Unusually physical and chemical characteristics of oil sands from Qaidam basin, NW China

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(Received March 5, 2004; Accepted July 29, 2004)

Gas chromatography (GC), gas chromatography-mass spectrometry (GC/MS), supercritical fluid chromatography (SFC), elemental analysis, infrared absorption spectroscopy (IR), thermal analysis (TG/DTA), Rock-Eval pyrolysis, as well as viscosity and density analysis revealed that oil sands from Qaidam basin, Qinghai Province of China, are highly concentrated in light components (≤C23), with saturated hydrocarbons (including most n-alkanes) comprising between 49.6 to 71.4% of total organics (wt.%). Their physicochemical characteristics are very similar to those of heavy oils, rather than other oil sand bitumens. The above analyses suggest that Qinghai oil sands originate from a terrigenous source, similar to oils from the surrounding area. Additionally, the existence of n-alkanes shows that the oil sands are weakly biodegraded, and that the formation of these unusual oil sands is related to the particular geographic/climatic conditions of Qaidam basin. No other known oil sands with chemical composition and distribution similar to that in Qinghai have been documented. Exploitation should be initiated with drilling wells followed by open pit mining.

Keywords: oil sand, chemical composition, physical property, genesis, Qaidam basin

INTRODUCTION

Oil sands are sedimentary rocks that contain bitumen or heavy oil, and are also known as tar sands or asphaltic sands. Oil sand bitumen and/or heavy oil are formed by low temperature alteration of crude oil, by biodegradation, water washing or light-hydrocarbon volatilization, thus resulting in concentration of high molecular weight hydrocarbons and heteroatomic compounds of resins and asphaltenes. Oil sand often exists at the edge, and within shallow layers of a basin, and may be exposed at the surface by tectonic uplift (Chilingarian and Yen, 1978; Niu and Hu, 1999).

Oil sands are an important component of the global petroleum resource base. Countries rich in oil sands, such as Canada and Venezuela, have tried different exploitation methods and uses of oil sands since the early 20th century (Chilingarian and Yen, 1978). Asphalt and synthetic oil extracted from oil sands now comprise more than a quarter of the total liquid petroleum consumption in Canada. Though oil sand utilization is currently limited to a small number of countries, oil sand deposits may be recovered as a supplementary resource (Chilingarian and Yen, 1978; Niu and Hu, 1999). Therefore, investigation and exploitation of oil sands as an auxiliary resource is important.

China also has widely distributed and abundant oil sands (Niu and Hu, 1999). However, investigation is only in the preliminary stages and so far no exploitation has been carried out. According to Guo and Qian (1998), the physical and chemical characteristics of oil sands in the Xinjiang and Inner Mongolia Provinces are similar to those of Athabasca, Canada, and Utah, USA. In contrast, we found that the physical and chemical characteristics of oil sands exposed in Qaidam basin, Qinghai Province, are unique. In addition, we also discuss the genesis of this unique oil sand in this paper.

The Qaidam basin is a non-marine, petroliferous basin on the northeastern margin of the Tibet Plateau. Its area is about 121,000 km², bound by the Aerjin Mountains, the Qilian Mountains and the Kunlun Mountains (Fig. 1). The main potential source rocks are sedimentary sequences from Tertiary saline lacustrine deposits and Jurassic freshwater lacustrine or terrestrial strata. There are three petroleum systems of Jurassic, Tertiary and Quaternary in the basin (Ritts et al., 1999; Hanson et al., 2001; Wang, 2003). Qinghai oil sands are located in the Mangya secondary depression in western Qaidam basin, which belongs to the Tertiary petroleum system. The Tertiary is the only source rock in this area (Wang, 2003; Xu et al., 2003). Most of the oil fields are located in the western depression of the Qaidam basin (see Fig. 1).

Exposed oil sands in Qinghai were discovered in 1947.
The reservoir sandstone of the lower Youshashan Formation (N$_2^1$) of the Tertiary was uplifted to exposure by a strike-slip reversed fault in the geologic era of N$_2^3$ to Q, and a cliff with 150 m apparent bed thickness was formed. The Oil Sand Hill is insulated from the surrounding oil fields. All N$_2^1$ strata in the Oil Sand Hill are almost flat-lying, and well-exposed. So, there is no new crude oil to supply after it formed. The Oil Sand Hill is pristine, i.e., there has been no recent tectonic movement. According to Lei et al. (1998), there are 53 layers of medium or fine-grained oil sands in the exposed rock, which is divided into 133 layers classed by lithology. Among them, the 13th, 15th, 24th, 30th and 68th oil sand strata are the main and representative reservoir sandstones. The oils nearby originate from terrigenous organic matter and are still of lower maturation. Their physical characteristics are also similar to common oils from many other oil fields in China (Wang and Chen, 1988; Gao and Chen, 2002).

