Geophysics comes of age in oil sands development

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ABSTRACT
Most energy forecasters predict that the development of shallow heavy oil reserves in Canada's enormous oil sand deposits will play a vital role in bridging the gap between North America's present reliance on conventional oil, and the full integration of alternative energy supplies. Over the five years, a number of surface geophysical techniques have been successfully applied to oil sands exploration and development. These innovations have come after over twenty years of near stagnation in the area of innovative applications of geophysics to the oil sands. These new applications include the direct exploration and detection of oil sands, the calculation of bitumen saturation from surface, the exploration for water supplies beneath the oil sands, geological mapping, mapping and imaging of thick clays and shales for geotechnical purposes, muskeg thickness mapping, and non-intrusive monitoring of leachate plumes. Geophysical techniques successfully applied to these problems include 2-D electrical resistivity imaging, transient EM, ground penetrating radar, and high resolution seismic reflection. Other techniques which will probably be used in the very near future include induced polarization, surface nuclear magnetic resonance, and various push-probe sensing techniques. This paper will review present applications of the above techniques in the surface mineable ore reserves of the Athabasca deposit.

RÉSUMÉ
La plupart des prévisionnistes d'énergie prévoient que le développement des réservations lourdes peu profondes d'huile dans les énormes gisements de sable du pétrole du Canada jouera un rôle essentiel en établissant le lien entre la confiance actuelle de l'Amérique du Nord dans le pétrole conventionnel, et la pleine intégration des approvisionnements en énergie alternative. Au cours des cinq années, un certain nombre de techniques géophysiques extérieures ont été avec succès appliquées aux sables exploration et développement d'huile. Ces innovations sont venues ensuite sur vingt ans de stagnation proche dans le domaine d' applications innovatrices de la géophysique aux sables d'huile. Ces nouvelles applications incluent l'exploration et la détection directe des sables d'huile, le calcul de la saturation de bitume de la surface, l'exploration pour des approvisionnements en eau sous les sables d'huile, tracer géologique, tracer et formation image des argiles et les schistes épais pour des buts géotechniques, épaisseur de muskeg traçant, et surveillance non-intrusive des plumes de lixiviat. Les techniques géophysiques avec succès appliquées à ces problèmes incluent la 2-D formation image électrique de résistivité, fin de support passagère, ont rectifié le radar pénétrant, et la réflexion séismique de haute résolution. D'autres techniques qui seront employées probablement à très court terme incluent la polarisation induite, la résonance magnétique nucléaire, et divers extérieurs pousser-sondent sentir des techniques. Cet article passera en revue les applications actuelles des techniques ci-dessus dans les réservations exploitables extérieures de minerai du dépôt d'Athabasca.

INTRODUCTION

Conventional oil and gas production is steadily declining in North America. In Canada's Western sedimentary basin, the decline of conventional oil production is particularly rapid. Presently, Alberta's oil sands contribute about 50% of Canada's petroleum requirements. The Alberta Energy and Utilities Board predict that the Alberta oil sands will be the principal source of Canada's crude oil over the next decade.

The oil sands, often incorrectly referred to as "tar sand," are most accurately described as bitumen saturated sands. The bitumen content in the deposits is classified as lean, intermediate, and rich according to minimum saturation values by weight of 3, 5, and 10 per cent (Minken, 1974). There are an estimated 1.7 trillion barrels of bitumen in place, more oil than found in the reserves of the entire Middle East, and approximating one third of the world's known reserves (Alberta community Development, 2008).

Alberta's oil sands are found in four major deposits: Athabasca, Cold Lake, Peace River and Wabasca. Together, they comprise nearly 31,000 square miles, an area greater than the land mass of Ireland. The Athabasca deposit is the largest, and the only reserve which is shallow enough to be surface mined. Presently, there are four oil sand mining operations and more than a dozen in situ pilot operations which, together, account for about 1.4 million barrels of bitumen per day.

The oil sand mines of northern Alberta represent the largest mining operations of any kind on the planet. As a result, there are numerous engineering concerns of enormous proportions including mine planning, tailings containment, water supply, and land reclamation. Geophysical methods play an important role in each of these areas, and will continue to play an expanded role as new techniques find appropriate applications.

GEOTECHNICAL SITING OF MUSKEG PILES

One of every six dollars spent on oil sands development is allocated to land reclamation. A principal component of land reclamation is stripping the muskeg cover, and storing it for future reclamation purposes. Geophysics plays important roles in estimating the volume of muskeg to be stripped, and in siting the optimal location for building the muskeg piles.

Ground penetrating radar (GPR) is a rapidly applied technique for profiling the muskeg/till, muskeg/oil sand, or muskeg/Clearwater shale contact. Depths from the profiles can be compiled together into a muskeg thickness map from which volumes can be calculated and stripping planned.

