14 APPENDED DOCUMENTS

14.1 Appendix 1: ***CANADA'S OIL SANDS AND HEAVY OIL DEPOSITS***

Vast deposits of viscous bitumen (~350 x $10^9 m^3$ oil) exist in Alberta and Saskatchewan. These deposits contain enough oil that if only 30% of it were extracted, it could supply the entire needs of North America (United States and Canada) for over 100 years at current consumption levels.

The deposits represent "plentiful" oil, but until recently it has not been "cheap" oil. It requires technologically intensive activity and the input of significant amounts of energy to exploit it. Recent developments in technology (horizontal drilling, gravity drainage, unheated simultaneous production of oil and sand, see attached note) have opened the possibility of highly efficient extraction of oil sands at moderate operating cost. For example, the average operating costs for a barrel of heavy oil was CAN$10-12 in 1989; it was CAN$5-6 in 1996, without correcting for any inflation. This triggered a “mini-boom” in heavy oil development in Alberta and Saskatchewan until the price crash of 1997-1998. However, reasonable prices have triggered more interest in the period 2000-2001, and heavy oil and oil sands development is accelerating. At present, heavy oil production is limited by a restricted refining capacity (upgraders designed specially for the viscous, high sulfur, high heavy metal content crude oil), not by our ability to produce it in the field.

Currently (2002), nearly 50% of Canada's oil production comes from the oil sands and the heavy oil producing, high porosity sandstone reservoirs which lie along the Alberta-Saskatchewan border. This is a higher percentage of the national consumption produced from heavy oil (< 20° API gravity) than any other country in the world. It will likely slowly grow and rise above 50% in the future, even as new offshore conventional oil in eastern Canada comes into production, because conventional oil reservoirs in Alberta continue to decline in production.

Resources are found mainly in high porosity (28-32%) quartz arenites to arkosic sands that cover large areas and lie up-dip from the purported source rocks to the SW. However, there are vast amounts of heavy oil as well (about 15% the oil volumes of the oil sands) in fractured carbonate rocks of 10-14% porosity underlying a large triangular region of north central Alberta. In addition, there is a large amount of heavy oil (less viscous that the bitumen of the major oil sands deposits) in a series of thinner blanket sands and channel sands extending all the way from Suffield Alberta to zones overlying the Cold Lake Oil Sands near Bonnyville, and extending well into Saskatchewan (100-120 km east of the border in some areas). The latter deposits, called the “heavy oil belt”, are currently the sites of most development attention because the oil is less viscous and it can be produced by a technology called "CHOPS" (Cold Heavy Oil Production with Sand).

The arenaceous rocks in which the heavy oil deposits are found were laid down in 110-100 MYBP (Middle Cretaceous), buried (to a maximum depth that is probably 500-750 m deeper than today), and oil ingress purportedly occurred at about the time of maximum burial depth (~60-70 MYBP). Since that time, the region has been characterised by erosion as the Cretaceous sea retreated, and the Laramide Orogeny came to dominate the tectonic fabric of the region. In fact, to this day, the maximum horizontal stress, even in the Athabasca oil sands, is pointed directly towards the mountains, despite the thinness of the sedimentary cover and a distance exceeding 500 km. This reflects the continental drift direction and the fabric of the Rockies, but the mechanism by which these tectonic stresses can be transmitted into soft sediments such a distance away is not understood.

The source rocks for the oil sands are supposedly from the Cretaceous and Jurassic shales in the Alberta Syncline 300-700 km to the SW. Rapid sedimentation of organic rich argillaceous material caused large flow volumes to be generated as the result of compaction. Deep burial (probably in excess of 1500 m of sediments have been removed from the axis of the Alberta Syncline) took the kerogenous source rocks into the right T, p domain for organic diagenesis to occur, and gas and oil were generated from the kerogen.

Regional flow from the SW to the NE developed, approximately at 90° to the mountains, as the flow direction was imposed by the layered permeability structure of the unfaulted and unfolded sediments away from the disturbed belt, combined with the elevation difference between the depositional site and the mountains. The mountains essentially acted (and act today) as the recharge region for all the deep groundwater flow in the WCSB, even though some of these waters in sandstones are older than 40 MYBP. However, a particularly permeable path existed, and flow, was concentrated in the permeable (karstic) Pre-Cretaceous unconformity which underlies all of the WCSB. This is the most permeable path in the Basin, and potentiometric data indicate that even today it is a major pathway for deep groundwater.