**EXPERIMENTAL**

**Sample collection**

Five samples of exposed oil sands were taken from different layers of the lower Youshashan Formation (N$_2^1$) of Tertiary in Qinghai Oil Sand Hill (see Table 1). We used a small drilling rig for sampling, and obtained cores of 40 mm diameter. Oil sands from 0.2 m to 2 m deep were crushed with a cracker and then sieved with a 0.21 mm diameter sieve for thermal analysis (TG/DTA), Rock-Eval pyrolysis and extraction.

A modified Soxhlet extractor was used to extract asphalt and heavy oil from the oil sands. Solvent used in this process consisted of 74% toluene and 26% isopropyl alcohol (wt.%). A small amount of the extracts were used for distillation simulations, infrared analysis and elemental analysis, while most of the extracts were used for separating saturated hydrocarbons, aromatics, resin and asphaltene on a silica gel/alumina column chromatograph using n-heptane, benzene and methanol, respectively.

**Analyses**

Density of oil was measured in a SY-I oil densimeter made in China, according to Chinese standard GB1884-83; while a specific gravity bottle was used for measuring the density of oil sands, using Chinese standard GB2540-88. A glass capillary viscosimeter BMN-1 made in China was used for oils, according to Chinese standard SY3607-82.

Rock-Eval pyrolysis: a programmed pyrolysis instrument, Rock-Eval III, with 100 mg oil sand specimen and helium gas as carrier at flow rate of 100 mL/min and FID detector, heating rate being 10°C/min from 200 up to 600°C. The weight loss was calculated from FID record.

Thermal analysis (TG/DTA): a Mettler TA1 thermogravimeter, with 20 mg oil sand specimen and air as carrier (50 mL/min), heating rate of 10°C/min, temperature range from ambient temperature to 600°C.

Elemental analysis of extracts was carried out on a Perkin Elmer 240B elemental analyzer. A Nicolet 170SX was used for infrared spectrometry of extracts.
For distillation simulations, the US standard ASTMD-2887 was used. HP-5880 gas chromatograph was used with OV-1 column. Temperature in gasifying chamber and of detector with hydrogen flame was 380°C. Temperature of column rose at speed of 10°C/min to reach 340°C using N₂ as carrier and CS₂ as sample solvent, sample amount being about 0.4 mL.

HP-SFC instrument (Model 5700) was used for supercritical fluid chromatography (SFC) analysis of saturated hydrocarbon components, a double detecting system (FID and UV) with selectivity and high sensitivity against hydrocarbons. The analyzing conditions were: 5 m × 10 m DB-5 column (0.2 μm liquid film), CO₂ fluid phase, with column temperature of 150°C and pressure of 13.8–38.0 MPa, feeding amount being 0.1 mL, split ratio 1:5. An entire column flow limitor was used.

Gas chromatographic analysis of saturated hydrocarbons was performed with a Shimadzu model GC-7A; the stationary phase was SE-54 (30 m × 0.25 mm i.d.), split ratio 20:1, heating rate being 4°C/min from 130 to 280°C, with 280°C injection port and helium as carrier. GC/MS analysis of saturates was carried out on a Finnigan-MAT TSQ-45 GC/MS/MS combined instrument, with an identical GC column and conditions as for GC analysis. MS conditions were: ion source 250°C, electron energy 70 eV, electron multiplier 1300 eV and 250 μA, a total scan time of 0.95 sec.

GC/MS analyses of aromatic hydrocarbons were performed using a Finnigan-MAT TSQ-45 GC/MS/MS instrument. GC conditions were: 30 m × 0.25 mm i.d. SE-54 column, helium carrier gas (6.89 × 10⁴ Pa), split ratio 20:1, gasification chamber 300°C; after an initial period (1 min) at 100°C, the column was temperature programmed from 100 to 300°C at 3°C/min, then keeping the temperature 15 min. MS conditions were: +/EI/Q, electron energy 70 eV, transfer line temperature ca 270°C, ion source temperature 180°C, and compounds identified using standard samples, NBS spectrum warehouse and data for retention index.