Muskeg piles are preferably built above remnants of the Clearwater Formation, a marine and shoreface sedimentary deposit consisting of glauconitic fine to medium sand, silt, clay and shales. The majority of the Clearwater was eroded during the Tertiary and Quaternary glaciation. Remnants of the Clearwater Formation conformably overlie the Cretaceous oil bearing sands, thus decreasing the mineable reserves in these areas. Mapping the location of Clearwater remnants is, therefore, critical in siting muskeg piles and consequently minimizing the area of the mine to be sterilized. Delineating the thickness of these clay remnants may be a critical geotechnical concern as large earth works may lead to instabilities and failure. 2-D electrical resistivity surveying has been used extensively in delineating the Clearwater Formation.

WATER EXPLORATION

The extraction process of the bitumen from the sands uses vast amounts of water. Groundwater is the preferred water source in oil sands development as groundwater's use minimizes pipeline and surface intake costs, impact to surface water bodies important to the native communities is minimized, and siltation is not a significant problem. Geophysics is used extensively in developing water resources. These applications include EM31 and EM34 terrain conductivity mapping of shallow, Pleistocene channels; 2-D electrical resistivity mapping of river connected, deep, bedrock Pleistocene paleovalleys; and 2-D resistivity mapping of basal aquifers beneath oil sand bodies.

TAILINGS CONTAINMENT

Bitumen is separated from the oil sands using vast quantities of hot water. Through this hot water extraction process, the water becomes contaminated with clays and bitumen. As a portion of this contaminated water cannot be recycled through the extraction process, there is a net accumulation of liquid tailings (Page, 1974). These tailings are contained in settling basins by dikes and berms that, together, comprise the largest earth filled structures in the world.

A number of environmental issues relate to these impoundments including monitoring leachate migration, stability of the geotechnical structures, consolidation of the tailings, and salt migration within the tailings. Electromagnetic (EM) terrain conductivity mapping and 2-D electrical resistivity surveying have been used extensively for leachate mapping. Push probe conductivity surveys are also planned for this application. Geophysical logging and 2-D resistivity surveys are planned for investigating the interior of the dikes and berms. Ground penetrating radar surveys are planned for monitoring tailings consolidation. EM and 2-D resistivity surveys are planned for monitoring salt migration within the tailings piles.

OIL SAND EXPLORATION

More than 650 billion barrels of heavy oil are in place in the basal Cretaceous McMurray sands of the Athabasca deposit. The McMurray Formation can be up to 150 m thick (Jardine, 1974). Delineation of the McMurray sands, themselves, is a relatively easy task for seismic reflection, transient EM, and DC resistivity surveys; the McMurray is generally bounded from above by the electrically conductive Clearwater shales, and from below by surprisingly conductive Devonian limestone and marls which also provide strong seismic reflection boundaries.

Despite the relative ease of delineating the top and bottom of the McMurray Formation, the direct detection of heavy oil is not trivial. The McMurray, itself, is divided into an Upper Unit and Lower Unit. The Lower Unit is composed of thick, massive fluvial sands and a swampy lacustrine facies. The Lower Unit, which is usually barren of oil, has pore waters which may vary in salinity from fresh to brine. The Upper Unit can be divided into three facies including fluvial, estuarine, and marine. The richest oil sands are usually in the coarser-grained deposits; nevertheless, the vertical distribution of the bitumen is very complex. The oil/water contacts vary from normal horizontal to vertical boundaries (Jardine, 1974). The bitumen may exist in clean sand interbeds. Thick water sands may exist within bitumen deposits. Because of the complexity of the ore deposit, seismic, geoelectrical, and borehole geophysical techniques all provide important and complementary information. A nuclear magnetic resonance (NMR) pilot program is planned for mapping bitumen saturations from surface.

DEVONIAN SURFACE MAPPING

As part of the oil sands mining process, thick sections of the Cretaceous McMurray Formation require dewatering down to the underlying Devonian limestone. The top of the Devonian is usually less than 200 m below ground surface, and often less than 120 m below ground surface. The limestone surface relief can be very irregular due to faulting, karst features, and salt dissolution and consequent collapse beneath the limestone. High resolution seismic reflection surveys have been found to be the most useful technique for mapping the top of the Devonian. The availability of sonic and density logs is invaluable in the creation of synthetic seismograms and subsequent time to depth conversion. 2-D electrical resistivity and transient EM surveys have been a useful and often complementary cross-check of the seismic data.

CONCLUSION

The Athabasca oil sand deposits will likely be the most important petroleum source for North America over the next decade. As seventeen per cent of this deposit lies at depths shallow enough to be recovered by open pit mining techniques, the ore is a good target for a number of different geophysical techniques. The gargantuan scale of these mining projects creates various environmental, geotechnical, exploration and mine planning problems that are amenable to the application of near surface geophysical methods.

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