Probably the oil migrated into the carbonates (Devonian age) at the same time as it migrated into the sands, as it appears to be geochemically similar, and these rocks are also up-dip of the source rocks. However, a fundamental difference between the sands and the carbonates is the nature of flow through the strata. The sands are unfractured, and displacement during oil and gas invasion was clearly by porous medium flow. Low permeability streaks (silty or clayey bands) have lower oil saturations, and are sometimes oil-free. The carbonate reservoirs, however, have a dual porosity system: matrix porosity in the blocks is 10-14%, but about 1% of the porosity exists as a highly permeable fracture network (joints), and this was undoubtedly the ingress path for hydrocarbons, with the partial saturation of the matrix occurring more slowly. These different fabrics have substantial implications on recovery technology. The carbonate reservoirs directly underlie the basal Cretaceous deposits of the McMurray Formation and the Clearwater Formation (the McMurray Formation is locally absent from a paleotopographic high running NNE-SSE about 100 km west of Ft. McMurray).

The oil that invaded and saturated the sands flowed under conditions of higher pressure gradients and higher temperatures than today. This condition existed for a number of reasons:

- The rocks were more deeply buried, therefore the temperature was higher.
- The continued compaction during deep burial generated fluid expulsion from the rocks themselves, providing substantial flow volumes (along with the elevation effect).
- Generation of hydrocarbons generated excess pressures in the Alberta Syncline region, aiding the driving forces.
- Mineral transitions, mainly smectite→illite, but perhaps also gypsum→anhydrite and calcite→dolomite, aided in maintaining the pore pressures high and provided driving forces.

Even today, the deeper parts of the Alberta syncline are somewhat overpressured; at depth (>3000 m), pressures about 50% above hydrostatic are encountered regularly.

As the oil approached the surface, moving gradually up-dip, it started to interact with oxygenated waters from more local groundwater circulation cells. This laving with surficial waters, which contained minute amounts of dormant bacteria led to:

1. Biodegradation of the oil as the living organisms consumed the lighter hydrocarbons, generating energy for their existence, methane (which has largely escaped), various hydrocarbons, many of them with aromatic groups, and high molecular weight polysaccharides from their cell walls. (The latter causes difficulties in extractive processes.)
2. Loss of light ends, which evaporated off or were carried away in the circulating groundwaters.
3. Fixation of substantial amounts of sulphur compounds in the oil, such that the sulphur content of these crude oils is as high as 4% in some areas, an exceptional value.
4. Fixation of significant amounts on heavy metals, particularly Nickel and Vanadium, in unusual molecular structures in the large organic molecules.

Today, all the major oil sand reservoirs that are shallower than about 200 metres have no free gas cap, although there is CH_4 (and a bit of CO_2) in solution in the oil equilibrated at or just below the pore pressure. Deeper reservoirs, as shallow as 250-300 m south of Ft. McMurray, Alberta, have small gas caps, many of which are currently being exploited.

(Incidentally, the topic of biodegradation is fascinating, as it appears that certain types of bacteria can decrease in size by 95% or more, comprising genetic material only, forming a "spore" which only reactivates if food and energy conditions are appropriate. There remain at least several excellent biogeochemical theses to be done in this area, once a visionary enters the field.)

A major factor in the development of the major reservoirs which we now call the Athabasca and Cold Lake Oil Sands was the pre-Cretaceous salt solution activity. This involved the dissolution of the Prairie Evaporites salt beds along a NNE-SSW front extending all the way from Great Slave Lake in the Northwest Territories to south west central Saskatchewan, and on into Manitoba. This solution involved slow collapse of the overlying carbonate rocks and opened the joints, caused local mild folding, and so on. It also created local closure on strata in some areas where the solutioning continued after the region became a depositional centre in Cretaceous times. The heavy oil and oil sands of Alberta lie mainly along the axis of this feature of the Western Canadian Sedimentary Basin.

