. Of all the properties, specific gravity, or American Petroleum Institute gravity, is the variable usually observed to be changing. This may simply reflect compositional differences, such as the gasoline content or asphalt content, but analysis may also show significant differences in sulphur content or even in the proportions of the various hydrocarbon types.

In the more localized context of the Athabasca deposit, inconsistencies arise presumably because of the lack of mobility of the bitumen at formation temperature (approximately 4°C, 39^{o}F). For example: the proportion of bitumen in the tar sand increases with depth within the formation. Furthermore, the proportion of the non-volatile asphaltenes or the non-volatile asphaltic fraction (asphaltenes plus resins) in the bitumen also increases with depth within the formation that leads to reduced yields of distillate from the bitumen obtained from deeper parts of the formation. In keeping with the concept of higher proportions of asphaltic fraction (asphaltenes plus resins), variations (horizontal and vertical) in bitumen properties have been noted previously, as have variations in sulphur content, nitrogen content, and their metals content.

Obviously, the richer tar sand deposits occur toward the base of the formation. However, the bitumen is generally of poorer quality than the bitumen obtained from near the top of the deposit insofar as the proportions of non-volatile coke-forming constituents (asphaltenes plus resins) are higher (with increased proportions of nitrogen, sulphur, and metals) near the base of the formation.

The determining factor is site specificity.

The Canadian Melville Island deposits lie on the north shore of Marie Bay, Melville Island, some 1450 miles north of Edmonton, Triassic sandstone of the Bjorn Formation are impregnated with a bituminous material. This deposit was discovered in 1962 and the sands occur at intervals along a 60-mile outcrop. The richer sands tend to be associated with structurally high areas or are closely related with faults.

The major tar sand deposits of the United States occur within and around the periphery of the Uinta Basin Utah. These include the Asphalt Ridge, Sunnyside, Tar Sand Triangle, and the Peor (PR) springs deposits. Asphalt Ridge lies on the northeastern margin of the central part of the Uinta Basin at the contact of the tertiary beds with the underlying Cretaceous Mesa Verde Group. The Mesa Verde Group is divided into three formations; two of which, the Asphalt Ridge sandstone, and the Rim Rock sandstone are beach deposits containing the viscous bitumen. The Rim Rock sandstone is thick and uniform with good reservoir characteristics, and it may even be suit able for thermal recovery methods. The Duchesne River formation (Lower Oligocene) also contains bituminous material, but the sands tend to be discontinuous.

The Sunnyside deposits are of a greater extent than Asphalt Ridge and are located on the southwest flank of the Uinta Basin. The tar sand accumulations occur in sandstone of the Wasatch and lower Green River formations (Eocene). The Wasatch sandstone contains bitumen impregnation, but is lenticular and occupies broad channels cut into the underlying shale and limestone; the Green River beds are more uniform, and are laterally continuous. The source of the bitumen in the Asphalt Ridge and Sunnyside accumulation is considered to be the Eocene Green River shale.

The Peor (PR) springs accumulation is about 60 miles (96.5 km) east of the Sunnyside deposit and occurs as lenticular sandstone (Eocene Wasatch formation.) There are two main beds from 30 to 85 feet (9 meters to 26 meters) thick with an estimated overburden thickness of zero to 250 feet (zero to 76 meters.) The tilt of the southern flank of the Uinta Basin has left this deposit relatively undisturbed except for erosion, which has stripped it of its cover allowing the more volatile constituents to escape. In the central south-east area of Utah, some deposits of bitumen-impregnated sandstone occur in Jurassic rock, but the great volume of in-place bitumen occurs in rocks of Triassic and Permian age. The Tar Sand Triangle is considered to be a single, giant stratigraphic trap containing the bitumen.

