Heavy oil is defined by the U.S. Department of Energy as having API (American Petroleum Institute) gravities that fall between 10.0° and 22.3° (Nehring et al., 1983). Extra-heavy oils are defined as having API gravities less than 10.0° API. Heavy oils are classified as such using API gravity rather than viscosity values. Two important distinctions must be made between API gravity and viscosity. First, viscosity determines how well oil will flow while API gravity typically determines the yield from distillation. Additionally, temperature and paraffin content can have a large effect on viscosity values while API gravity is not affected by these parameters.

Heavy oil has recently become an important resource as conventional oil reservoirs are in decline. More than 6 trillion barrels of oil in place have been attributed to the heaviest hydrocarbons. This is more than three times the amount of combined world reserves of conventional oil and gas. Of particular interest are the large heavy oil deposits of Canada and Venezuela, which together may account for about 55–65% of the known < 20° API oil deposits in the world (Kopper et al., 2002).

Compositions. Heavy oils usually begin as lighter oils (30–40° API) and are then altered, often by biodegradation. With aerobic biodegradation, meteoric water supplies nutrients, and oxygen and bacteria attack the lighter alkanes (straight chains) by oxidation, leaving the more complex compounds such as resins and asphaltenes behind (Box 1). This is the most common mechanism for shallow heavy oils.

In contrast, in deep reservoirs, anaerobic alteration can take place. In this case, the lighter alkanes are reduced to methane. This produces the seemingly contradictory result of producing heavy oils but the associated gases become lighter. A completely different potential mechanism involves the precipitation of asphaltenes. The solubility of asphaltenes in crude oil is strongly pressure dependent. As oils migrate, or the reservoir is slowly raised from greater depths, asphaltenes drop out of solution and form tar mats. Heavy oil rims or mats may be much more common than expected, due to the difficulty in distinguishing these in standard logs.

Unfortunately, many of the geophysical properties of heavy oils are complex and difficult to measure. Table 1 shows the compositions of several heavy oils, both from fluid samples (A) or extracted from rock samples (B).

![Figure 1. Schematic view of the water coating each sand grain (from Mossop, 1979).](image1.png)

![Figure 2. A section from the Resdeln core (Athabasca) shows how the oil sand (black) can be broken by shale lenses (gray).](image2.png)
oils are still poorly understood. As the alkanes decrease and resins and asphaltenes increase, oils become more dense and viscous. Table 1 presents the liquid chromatographic analysis of our heavy oil samples. These are samples from Canada, Venezuela, Alaska, Texas, and California. The high asphaltene and resin contents are recorded in the outcrop samples (Uvalde, Goleta) and are a result of the intensive biodegradation common in the very near surface. The exception is the Tar Mat 1 sample recovered from the deepwater Gulf of Mexico which contains the highest asphaltene content (52%). It has been reported that this mat is a result of anaerobic biodegradation (Tim Lane, personal communication), but the low resin content and high saturates suggest some asphaltene precipitation. The outcrop samples also show relatively high sulfur content (Table 2).

Argillier et al. (2001) conducted a rheological study of several heavy oils and concluded that the asphaltene content was a controlling factor for viscosity. Their data indicate that when the asphaltenes passed a critical weight fraction (around 10%), viscosity increased dramatically. They speculate that the long asphaltene chains begin to congregate and tangle. In contrast, increased resin content actually decreased viscosity. However, a recent analysis by Hossain et al. (2005) found no strong viscosity correlation with asphaltene content. Because viscosity partly controls our seismic velocities, the influence of asphaltenes and resins will need to be examined more thoroughly. Details of velocity and viscosity analysis are presented in following section.