**RESULTS AND DISCUSSION**

**Analytical results**

In terms of group composition, the saturated hydrocarbon contents of Qinghai oil sands are very high—49.6–71.4%, while resin and asphaltene contents are rather low—25.6–45.6%, the ratios of hydrocarbon/non-hydrocarbon are 1.19–2.91, and the ratios of aromatics/saturates are 0.04–0.26 (see Table 2). Infrared analysis confirms that Qinghai oil sands are highly concentrated in saturated hydrocarbons. The spectrum of extracts shows strong absorption of saturated hydrocarbons (e.g., 2960 cm⁻¹, 2860 cm⁻¹, 1460 cm⁻¹, 1380 cm⁻¹ and 720 cm⁻¹), and much less intense absorption of

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**Table 1. Qinghai oil sand samples in the lower Youshashan formation (N₂₁) of Tertiary**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Oil sand layer No.</th>
<th>Density of oil sand (g/cm³)</th>
<th>Porosity (%)</th>
<th>Oil content (%)</th>
<th>Density of oil (g/cm³)</th>
<th>Oil viscosity (Pa•s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>2.13</td>
<td>24.0</td>
<td>5.83</td>
<td>0.900</td>
<td>0.818</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>2.11</td>
<td>28.8</td>
<td>5.50</td>
<td>0.920</td>
<td>0.857</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>2.17</td>
<td>21.9</td>
<td>2.83</td>
<td>0.923</td>
<td>0.826</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>2.08</td>
<td>20.4</td>
<td>6.51</td>
<td>0.919</td>
<td>0.820</td>
</tr>
<tr>
<td>5</td>
<td>68</td>
<td>2.06</td>
<td>24.5</td>
<td>6.10</td>
<td>0.910</td>
<td>0.819</td>
</tr>
</tbody>
</table>

Density and viscosity are measured at 20, 24°C respectively.

<table>
<thead>
<tr>
<th>Sample No. or Location</th>
<th>Saturated HC (%)</th>
<th>Aromatic HC (%)</th>
<th>Resin (%)</th>
<th>Asphaltene (%)</th>
<th>Aromatics/Saturates</th>
<th>Hydrocarbon/Non-hydrocarbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.4</td>
<td>3.0</td>
<td>23.5</td>
<td>2.1</td>
<td>0.04</td>
<td>2.91</td>
</tr>
<tr>
<td>2</td>
<td>50.5</td>
<td>3.9</td>
<td>44.5</td>
<td>1.1</td>
<td>0.08</td>
<td>1.19</td>
</tr>
<tr>
<td>3</td>
<td>63.3</td>
<td>2.9</td>
<td>31.8</td>
<td>2.0</td>
<td>0.05</td>
<td>1.96</td>
</tr>
<tr>
<td>4</td>
<td>49.6</td>
<td>13.0</td>
<td>31.4</td>
<td>6.0</td>
<td>0.26</td>
<td>1.67</td>
</tr>
<tr>
<td>5</td>
<td>70.5</td>
<td>3.9</td>
<td>23.6</td>
<td>2.0</td>
<td>0.06</td>
<td>2.91</td>
</tr>
<tr>
<td>Fengcheng, Xinjiang</td>
<td>41.98</td>
<td>14.71</td>
<td>37.19</td>
<td>6.12</td>
<td>0.35</td>
<td>1.31</td>
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<tr>
<td>Erlian, Innermongolia</td>
<td>22.48</td>
<td>17.11</td>
<td>49.60</td>
<td>10.81</td>
<td>0.76</td>
<td>0.66</td>
</tr>
<tr>
<td>Alberta, Canada</td>
<td>22.0</td>
<td>21.0</td>
<td>39.0</td>
<td>18.0</td>
<td>0.95</td>
<td>0.75</td>
</tr>
</tbody>
</table>

*See Guo and Qian (1998); †see Chilingarian and Yen (1978).
heteroatomic functional groups (e.g., 3200–3600 cm$^{-1}$, 1700 cm$^{-1}$, and 1000–1300 cm$^{-1}$) and aromatic hydrocarbons (3030 cm$^{-1}$, 1600 cm$^{-1}$, and 730–900 cm$^{-1}$) (see Fig. 2a). These are outwith the range of documented compositions. Generally, saturated hydrocarbon components of other oil sands are lower than 30%, most of which are lower than 25%, while the content of resin and asphaltene is significantly higher (mostly >50%) with more aromatic components (Chilingarian and Yen, 1978; Hepler and Hsi Chu, 1989; Guo and Qian, 1998; Gao and Xu, 2002).

