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Mineralogical and chemical composition of petrologic end members of Alberta oil sands

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HIGHLIGHTS

- Bitumen removal was the most effective in the coarse grained quartz-rich samples.
- The toluene insoluble organic carbon was associated mainly with the clay minerals.
- The quantitative mineralogical analysis correlated well with chemical composition of the oil sands.

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ABSTRACT

The Alberta oil sands ores are a combination of four petrologically different kinds of rocks, called "end members", deposited in marine and estuarine sedimentary environments. The combination of the different end members affects the properties of the oil sands. Applying organic solvents for bitumen extraction from the oil sands is an alternative to the current commercial hot water extraction process. Certain minerals (mainly clay minerals) in the oil sands may affect processability of the ore during non-aqueous extraction.

The aim of the present study was to perform mineral and chemical characterization of the four end members in order to better understand the mineralogical and geochemical factors affecting bitumen extraction and subsequent solvent recovery from the extraction tailings.

The as-received end members and their different size fractions were examined using XRD, QXRD, FTIR, ICP-MS and C, H, N and S content analysis. The results revealed variable amounts of toluene insoluble organic carbon in the samples after bitumen removal. The amount was higher in the finer size fractions, indicating its association mainly with the clay minerals. Bitumen removal was the most effective in the coarse grained quartz-rich samples containing a minimal amount of the clay minerals. The four end members consisted of quartz, clay minerals (kaolinite, illite, mixed layer illite–smectite and chlorite), carbonates (calcite, dolomite and siderite), K-feldspar, TiO_2 minerals (anatase and rutile) and pyrite. The highest relative amount of mixed layer illite–smectite was found in the finest fractions (<0.2 μm). The expandability (S_{XRD}) of illite–smectite was $10 \pm 2\%$. The quantitative mineralogical analysis correlated well with chemical composition analysis of the petrologic end members of the oil sands.

1. Introduction

The Alberta oil sands deposits represent the third largest reserve of oil on the planet [1,2]. The deposits consist of bitumen (4–18 wt%), inorganic materials (55–80 wt%) and water (2–15 wt%) [3]. Shallow oil sands ores are mined by surface mining methods and bitumen is recovered by water extraction processes. For deep deposits, steam assisted gravity drainage (SAGD) technology is used. The most significant shortcomings of water-based bitumen extraction are high fresh water and energy consumption. Alternative non-aqueous solvent bitumen extraction processes have been investigated since the mid 1960s [4–8], due to their potential advantages such as high bitumen recovery even from low grade oil sands ores and the elimination of slow settling, sludge tailing ponds with stable suspensions.

The oil sands composition is one of the most important factors affecting aqueous and non-aqueous bitumen extraction and waste management. In the oil sands industry, it is generally recognized that the coarse sands do not cause any problem throughout extraction process. On the other hand, nano and microsize minerals, mainly clay minerals, are most detrimental [9–13]. These minerals

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may interact with the solvent, bitumen and/or connate water due to their small particle size, high specific surface area, swelling capacity, cation exchange capacity, layer charge and specific physicochemical properties. In general, bitumen recovery decreases with increasing fines content (particles smaller than <44 μm) in the oil sands ore [10,14–16]. Wik et al. [17] demonstrated that small particle size is a contributing factor affecting bitumen recovery but comparison tests with ultra fine silica particles (<0.3 μm) showed that mineralogy is a more important parameter.

Different types of clay minerals may have different impact on the processability of oil sands ore during the extraction process. Laboratory experiments have shown that the addition of montmorillonite and calcium ions into oil sands ore decreased bitumen recovery, whereas the addition of kaolinite or illite did not have a significant effect on bitumen recovery [18–22].

To predict the behavior of oil sands during non-aqueous bitumen extraction processes and solvent recovery from the extraction tailings, it is thus essential to develop a deep understanding of the mineralogical composition and geochemical factors of oil sands and in particular their clay size fraction.

Previous studies investigating the mineral composition of Alberta oil sands have reported kaolinite, illite, smectite, chlorite and mixed layer clay minerals as the main clay constituents of oil sands [23–28]. However, the mineral composition of Alberta oil sands can vary significantly across the deposit. The clay fraction (<2 μm) consists predominantly of kaolinite and illite with smaller amounts of chlorite, discrete smectite and mixed layer clay minerals [23]. Illite–smectite and kaolinite–smectite both with low expandability (%S_{XRD} 10–40) are reported as the most common mixed layer clay minerals in Alberta oil sands [26,28–30]. Other researchers, on the other hand, have observed kaolinite and illite as the major clay minerals, but no discrete smectite or mixed layer clay minerals [31–34]. However, it should be note, that the authors have not performed a detailed characterization of clay size fraction (<2 μm) such as comparison of diffraction patterns produced from air dried and ethylene glycol solvated oriented preparations, which is a diagnostic test to distinguish between swelling (e.g. smectite and mixed layer clay minerals) and non-swelling clay minerals (e.g. kaolinite and illite) [35].