Oil sands. Heavy oil reservoirs tend to be shallow with less effective seals than traditional reservoirs possibly allowing for some light hydrocarbons to escape early in the migration process. Clay contents vary considerably and may have adverse effects on extraction techniques. One important aspect of oil sands is the water versus oil wettability. In some heavy oil reservoirs, the crude oil bonds directly to mineral surfaces. Clay contents vary considerably and may have adverse effects on extraction techniques. One important aspect of oil sands is the water versus oil wettability. In some heavy oil reservoirs, the crude oil bonds directly to mineral surfaces.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample type</th>
<th>Sulfur content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GoM Tar Mat 1</td>
<td>Extract</td>
<td>6.11</td>
</tr>
<tr>
<td>Monterrey Goleta</td>
<td>Extract</td>
<td>5.06</td>
</tr>
<tr>
<td>Anacacho Uvalde</td>
<td>Extract</td>
<td>9.13</td>
</tr>
<tr>
<td>SR-1</td>
<td>Extract</td>
<td>5.27</td>
</tr>
<tr>
<td>Ugnu-1</td>
<td>Oil</td>
<td>1.54</td>
</tr>
<tr>
<td>Ex-1</td>
<td>Oil</td>
<td>2.54</td>
</tr>
<tr>
<td>H-1</td>
<td>Oil</td>
<td>3.68</td>
</tr>
<tr>
<td>CL-1</td>
<td>Oil</td>
<td>3.93</td>
</tr>
<tr>
<td>Pt. Ped. DST3</td>
<td>Oil</td>
<td>2.25</td>
</tr>
</tbody>
</table>

In this section, we will compare some of the world’s major heavy oil reservoirs (Figure 3) and discuss some of the problems faced in producing these reservoirs. There are several prevailing issues that will be seen repeatedly in various fields around the world. The heavy oil reservoirs tend to consist of unconsolidated sandstone which creates two important challenges. The first is how to make accurate rock property (especially porosity) measurements when the core is almost always severely disturbed. The second deals with the fact that sand is often produced with the oil in order to maintain economic levels of production. The creation of wormholes, or high permeability zones created by sand production, can greatly increase well productivity. It is still not well understood how the production of sand with oil will change porosity, permeability, and formation stability.

Another phenomenon that is not yet fully understood is referred to as foamy oil. This is a phenomenon where gas comes out of solution but becomes entrained in the oil phase, and the flow behavior remains that of single phase oil with a higher compressibility (Ehlig-Economides et al., 2000). This behavior can also drastically increase well productivity.

Finally, it is often necessary to perform extensive steam injection to reduce the viscosity of the heavy oils so that it will flow to production wells. Therefore, it will be extremely important to understand and be able to monitor the steam front. This will allow for the appropriate determination of steam paths and the effects of steam injection on the reservoir and production.

Kern River Field, Bakersfield, California. The Kern River Field in Bakersfield, California, was discovered in 1899. There is an excellent discussion of this field in the autumn 2002 Oil Review.
Some facts in that article are summarized in this section. The oil is approximately 10–15° API density and 500–10 000 cp viscosity. The field, with an aerial extent of 6 × 4 mi, is estimated to contain 4 billion barrels of original oil in place (OOIP). However, cold production peaked in the field at just over 40 000 b/d in the early 1900s (Figure 4).

The operator, Chevron, initially placed bottomhole heaters in the wells in the mid-1950s; this was able to slightly increase production. Then, in the 1960s, steam injections proved to be extremely successful. There was a dramatic decrease in oil viscosity and by 1973, 75% of Kern River production was from steam injection projects. Due to this fact, one of the most important challenges in this field will be monitoring heat distribution. Chevron has used a variety of technologies to mon-
itor steam fronts including crosswell EM surveys, electromagnetic propagation tools, and reservoir saturation tools for modeling purposes.

**Ugnu and West Sak fields, North Slope, Alaska.** There is considerable variety in the heavy oils that reside on the North Slope of Alaska. West Sak Field has much lower permeability, slightly higher temperature, and a higher GOR than Ugnu Field. Perhaps the most substantial difference is the fact that West Sak oil has an API gravity value of 17–21°, locating this oil at the lightest end of heavy oils. Meanwhile, Ugnu Field contains oil with API gravity values of 8–12°, classifying this oil as extra heavy oil. There is also a substantial difference in viscosity: 20–90 cp for West Sak oil versus 2000–10,000+ cp for Ugnu oils. Clearly these fluid properties will have a large effect on the challenges faced by operators in producing these areas (Weiss, 2004).

**The unique Alaskan environment also presents a challenge for heavy-oil production in Alaska.** Permafrost can affect steam quality. There are environmental damage concerns that do not exist outside of the fragile Alaskan ecosystem.

**Biodegradation:** The destruction of petroleum and related bitumens by bacteria. At temperatures below 88°C, the petroleum in reservoirs, oil seeps, and asphalt paving, as well as the gasoline in storage tanks are susceptible to bacterial degradation, which converts hydrocarbons to alcohols, acids, and other water-soluble products.