The oil sands in Qinghai Province contain more hydrogen and less carbon than common oil sands, the H/C atomic ratio ranging from 1.71 to 1.96 (see Table 3), similar to that of normal crude oil. Such high H/C atomic ratio can only be achieved by the oil sands having a high proportion of saturated chain hydrocarbons.

Comparing our Rock-Eval pyrolysis results with those of oil sands coming from all over the world (Hepler and Hsi Chu, 1989; Gao and Xu, 2002), the first distillation peak of organic matter from Qinghai oil sand at low temperatures is significantly larger, while the second cracking peak at high temperatures (640 K) is very small (see Fig. 3). As for the DTA curve, not only does it exhibit a larger initial peak and a smaller secondary peak, but also the maximum temperatures of both peaks are significantly low compared with Xinjiang and other oil sands (Gao and Xu, 2002). A simulation distillation test reveals that Qinghai oil sands are highly concentrated in light components. Oil sands from Qinghai, contrast with oil sands in Xinjiang, Inner Mongolia and Canada in containing light components distilled at lower temperatures. The accumulated distillate amount of Qinghai oil sands is much higher than oil sands from other countries and regions—43.0–46.1% at 500°C (see Table 4), in fact similar to some normal crude oils. This indicates that the oil quality of Qinghai oil sand is good with high amounts of

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**Table 3. Comparison between elemental analysis results of oil sand bitumen (heavy oil)**

<table>
<thead>
<tr>
<th>Sample No. or Location</th>
<th>C (%)</th>
<th>H (%)</th>
<th>O (%)</th>
<th>N (%)</th>
<th>S (%)</th>
<th>H/C atomic ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No. or Location</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>83.9</td>
<td>13.1</td>
<td>0.9</td>
<td>0.8</td>
<td>1.3</td>
<td>1.87</td>
</tr>
<tr>
<td>2</td>
<td>84.8</td>
<td>12.1</td>
<td>1.2</td>
<td>0.9</td>
<td>1.0</td>
<td>1.71</td>
</tr>
<tr>
<td>3</td>
<td>84.6</td>
<td>12.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.1</td>
<td>1.73</td>
</tr>
<tr>
<td>4</td>
<td>83.4</td>
<td>13.0</td>
<td>1.0</td>
<td>0.9</td>
<td>1.7</td>
<td>1.87</td>
</tr>
<tr>
<td>5</td>
<td>82.7</td>
<td>13.5</td>
<td>1.1</td>
<td>1.1</td>
<td>1.6</td>
<td>1.96</td>
</tr>
<tr>
<td>Fengcheng, Xinjiang</td>
<td>86.05</td>
<td>11.21</td>
<td>1.99</td>
<td>0.3</td>
<td>0.45</td>
<td>1.56</td>
</tr>
<tr>
<td>Erlian, Innermongolia</td>
<td>84.64</td>
<td>10.08</td>
<td>2.34</td>
<td>0.3</td>
<td>2.64</td>
<td>1.42</td>
</tr>
<tr>
<td>Alberta, Canada</td>
<td>83.1</td>
<td>10.6</td>
<td>1.1</td>
<td>0.4</td>
<td>4.8</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Content of sulfur is the result of subtraction.

*aSee Guo and Qian (1998); bsee Chilingarian and Yen (1978).*

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**Fig. 2. Infrared spectra of Qinghai oil sand bitumen. a: oil sand bitumen in more than 0.2 m depth; b: oil sand bitumen on the surface. Note: The intense absorption of B) 2960 cm$^{-1}$, 2860 cm$^{-1}$ (-CH$_2$-, -CH$_3$), E) 1460 cm$^{-1}$, 1380 cm$^{-1}$ (-CH$_2$-, -CH$_3$), G) 720 cm$^{-1}$ [(-CH$_2$)$_n$] of bitumen in depth is much more than those on the surface, while the intense absorption of A) 3200–3600 cm$^{-1}$ (O-H), C) 1700 cm$^{-1}$ (C=O), D) 1600 cm$^{-1}$ (ph-, F) 1200 cm$^{-1}$ (C-O) of bitumen in depth is much less than those on the surface.**

**Fig. 3. The distillation peak of organic matter is significantly higher and cracking peak is very low in Rock-Eval curve of Qinghai oil sand. a: peak intensity curve; b: cumulative weight loss curve.**
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light components, whereas oil sands in Xinjiang, Canada and other areas are comparatively heavy.