The sands (sandstones?) are 98% uncemented (referred to in the petroleum industry as "unconsolidated sandstones"). It is apparent that the ingress of bitumen has essentially stopped diagenetic processes, and the sands do show strong evidence of the early effects of pressure solution and recrystallization, but true cementation is quite rare, and significant calcite cemented zones are rare. All the deposits contain concretionary beds, and, based on fragmental organic detritus and other evidence, these likely represent periods of exposure of the strata during the sedimentation processes to atmospheric oxygen rich conditions, generating complex carbonate cements (Fe-Mg-Ca carbonates). During sedimentation of these relatively coarse-grained facies, water depth was shallow, therefore sea level changes could easily expose the sedimentary surface to the air and sub-aerial processes could arise.

The bitumen does not flow under "normal" conditions; in general, it must be heated to flow, or else sand must be produced along with the oil ("sand production", now referred to in the industry as CHOPS). This means that energy has to be added, or special steps taken to promote production of oil. In all of the deposits, an ordinary well, without sand production, will make no more than 0.5 to 3 barrels per day (1 m^3 » 6.4 oil field barrels of 42 gallons each).

The oil sands exist in four major deposits (other than the carbonates):

The **Athabasca Oil Sands**, more or less centred around the airport 15 km south of Ft. McMurray and taking the shape of a N-S elongated ellipse, is by far the largest deposit, probably containing in excess of 150 x $10^9 m^3$ oil. The deposit is in sedimentary arenaceous deposits that are classified as an estuarine accretion plain; detrital matter mainly from the shield; quartzose mineralogy (» 95%) with micaceous material. Kaolinitic-illitic clay mineralogy is typical, and minor feldspars and chert fragments are present. The clay mineralogy in the McMurray Formation reservoir changes from bottom to top in an interesting manner: vermiculite occurs at the bottom (a residual material from the long sub-aerial weathering on the carbonate surface) but disappears within 10 m, and smectite, clearly of volcanic ash degradation origin, begins to be present as a minor constituent about 10 metres from the top of the Formation. Of course, smectite is the dominant clay mineral in higher strata. The bitumen is highly viscous and is often of a specific gravity greater than water (API gravity less than 10°). We know that the oil invaded when the gravity was less than water because oil overlies oil-free water sands in many areas. At present, the depth of burial is 0 m to 600 m. The reservoir is exclusively in the McMurray Formation, and is up to 80-85 m in some areas. The McMurray sequence displays excellent fining-upwards granulometry, with pebble conglomerates (channel fill in rapidly flowing streams) found near the base, and laminated fine-grained sands and clayey silts at the top. Commonly, over most oif the area, there is a thick (2-8 m) band of oil-free clayey silt about two-thirds of the way from the bottom, and this barren zone causes problems sometimes for communication of thermal processes with the upper reservoir, which is less rich in oil on a weight basis. The aggregate thickness of oil saturated material varies from 15-20 m to in excess of 65 m in some localities; bitumen saturation in the oil-rich zones are on the order of 90% of pore volume, 14% by total weight. In the leaner zones in the top of the Formation, the oil content averages perhaps 6-9% by weight. The McMurray Formation overlies the karstic carbonates and there is a +200 million year hiatus, an unconformable one, between the gently-folded carbonates, and residual deposits up to 40 m thick are found in the low parts of the pre-Cretaceous erosion surface, with thin paleosols on the high points, where it has not been eroded off by the strong streams that laid down the coarse-grained lower McMurray Formation sediments. The McMurray Formation is conformably overlain by the Clearwater Formation, which comprises smectitic-illitic-kaolinitic clay shale and silty clay strata up to 50 m thick.