The Californian deposits are concentrated in the coastal region west of the San Andreas Fault. The largest deposit is the Edna deposit, which is located midway between Los Angeles and San Francisco. It consists of conglomerate, sandstone, diatomaceous sandstone, and siliceous shale. The deposit occurs as a stratigraphic trap and outcrops in scattered areas on both flanks of a narrow syncline. The deposit extends over an area of about 7000 acres and occurs from outcrop to 100-feet (30-meters) depth. The accumulation is thought to have been taken from the underlying organic and petroliferous Monterey shale.

The Sisquoc deposit (Upper Pliocene) is the second largest in California and occurs in sandstone in which there are as many as eight individual tar sand units. The total thickness of the deposit is about 185 feet, (56 meters) occurring over an area of about 175 acres, with an overburden thickness between 15 and 70 feet (4.6 meters and 21 meters). The reservoir sands lie above the Monterey shale, which has been suggested to be the source of the bitumen.

The third California deposit at Santa Cruz is located approximately 56 miles (90 km) from San Francisco. The material occurs in sandstone of the Monterey and Vaqueros formations, which are older than both the Edna and Sisquoc reservoir rocks. The Santa Cruz tar sands are discontinuous and overlie the pre-Cretaceous basement.

South Texas holds the largest reserves in the state of heavy crude oil fields and tar sand deposits. The tar sand deposits occur in the San Miguel tar belt (Upper Cretaceous) mostly in Maverick and Zavalla counties, as well as in the Anacadro limestone (Upper Cretaceous) of the Uvalde district. The Kentucky tar sand deposits are located at Asphalt, Davis-Dismal Creek, and at Kyrock; they all occur in non-marine Pennsylvanian or Mississippian sediments. The three deposits appear as stratigraphic traps and are thought to have received their bitumen, or bitumen precursor, from the Devonian Chattanooga shale. Tar sand deposits in New Mexico occur in the Triassic Santa Rosa sandstone, which is an irregularly bedded, fine- to medium-grained micaceous sandstone. The bitumen, or bitumen precursor, is thought to have migrated upward from the underlying Permian San Andreas limestone through sinkholes in the karst surface of this formation. Finally, the tar sand deposits in Missouri occur over an area estimated at 2000 square miles in Barton, Vernon, and the Cass Counties, and the sandstone bodies that contain the bitumen are middle Pennsylvanian in age. The individual bitumen-bearing sands are approximately 50 feet (15 meters) in thickness except where they occur in channels which may actually be as much as 250 feet (76 meters) thick. The two major reservoirs are the Warner sandstone and the Blue jacket sandstone that at one time were regarded as blanket sands covering large areas. However, recent investigations suggest that these sands can abruptly grade into barren shale or siltstone.

Tar sand deposits in Venezuela occur in the Officinal–Tremblador tar belt that is believed to contain bitumen-impregnated sands of a similar extent to those of Alberta, Canada. The Officinal formation overlaps the Tremblador (Cretaceous) formation and the organic material is typical bitumen, having API gravity less than 10^{o}. The Guanaco Asphalt Lake occurs in deposits that rest on a formation of mid-Pliocene age. This formation, the Las Piedras, is principally brackish sandstone to freshwater sandstone with associated lignite. The Las Piedras formation overlies a marine Upper Cretaceous group; the Guanaco Lake asphalt is closely associated with the Guanaco crude oil field that produces heavy crude oil from shale and fractured argillite of the Upper Cretaceous group.

Other major geological and geochemic studies have been carried out on the Orinoco deposit because of its size and relative importance in the energy economy of Venezuela. The geological setting of the Orinoco deposit is very complex, having evolved through three cycles of sedimentation. Both structural and stratigraphic traps, depending on the location, the age of the sediment, and the degree of faulting contain the bitumen. The tar sands are located along the southern flanks of the eastern Venezuelan basin where three distinct zones are apparent from north to south: a zone of tertiary sedimentation; a central platform with transgressive overlapping sediments; and a zone of Proterozoic erosion remnants covered by sediments. The deposit also contains three systems of faulting. All the faults are normal and many are concurrent with deposition.