The clay fraction (<2 μm) of oil sands may also contain variable amounts of non-clay minerals. Approximately 90 wt% of non-crystalline inorganic compounds, attributed to Fe and Al oxides with tightly bound organic matter, were observed in the clay size fraction of Alberta oil sands [36]. In addition, nanosized hematite and magnetite were identified in the clay fraction of Alberta oil sands by electron microscopy [37].

Although the oil sands deposit in Alberta displays a wide variety of mineral composition, the mineral and textural variability can be described in terms of a mixture of four petrologic "end members", i.e., estuarine sand, estuarine clay, marine sand and marine clay [38,39]. Mined Alberta oil sands ores are a combination of these four petrologically different end members, deposited in marine and estuarine sedimentary environments. Thus, understanding these four end members will lead to a better understanding of the entire deposit.

The aim of the present study was to perform mineralogical and chemical characterization of the four end members of Alberta oil sands in order to better understand the effect of mineralogical and geochemical factors on bitumen extraction and solvent recovery from the extraction tailings.

2. Geological settings

The investigated samples belong to the Lower Cretaceous Mannville Group. The Lower Cretaceous Mannville Group or equivalent sedimentary rocks (Aptian to Albian age, ∼120–100 million years ago) contain the bulk of the bitumen reserves in Alberta. The Athabasca oil sands region is the largest, in terms of area and reserves, of Albertás three oil sands areas (Cold Lake, Athabasca and Peace River) (Fig. 1) [40]. The majority of bitumen in the Athabasca oil sands area occurs in the McMurray/Wabiskaw deposit, although most of the resource occurs within the thicker McMurray Formation [41]. The McMurray Formation is the lowest formation in the Lower Cretaceous Mannville Group and directly overlies a regional unconformity developed on Devonian carbonates (Fig. 2). The Wabiskaw Member [42] which is the lower part of the Clearwater Formation directly overlies the McMurray Formation. The McMurray Formation represents the initial sedimentation on the regional unconformity as a response to rising sea level to the north. Due to lithological variability the McMurray Formation has been subdivided into three informal unites. The lowest parts of the formation are the results of deposition in ridge and valley systems developed on Devonian carbonates and represent continental sedimentation [43] while the middle and upper parts of the McMurray Formation indicate an increasing marine influence [40]. The lower parts of the McMurray Formation are characterized by cross stratified fine to coarse pebbly sands or conglomerates with coal and paleosols [44–46]. The middle members of the McMurray Formation are dominated by intercalations of fine sands and mud, deposited in tidally-influenced marginal marine channels [47,48]. The upper members of the McMurray Formation consist of tidally-influenced deposits and/or marine bar sands [49] and are thickest towards the north.

3. Materials and methods

3.1. Materials

Four oil sand ores, collected by Syncrude Canada Ltd. in the North Mine, Fort McMurray, Alberta, were used in the present

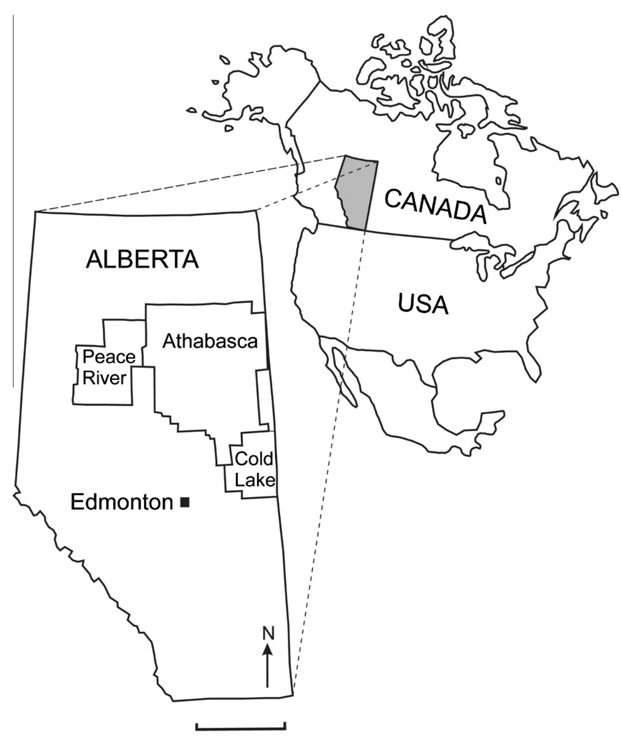

Fig. 1. Location of three major oil sands areas in Alberta (Cold Lake, Athabasca and Peace River) (modified from www.ags.gov.ab.ca/energy/oilsands [68]).