The **Cold Lake Oil Sands** is of a roughly circular shape approximately centred about 20 km north of Bonnyville, Alberta, contains probably in excess of 60 x $10^9 m^3$ oil in sedimentary arenaceous deposits that are classified as deltaic deposits. It has good lateral continuity, but as in any clastic sequence, there are regions where it is a thick uniform sand (along the delta axis), and others where it is cut by many silty and clayey strata (off the delta axis). The reservoir is the Clearwater Formation, which was argillaceous in the Ft. McMurray region, but here, further south, is a fine-grained and relatively uniform sand. The detrital matter provenance is mainly from the west, and is associated with the eastwards migration of the divide between shield and cordilleran sediment provenance. In general it is of litharenitic composition with quartz (>40%?), feldspars (10-30%?), siliceous (felsic) volcanic glass shards displaying various degrees of alteration and recrystallisation (5-20%?), lithic fragments (5-15%?), and with a smectitic-illitic clay mineralogy. As mentioned, smectite only appears in the sedimentary column in very late McMurray times, and becomes much more common in the Clearwater Fmn. It is associated with the initiation of Cretaceous vulcanism to the south-west, Crowsnest Pass area and points SW, and the clays were transported eastwards in streams, or were deposited directly as felsic volcanic ash which geochemically altered to smectite. The bitumen is highly viscous but considerably less so that the Athabasca oil sands, somewhat less sulphurous, and the depth of burial is 400 m to 600 m. The Clearwater Formation is the dominant reservoir and the thickness of oil saturated material varies from 15-20 m to in excess of 35 m. In the southern part of the Cold Lake oil sands deposit, the overlying Grand Rapids Formation can be an important reservoir.

The **Wabasca** (or Wabiskaw) **Oil Sands** contain probably in excess of 15 x $10^9 m^3$ oil in sandstone deposits classified as barrier bar and beach glauconitic sands. The deposit lies above the western part of the Athabasca Oil Sands and extends westwards somewhat beyond the McMurray Formation edge. In many regions, the Wabasca is oil rich and it also overlies the oil-rich McMurray, forming two stacked reservoirs. Detrital matter arrived mainly from the west (but mixed nonetheless with a small component of sediments from the shield, as evidenced by a trace heavy mineral suite diagnostic of igneous rocks). It has a litharenitic composition with quartz (>40%?), feldspars (10-30%?), glauconitic pellets (representing the alteration product of a lot of piscine faeces??); volcanic shards (3-10%?), lithic fragments, and a clay mineral suite characterised by smectitic-illitic clay minerals. The bitumen is highly viscous, similar to the Athabasca Oil Sands deposit. The present depth of burial is 100 m to 700 m. The Wabasca is classified as the lowermost Member of the Clearwater Formation, and therefore overlies the McMurray Formation conformably, although it is invariably separated from the McMurray reservoir by a minimum of 6-8 metres of clay shales and silts. The reservoir and the thickness of oil saturated material varies from 0 m to perhaps as much as 8-10 m in some cases. The overlying argillaceous part of the Clearwater Formation forms the "caprock".

The **Peace River Oil Sands** probably contains in excess of 30 x $10^9 m^3$ oil in sedimentary arenaceous deposits classified as beach sands laid down against the protruding sediments of the Peace River Arch, a gently up-doming feature in the north-east and central part of Alberta. The detrital matter provenance was exclusively from the west (but mixed), litharenitic composition with quartz (>40%?), feldspars (10-30%?), glauconitic pellets (representing the alteration product of a lot of piscine faeces??); volcanic shards (3-10%?), lithic fragments and minor smectitic-illitic clay minerals. The bitumen is highly viscous, similar to the Athabasca deposit, the depth of burial is 500 to 700 m, and the reservoir is the

Bluesky-Gething Formation which is about the same age as the McMurray Formation. The thickness of oil saturated material varies from 5 m to perhaps as much as 25 m in some cases.

The **Heavy Oil Belt** straddling the border of Alberta and Saskatchewan is a series of thin (5-18 m) blanket sands and many channel sands, as thick as 35 metres in some areas along the axis of old river channels. Some of these channels are 30-40 km long. The Formation names change in various localities, but the major sand units for the channel deposits and blanket sands in the Lloydminster area called the Waseca, GP, Cummings, Sparky, Lloydminster, Grand Rapids and so on. The oil is considerably lighter in density (11-18°API gravity) and of much lower viscosity as compared to the major oil sands deposits, therefore it is easier to produce, which is why it is the focus of much of the recent increases in heavy oil production.

Finally, the **Carbonate Triangle** is a triangular-shaped deposit of heavy oil in the fractures and porosity space of jointed limestones and dolomite, and contains perhaps as much as 15% of the total heavy oil in Alberta. This was emplaced by up-dip migration, but into older rocks, along the pre-Cretaceous unconformity which rises to the NE. The petroleum is of the same age as that in the other heavy oil and tar sand deposits, also biodegraded to a more viscous and immobile mass. In these carbonates, probably only steam-assisted gravity drainage is a viable technology for economic extraction.