Supercritical fluid chromatographic analysis of saturates shows that straight-chain alkanes in Qinghai oil sands range from C\(_5\) to C\(_{45}\) and maximize around C\(_{27}\) (see Fig. 4). Though the content of hydrocarbons eluted before C\(_{20}\) is comparatively low due to volatilization (including that in the processes of extraction and column chromatography) and biodegradation, most of alkanes are C\(_{35}\) or smaller compounds; those larger than C\(_{40}\) are very limited. The chromatogram in Fig. 4 shows that oil sands from Qinghai not only contain abundant saturated hydrocarbons, but they also contain a high proportion of light hydrocarbon components (≤C\(_{23}\)). GC analysis of saturates is consistent with this result and further supports our conclusion (see Fig. 5a), e.g., Pr/Ph = 0.98–1.05, Pr/nC\(_{17}\) = 0.81–0.86, Ph/nC\(_{18}\) = 0.70–0.75, CPI = 1.07–1.13. The clear odd-over-even carbon number predominance of normal alkanes in Qinghai oil sands shows that they originate from terrigenous sources and are still in low thermal maturation, similar to oils from the oilfield nearby (Wang and Chen, 1988; Gao and Chen, 2002). This situation also indicates that Qinghai oil sands underwent little geochemical change. The specific organic chemical components in Qinghai oil sands are very seldom seen in other oil sands. This is one of the most significant features of these oil sands and this has not been reported in other oil sands from other areas. The saturated hydrocarbons in other known oil sands all lack normal alkanes, especially missing low molecular weight n-alkanes and instead possessing mostly branched-chain alkanes and cycloalkanes: this is an inevitable result of biodegradation (Niu and Hu, 1999).

In Qinghai oil sand there are many 1- to 5-ring cycloalkanes (Gao et al., 2001). The highest relative
amounts of terpanes are pentacyclic triterpanes, while bicyclic terpanes, diterpanes and tetracyclic terpanes are also relatively abundant (see Fig. 6). Oleanane and gammacerane were identified (see Fig. 7), and a small amount of C_{29}-dimethyl hopane (i.e., 25-norhopane) was also identified at m/z 177. Further, C_{27}, C_{28}, C_{29} steranes are in high, low, high abundance respectively, with C_{29} steranes dominant (see Fig. 8). The ratios of C_{27}, C_{28}, C_{29} 5α-cholestanes 20R are approximately 32:14:54, while 5α-C_{27}/C_{29} = 0.58–0.63, 5α-C_{28}/C_{29} = 0.25–0.29, and the ratios between hopane and sterane range from 5.1 to 5.5. These results show that Qinghai oil sand bitumen originated from terrigenous organic matter, similar to oils from the surrounding area (Wang and Chen, 1988; Gao and Chen, 2002; Xu et al., 2003). The ratios of 18α(H)-trinorneohopane/17α(H)-trinorhopane (Ts/Tm) are 0.75–
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Fig. 8. Mass chromatogram of m/z 217 steranes reveals that oils from Qinghai oil sand are in lower thermal maturation and possess similar sterane distribution like subsurface oils and Tertiary source rocks around.

0.81, while C_{31} 22S/22(R+S) = 0.52–0.56 and C_{32} 22S/22(R+S) = 0.40–0.44. For C_{27–C_{29}} 5α steranes 20R/20S = 2.2–2.6, C_{29} 5α–20S/20(R+S) = 0.23–0.27. They are also similar to oils from adjacent fields (see Table 5) and further indicate that oils from Qinghai oil sand are at low thermal maturation.

Although the relative concentration of aromatic hydrocarbons in Qinghai oil sand is lower than in other oil sands (see Table 2), many types of aromatic compounds were identified by GC/MS, including naphthalene, phenanthrene, anthracene, chrysene, fluoranthene, benzopyrene, dibenzothiophene, biphenyl, dibenzofuran, fluorine, pyrene, aromatic-sterane series, retene and perylene. The relative abundance of teracyclic compounds is high (about 44.5% of total aromatics), while the relative abundance of naphthalene compounds is much lower (about 0.14% of total aromatics), and heterocyclic aromatics (e.g., benzopyridine, benzopyrrole, benzotheophen, dibenzofuran, etc.) are about 8.50% of total aromatics. The Methylphenanthrene index (MPI: 0.91–0.94), Dimethylphenanthrene index (DPI: 1.05–1.09), and Methylnaphthenic ratio (DNR: 1.40–1.48) (Table 5) are similar to those of nearby source rocks and crude oils (Tuo, 1996).