**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 being largely soluble in carbon disulfide.

**Paraffin:** (Alkane) A hydrocarbon with the molecular formula C_{n}H_{2n+2}. It includes normal straight-chain paraffins and branched alkanes, such as methane, ethane, propane, and isobutane.

**Pyrobitumen:** Black to dark brown, hard bitumens that are insusible and relatively insoluble in carbon disulfide. Albeftite, wurtzilite, and impsonite are pyrobitumens.

**Resin:** Petroleum resins are the fraction of residuum that is insoluble in liquid propane but soluble in normal pentane. Plant resins are terpenoids ranging in molecular size from sesquiterpenes (C_{15}) to tetraterpenes (C_{40}). They contain the olefinic double bonds of the isoprene building block that, when exposed to air, causes the liquids to polymerize and oxidize to hard resins. Balsam and mastic are plant resins.

**Duri Field, Indonesia.** Duri Field contains oil that has 20° API gravity, meaning it is light relative to most heavy oils and will have different properties than the extra heavy oils referenced elsewhere in this paper. For example, it has a fairly low viscosity and tends to have a higher GOR. The oil is still heavy enough to make production a challenge, and primary production peaked in this field at 65,000 b/d in the mid-1960s. It was thought that ultimate recovery would be only 7% of OOIP.
The heavy oil in Canada displays a range of API gravities between 8.5° and 15°. One very difficult problem faced in the production of Canadian heavy oils is its high viscosity. Although values as low as 100 cp can be found, the surface deposits of Athabasca reach viscosity values of >1 million cp. Dusseault noted that even after all parameters (T, p, µ, k) have been corrected for, Canadian oils are still notably less mobile than Venezuelan oils. This may be due to the fact that Canadian oils have substantially higher asphaltene content in general.

Another interesting characteristic of Canadian reservoirs is that the pore pressure tends to be about 15% less than hydrostatic pressure. This means that less gas will be present in solution with Venezuelan oils. Therefore, gas exsolution will not be such a large energy drive in Canadian reservoirs. Finally, Canadian reservoirs tend to have permeabilities on the range of 0.5–5 darcy, which is significantly lower than Venezuelan reservoirs.

Due to the difficult nature of producing the oils in Canada, many new technologies have been developed here. Horizontal well drilling was pioneered by the Canadian oil industry. CHOPS (cold heavy-oil production with sand) is a popular production approach where sand is encouraged to enter the well rather than blocked by screens or gravel packs. This method has several advantages because permeability is increased and plugging near the wellbore is prevented.

SAGD, a relatively new approach to production, consists of drilling two parallel horizontal wells—one used for steam injection, the other used for oil production (Figure 5). The idea is that the heated steam will rise while water and heavy oil will flow downward due to gravity flow. Once again, monitoring the steam front and its effects on the formation become an important consideration.

Faja del Orinoco, Venezuela. Venezuela also has extremely large heavy-oil deposits with an estimated OOIP in place of 1.2 trillion barrels. Due to more favorable reservoir conditions than Canada, horizontal wells have been the major technology used in Venezuela. The wells often take on very complex geometries (Figure 6). Another common procedure is to inject lighter oils into the wells in an attempt to lower the viscosity of the heavy oils. Other technologies may be increasingly employed in the near future if production slows.

The oil in the Faja del Orinoco ranges in oil density values from 8.5° to 10° API. As previously stated, the major difference between Venezuelan and Canadian heavy oils are the viscosity values found in each location. Venezuelan oil ranges from 1000 to 5000 cp. This is partially because the Canadian Athabasca producing sands reside at a much shallower depth than the Faja del Orinoco producing sands (Table 3). Therefore, lower formation temperatures exist in the Athabasca reservoirs. However, even with all other parameters set equal, Canadian oil still has a much lower viscosity than Venezuelan oil. This may be due to lower asphaltene content in Venezuelan oil. In general, permeability in the Venezuelan reservoirs ranges from 2 to 15 darcy.

In the future it may be important to experiment with new technologies beyond horizontal drilling in order to maximize production in the Faja del Orinoco. Three-dimensional imaging using seismic data has also proved challenging in this area. It is still not entirely understood why seismic data are not very diagnostic in this region even at relatively shallow depths.

Other significant heavy oil deposits worldwide. There are several very large heavy-oil deposits in eastern Utah that are estimated to contain more than 8 billion barrels of 8–14° API oil in place (Schamel and Baza, 2003) in fields such as Sunnyside, Circle Cliffs, Asphalt Ridge, and the Tar Sand Triangle. In addition to the technical challenges of producing this heavy oil, environmental concerns and land access have created challenges for producing these reserves.