The Bemolanga (Madagascar) deposit is the third largest tar sand deposit presently known and extends over some 150 square miles in western Madagascar with a recorded overburden from zero to 100 feet (zero to 30 meters). The average pay zone thickness is 100 feet (30 meters) with a total bitumen in-place quoted at approximately two billion barrels (approximately 2×10^9 bbl). The deposit is of Triassic age and the sands are cross-bedded continental sediments; and the coarser, porous sands are more richly impregnated. The origin of the deposit is not clear; the most preferred source is the underlying shale or in down-dip formations implying small migration.

The largest tar sand deposit in Europe is that at Selenizza Albania. This region also contains the Patos oil field throughout which there occurs extensive bitumen impregnation. This deposit occurs in middle-upper Miocene lenticular sands, characterized by a brackish water fauna. Succeeding Pliocene conglomerate beds, which are more generally marine-based, are also locally impregnated with heavy crude oil. The Selenizza and Patos fields occupy the crystal portions of a north-south trending anticline. Faulting also controls the vertical distribution of the accumulation. The Miocene rests on Eocene limestone and it is these that are thought by some to be the source of the tar.

The Trinidad Asphalt Lake [situated on the Gulf of Paria, 12 miles west-south-west of San Fernando and 138 feet (43 meters) above sea level) occupies a depression in the Miocene sheet sandstone. It overlies an eroded anticline of Upper Cretaceous age with remnants of an early tertiary formation still preserved on the flanks. The deposit is thought to derive from the argillite of the Upper Cretaceous formation that is known to contain heavy crude oil. After loss of the light ends during erosion and folding, the source beds were covered by Miocene clays alter which tensional faulting allowed asphaltic material to rise and impregnate the overlying upper Miocene freshwater sands.

The Rumanian deposits are located at Derna deposits and occur (along with Tataros and other deposits) in a triangular section east and northeast of Oradia between the Sebos Koros and Berrettyo rivers. The tar sand occurs in the upper part of the Pliocene formation and the asphalt is characterized by its' penetrating odor. The reservoir rock is non-marine, representing freshwater deposition during a period of regression.

Tar sands occur at Cheildag, Kobystan and outcrop in the south flank of the Cheildag anticline; there are approximately 24 million barrels (24×10^6 bbl) of bitumen in place. Other deposits in the former USSR occur in the Olenek anticline (north-east of Siberia) and it has been claimed that the extent of asphalt impregnation in the Permian sandstone is of the same order of magnitude (in area and volume) as that of the Athabasca deposits. Tar sands have also been reported from sands at Subovka and the Notanebi deposit (Miocene sandstone) is reputed to contain 20% bitumen by weight. On the other hand, the Kazakhstan occurrence, near the Shubar-Kuduk oil field, is a bituminous lake with a bitumen content that has been estimated to be of the order of 95% by the weight of the deposit.

Tar sand occurrences also occur in the Southern Llanos of Colombia where drilling has presented indications of deposits generally described as heavy crude oil, natural asphalt, and bitumen. Most of these occurrences are recorded below 1500 feet (457 meters). The tar sands at Burgan in Kuwait and at the Encarta and Bolivar coastal fields of the Maraca Ibo Basin are of unknown dimensions. Those at Encarta have been exploited and all are directly or closely associated with large oil fields. The tar sands of the Bolivar coastal fields are above the oil zones in Miocene beds and are in a litho logical environment similar to that of the Officinal–Tremblador tar belt. The small Miocene asphalt deposits in the Leyte Islands (Philippines) are extreme samples of stratigraphic entrapment and resemble some of the Californian deposits. Those of the Mefang Basin in Thailand are in Pliocene beds that overlie Triassic deposits and their distribution is stratigraphically controlled.