The physical properties of bitumen and heavy oil reflect their chemical composition. The density of crude oil from Qinghai oil sands is approximately 0.920 g/cm³ (at 20°C) and the crude oil viscosity is about 0.820 Pa•s (at 24°C). Qinghai oil sands have the composition of 2.83–6.51% heavy oil or bitumen, 0.7–1.2% water, 0.9–2.5% minerals and carbon residue and more than 90% sand, mud and clay (wt.%) with the density of 2.06–2.17 g/cm³, porosity of 20.4–28.8%, oil-bearing saturability of 33.1–68.4% and water-lubrication on the grain surface (Gao and Xu, 2002). According to the classification scheme of Wan and Luo (1996) for crude oil, heavy oil and bitumen, the Qinghai oil sands are in the range of common heavy oil and have not reached the range of bitumen. This type of exposed oil sand has not been reported from other parts of the world. Therefore, based on either the chemical components and distribution, or physical properties, oil sands from Qinghai are unique.

Cause of formation

The hydrocarbon composition of Qinghai oil sands clearly show that it formed from petroleum derived from terrigenous organic matter and has experienced biodegradation. As C_{29} steranes mainly come from terrestrial organic matter (Philp, 1985), the high concentration of C_{29} steranes in Qinghai oil sands implies that they are related to petroleum that is derived from terrigenous organic matter. Bicyclic terpanes, diterpanes, tetracyclic terpanes, oleanane as well as perylene are all direct evidence of terrestrial organic matter and gammacerane relates to lacustrine organisms (Philp, 1985; Wang and Chen, 1988). They are all present in Qinghai oil sands. The hopane/sterane ratio of the Qinghai oil sands range from 5.1 to 5.5, with the different abundance of oleanane from the Jurassic source rocks. These organic geochemical characteristics are consistent with the Tertiary petroleum
system in western Qaidam basin (Jiang and Yang, 1998; Jing et al., 2002; Xu et al., 2003). C_{29}-dimethyl hopanes are associated with biodegradation (Philp, 1985) and a low abundance of naphthalene compounds is characteristic of biodegraded crude oils (Niu and Hu, 1999). The regularly distributed straight-chain alkanes, the higher relative abundance of light components and lower heavy components of resin and asphaltene in Qinghai oil sands also suggest low level of biodegradation. The distribution pattern of alkylphenanthrenes from Qinghai oil sands is similar to these of crude oils in the early stage of biodegradation (Niu and Hu, 1999). The original crude oil may be in relatively lower maturity degree, as inferred from the gas chromatogram of saturates (i.e., clear odd-over-even distribution of normal alkanes) and the composition of sterane and terpane, i.e., very high R configuration over low S configuration, and low Ts/Tm ratio (see Figs. 7 and 8). Therefore, although the mechanism of formation of heavy oil in Qinghai oil sands is identical to that of other oil sands in that all are products of concentration and reformation of resin and asphaltene components due to alteration resulting from biodegradation and water washing, the degree of alteration is very different.

The causes that lead to the unique chemical composition and distribution of Qinghai oil sands can only be the specific geographic and climatic environment where they occur, because there is no new crude oil to supply and no recent tectonic movement. The principal environmental factors are: (1) little rain and mostly cloudless days in the entire area of northwest China, resulting in scarce groundwater; (2) very low annual temperature, and existence of permafrost layer; (3) high altitude, up to about 3000 m above sea-level, resulting in lower atmosphere oxygen content. In such conditions, there are a little bacteria and low degree of water washing and oxidation (Gao and Xu, 2002). The poor ground water results in poor circulation of oxygen-rich meteoric water underground, and reduces the rate of water washing, oxidation and biodegradation. Volatilization of light hydrocarbons also limited in extent. Oil sands in other areas occur in places that lack the conditions above. Qinghai oil sands are still at the stage when biological oxidation processes are slow and have not yet reached the stage when hydrocarbons, especially light hydrocarbons, almost disappear, as is the case for oil sands in other areas. Hydrocarbon components (including light hydrocarbons) in Qinghai oil sands, however, have not yet been strongly altered.