Heavy-oil reserves were discovered in the Bikaner-Nagaur Basin in India in 1991. The estimated OOIP is 14.6 million tons. PDVSA and Oil India Ltd. (OIL) were expected to start drilling for heavy oil in August 2005. The heavy oil in the North Cambay Basin in India is difficult to transport because of its high viscosity (10 000–16 000 cps). Oil-in-water emulsions have been proved to reduce viscosity by as much as two orders of magnitude.

In Brazil, special technological challenges will be faced in many heavy-oil fields because they are located in an offshore environment. This makes implementing thermal technolo-
gies such as SAGD extremely challenging and CHOPS uneconomic (Trindade and Branco, 2005). The heavy oil in this area tends to be of a lighter variety, around 15–20° API. A discussion of the challenges faced in developing this area can be found in Trindade and Branco’s paper from the SPE Latin American and Caribbean Petroleum Engineering Conference in June 2005. Some of the challenges are listed here:

- drilling of extended horizontal wells in a deepwater environment
- controlling sand production
- economic means of enhanced recovery (specifically artificial lift)
- economic separation of the heavy oils on offshore platforms

Additionally, there have been some reports of heavy-oil discoveries in the Bohai Sea of China, which has reserves estimated at 1.3 billion barrels. CNOOC’s Luda heavy-oil field, which came on production in 2005, is producing about 40 000 b/d. There has also been heavy-oil production from Liahe, Shengli, Xinjiang, and Henan fields (He et al., 1995). There are most likely many other heavy-oil deposits that have not yet been explored around the world.

Conclusion. Several known properties of many large heavy-oil deposits around the world have been summarized in this paper (Table 3). As can be seen, the summary is still incomplete, especially when it comes to properties such as wettability. It is difficult to find thorough discussions on the heavy oils of China, India, and deepwater Brazil, and there are probably heavy-oil deposits in many parts of the world that have not yet been discovered. As alternative energy resources become increasingly important in the near future because of declining conventional reserves, it will be imperative to quantify the properties of heavy oil, one of the largest alternative fuels that remain largely unexplored.


Appendix: Early application of heavy oils. Knowledge and use of heavy oils has persisted since antiquity. For example, so many tar seeps were common around the Dead Sea, that it had an alternative name associated with heavy oil. From Smith (1935):

“Along the shore are deposits of sulphur and petroleum springs. The surrounding strata are rich in bituminous matter, and after earthquakes lumps of bitumen are found floating on the water so as to justify its ancient name of Asphaltitis.”

Bitumen is petroleum hardened by evaporation and oxidation (Dawson, Modern Science in Bible Lands, 1889). The bituminous limestone, which burns like bright coal, is the so-called Dead Sea stone from which articles are made for sale in Jerusalem and Bethlehem. The floating lumps probably are from petroleum springs in the seabed. These springs were more common in ancient times. Genesis says the Vale of Siddim was wells—wells, i.e., full of wells, of bitumen.

It is suggested that the conflagration that consumed the legendary towns of Sodom and Gomorrah was a result of combustion of the local heavy-oil deposits.

“And Yahweh rained upon Sodom and Gomorrah sulphur and fire—from Yahweh, from the heavens—and He overturned these cities, and all the Circle, and all the inhabitants of these cities, and that which grew upon the ground. And Lot’s wife looked back as they fled to Sear and became a pillar of salt. And Abraham looked down upon Sodom and Gomorrah, upon all the land of the Circle, and saw, and, behold, the smoke of the land went up like the smoke of a furnace.” (Genesis 19:24-28).

Again from Smith (1935):

“Some have taken these words to describe such an eruption as that of Vesuvius upon Pompeii. But there is no need to invoke the volcano, and those are more in harmony with the narrative, who judge that in this bituminous soil took place one of those terrible explosions and conflagrations, which have broken out in the similar geology of the oil districts of North America. In such soil reservoirs of oil and gas are formed, and suddenly discharged by their own pressure or by earthquake. The gas explodes, carrying high into the air masses of oil which fall back in fiery rain, and are so indistinguishable that they float afire on water. Sometimes brine and saline mud are ejected, and over the site of the reservoirs are tremors and subsidence. Such a phenomenon accounts for the statements of the narrative.”

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