There is a small accumulation at Chumpi, near Lima (Peru), which occurs in tuffaceous sands and it is believed to be derived from strongly deformed Cretaceous limestone from which a petroleum-type was distilled as a result of volcanic activity. Finally, tar sand deposits have also been recorded in Spain, Portugal, Cuba, Argentina, Thailand, and Senegal, but most are poorly defined and are considered to contain (in-place) less than 1 million barrels (1 x 10^6 bbl) of bitumen.

The mineralogy of tar sand deposits is also worthy of note as it does affect the potential for recovery of the bitumen. Usually, more than 99% by weight of the tar-sand mineral is composed of quartz sand and clays. In the remaining 1%, more than 30 minerals have been identified, mostly calciferous or iron-based.

Particle size ranges from large grains (99.9% is finer than 1000 microns) down to 44 microns (325 mesh), the smallest size that can be determined by dry screening. The size between 44 and 2 microns is referred to as silt; sizes below 2 microns (equivalent spherical diameter) are clay.

Clays are aluminosilicate minerals, for some of which definite chemical compositions have been established. However, as used in this article, clay is only a size classification and is usually determined by a sedimentation method.

According to the previous definition of fines, the fines fraction equals the sum of the silt, and the clay fractions. The clay fraction over a wide range of fines contents is a relatively constant 30% by weight of the fines.

Hot water processing is based on the percentage of bitumen, and the percentage of the fines. The former may be determined analytically by extraction with toluene, arranged in such a way that both the water, and bitumen, contents are measured directly. In this article, percent fines refers to the weight percentage of the dried, extracted tar-sand mineral that passes a fixed mesh size such as 44 microns (325 mesh.) The percent fines may be conventionally determined by screening.

The Canadian deposits are largely unconsolidated sands with a porosity ranging up to 45% and have good intrinsic permeability. However, the deposits in the United States in Utah range from predominantly low-porosity, low-permeability consolidated sand to, in a few instances, unconsolidated sands.

In addition the bitumen properties are not conducive to fluid flow under normal reservoir conditions in either the Canadian or United States deposits. Nevertheless, where the general nature of the deposits prohibits the application of a mining technique (as in many of the United States deposits), a non-mining technique may be the only feasible bitumen recovery option.

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Biographical Sketch

Dr. James G. Speight has a Ph.D. in Organic Chemistry from the University of Manchester, England, and works for CDW Inc. as an Author/Lecturer/Technical and Business Advisor. Previously, he was Chief Executive Officer at the Western Research Institute (19901998). Dr. Speight has thirty years of experience in areas associated with the properties and processing of conventional and synthetic fuels. He has participated in, as well as led, significant research in defining the use of chemistry of heavy oil and coal. He has well over three hundred publications, reports, and presentations detailing these research activities. Dr. Speight is currently editor of the journal Petroleum Science and Technology (formerly Fuel Science and Technology International), editor of the journal Energy Sources, and co-editor of the journal Reviews in Process Chemistry and Engineering. He is recognized as a world leader in the areas of fuels characterization and development. Dr. Speight is also Adjunct Professor of Chemistry and Adjunct Professor of Chemical Engineering at the University of Wyoming as well as Adjunct Professor of Chemical and Fuels Engineering at the University of Utah. Dr. Speight is the author/editor/compiler of nineteen books and bibliographies related to fossil fuel processing and environmental issues. As a result of his work, Dr. Speight was awarded the Diploma of Honor, National Petroleum Engineering Society, For Outstanding Contributions to the Petroleum Industry in 1995 and the Gold Medal of Russian Academy of Sciences (Natural) for Outstanding Work in the Area of Petroleum Science in 1996. He has also received the Specialist Invitation Program Speakers Award from NEDO (New Energy Development Organization, Government of Japan) in 1987 and again in 1996. Dr. Speight also received the degree of Doctor of Sciences from the Scientific Research Geological Exploration Institute (VNIGRI), St. Petersburg, Russia For Exceptional Work in Petroleum Science in 1997.