The chemical and physical characteristics of oil sand bitumen on the surface are different from those of the oils over 0.2 m deep. Figure 5b is the gas chromatogram of saturates in Qinghai oil sand on the surface. The characteristics are the same as those of other oil sands, and all lack alkanes (Niu and Hu, 1999). The infrared spectra of its extracts possess less intense absorption of saturated

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CPI</th>
<th>Pr/Ph</th>
<th>Ts/Tm</th>
<th>Hopane/Sterane</th>
<th>MIP</th>
<th>DNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.07</td>
<td>0.99</td>
<td>0.75</td>
<td>0.52</td>
<td>0.50</td>
<td>0.55</td>
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<td>0.98</td>
<td>0.75</td>
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<td>0.55</td>
</tr>
<tr>
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<tr>
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<td>0.81</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
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<td>1.03</td>
<td>0.74</td>
<td>0.50</td>
<td>0.51</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Sample 6 is the oil from adjacent fields. See Tao (1996); See Xu et al. (2003).
hydrocarbons (e.g., 2960 cm\(^{-1}\), 2860 cm\(^{-1}\), 1460 cm\(^{-1}\), 1380 cm\(^{-1}\) and 720 cm\(^{-1}\)) and strong absorption of heteroatomic functional groups (e.g., 3200–3600 cm\(^{-1}\), 1700 cm\(^{-1}\), and 1200 cm\(^{-1}\)) and aromatic hydrocarbons (1600 cm\(^{-1}\) and 730–900 cm\(^{-1}\)) (see Fig. 2b), similar to that of Xinjiang and Inner Mongolia oil sands (Guo and Qian, 1998). The accumulated distillate amount of Qinghai oil sand on the surface is 35.0%, similar to Xinjiang oil sand (see Table 4). These characteristics imply that the alteration of Qinghai oil sand on the surface is much more intense than at depth. In addition, the density of oil sand bitumen is about 0.980 g/cm\(^3\) (at 20\(^{\circ}\)C) and its viscosity is approximately 50 Pa\(\cdot\)s (at 24\(^{\circ}\)C). These are both in the range of bitumen (Yan and Luo, 1996). This fact suggests that heavily altered oil sands at the surface can act as a seal to protect oil sands at depth from oxidation/biodegradation, like tar mats in oil-gas fields (Zhang et al., 1996). Therefore, the unique geographical and environmental conditions lead to the formation of unique oil sands which are rich in light components and have high concentrations of hydrocarbons, which are seldom seen.

In addition, as Qinghai oil sands contain abundant light components and are quite different from other oil sands, the exploitation method is necessarily different. After conclusive technical evaluation, we proposed the following scheme: Oil is exploited first by drilling horizontal wells, followed by an open mining technique (Gao and Xu, 2002).

**Conclusion**

The organic composition and compound distributions observed in geochemical analyses of oil sands in Qinghai, northwest China, are unique, with rather high concentrations of saturated hydrocarbons (49.6–71.4%), while the heavy components (resin and asphaltene) are very low (25.6–45.6%); saturated hydrocarbons are regularly distributed—mainly centered around \(C_{27}\) with a high proportion of light components (<C\(_{33}\)). The oil sands have a high H/C atomic ratio similar to normal crude oils. Distillation simulation curves, differential thermal analysis curves, GC and SFC analyses indicate the oil sands are highly concentrated in light components, and the physical parameters are similar to common heavy oils. Biomarkers show that Qinghai oil sands formed from biologically degraded crude oil which originated from terrigenous organic matter in lower thermal maturation. Biomarkers also show that the oil sands are still in the early stages of biodegradation. Such unique exposed oil sands can only have formed by the specific geographical environment in Qinghai and have not been found so far in other areas of the world. Qinghai oil sands must be exploited by means of a two-step process, i.e., drilling wells followed by open cast mining.

**Acknowledgments**—The authors would like to express their gratitude to the Chinese National Petroleum and Natural Gas Group Corporation (CNPC) as a sponsor, and to the Survey and Development Research Institute of Qinghai Petroleum Administration Bureau, CNPC, and Professor Ban-yun Wei and Professor Qi Fei from China University of Geosciences for their great help.

**REFERENCES**


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