Heavy Oil Reservoir Characterization using Integrated Geochemical and Geophysical Techniques

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Abstract

The Consortium of Heavy Oil Research by University Scientists (CHORUS) is an integrated multidisciplinary group at the University of Calgary with partners at the University of Alberta. Current research presented here includes: 1.) seismic numerical models for remote monitoring of subsurface processes in 4D, 2.) rock physics laboratory measurements of seismic velocities in variably saturated heavy oil sands for refining 4D monitoring techniques, and 3.) geochemical mapping of reservoirs using solid phase extraction and GC-MS techniques on core extract bitumen for determine fluid property heterogeneity. This work underscores some major problems associated with production of heavy oils and tar sands. Our research is currently geared towards 'cold production' of heavy oil (CHOPS) that involves high pressure production operations commonly producing significant volumes of sand. This type of production is known to generate high permeability conduits called 'wormholes' that propagate significant distances in the subsurface. Wormholes can be visualized as an uncased horizontal well, and may or may not be advantageous depending on location. The geochemical mapping and seismic monitoring research ongoing through CHORUS is useful to predict and monitor the propagation of subsurface cavities and wormholes. This work will help to clarify the effects of reservoir heterogeneity on production trends, and how reservoirs behave under stress due to cold production.

Keywords: Plover Lake, Bakken, heavy oil, cold production, seismology, time-lapse, rock physics, seismic velocity, geochemistry, biodegradation, viscosity, solid phase extraction, wormholes.

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Introduction

Heavy oil is the result of numerous processes acting on petroleum during migration, pooling and mixing within the reservoir. Microbial degradation over geologic timescales has been shown to be a primary degradation mechanism of petroleum into heavy oil. The oil-water contact, groundwater flow, and nutrient loading, largely control the rate of degradation, estimated at 10^{-8} kg hydrocarbons/kg oil/year for an unmixed oil column (Larter et al, 2003). The timing of oil charge, migration, and biodegradation of heavy oil deposits in Alberta and Saskatchewan have been discussed by numerous authors (Deroo et al, 1977, Mossop et al, 1994, Fowler et al, 2000, Riediger, 2001, Adams, 2004, Larter et al, 2006). This work suggests that migration distances in western Canada Sedimentary basin are controlled in part by immobilization of petroleum due to biodegradation (Adams, 2004).

Plover Lake is one of many scattered oil accumulations between Kindersley and Lloydminster (T[28-52]-R[21-28]W3). The oils are hosted in nearshore to fluvial facies of Mississippian-Cretaceous age. The Mississippian Bakken Formation at Plover Lake ranges from 6-18m thick and is composed of variably oil saturated fine lower-very fine lower sands, grading downwards to interbedded, kaolinitic, very fine lower sand-medium silt. Plover Lake is located just south of the Bakken subcrop along the edge of the pre-Cretaceous unconformity.

Detection of Cold Production Zones using Time-Lapse Seismology

The cold production of heavy oil will create depletion zones over time. In reservoir management, it is useful to delineate these zones for the purposes on infill drilling. Generally speaking, we wish to avoid the production footprint in primary production. Time-lapse seismology provides a tool for defining these footprint zones of high porosity wormholes and foamy oil.

By comparing monitoring seismic surveys, we note that cold production effects are manifested by delayed traveltimes and altered amplitudes. Both traveltimes and amplitudes indicate of reduced seismic velocity as production progresses. We see real data examples of this from eastern Alberta and western Saskatchewan. Figures 1-2 show aerial travel time differences proximal to well locations and cross-sections of seismic amplitude and reflection traveltime differences at the Bodo Field near Provost, Alberta. One of the key questions relates to the seismic resolution.

Figure 1 – Aerial map of well locations and traveltime differences between surveys at Bodo Field, Provost, Alberta.

Figure 2 – Amplitude (upper arrow) and reflection traveltimes (lower arrow) difference sections showing areas affected by lowering of seismic velocity at Bodo Field, Provost, Alberta.

In order to answer the questions of seismic resolution, we have done 3-D seismic modeling studies. Figure 3 shows how cold production zones and wormholes can be imaged using time-lapse seismology. The wormhole model is essentially a fractal-like (chaotic) series of wormhole channels from which we have computed 3-D synthetic seismograms. The wormhole zones are a fraction of the seismic wavelength. These data are then depth migrated to improve the spatial resolution. The results show that although individual wormholes are not resolved, the edge of the wormhole zones are detected to within the post-migration Fresnel diameter.

Figure 3 – Actual cold production/wormhole model (left) and seismic response (right) from computed 3d seismograms.

The modeling tests verify the results seen in real data. Seismic effects can be seen over the wormhole footprint – both in reflection traveltime and in amplitude. It is proposed that time-lapse seismology be used as a tool in this reservoir characterization.

Determining Vp and Vs of Heavy Oil Sands using Rock Physics

Two sections of oil sands from Plover Lake were available for testing. They were at depth 826.40 m to 827.90 m. Samples were obtained by drilling oil sand cores with a plastic pipe (1" in diameter), in which way, the content in the center of the pipe is minimum-disturbed. Figure 4 shows Plover Lake core and sampling pipe apparatus. Then two ends are chopped flat to mount transducers on. And after that, the whole set was wrapped with tygon and sealed to prevent leakage.

Figure 4 – Plover Lake core and sample apparatus used for measuring Vp and Vs of heavy oil sands.

Single P and S transducers as well as stacked transducers were used. The center frequencies are: 1MHz, 850kHz for P wave and 1MHz, 500kHz for S wave. Low frequency transducers are supposed to yield better results, but possibly due to reduced input energy (smaller area than 1MHz), these low frequency transducers gave poor results.

Different buffer materials were also tested. Plexiglas yields better results than common used alumina. This is probably because the match of impedance. But Plexiglas attenuates the waves more than alumina, therefore, it obscures the results to a certain degree. One has to calibrate these buffers before testing any sample.

Figures 5-6 show preliminary measurements of Vp and Vs for heavy oil sands over variable pressures. As pressure goes up, the length of the sample shrinks slightly, so does density. This is not a big problem for a 10mm sample, but could be a major problem for longer samples. Therefore, a new system that measures both length and density change is being built to yield more precise results.

Figure 5 – Vp and Vs measurements from Plover Lake heavy oil sands. Data were obtained by P-S stacked transducers, 1MHz, on a 10 mm long sample. Curves shown on the graph are for pressure up.

Figure 6 – Vs measurements made during pressure-up and pressure-down of sample apparatus. Data are from two separate runs, so high pressure velocities don't merge into one point. These curves are from a 35mm long sample and were obtained by single transducers, 1MHz.

Mapping Fluid Heterogeneity using Geochemistry

This section outlines some of the geochemical work underway with the CHORUS project in partnership with the Petroleum Reservoir Group at UoC. The following will discuss the observed level of oil biodegradation for the Bakken Formation heavy oils at Plover Lake. This paper presents data from the first 20 samples analysed from core of 2 wells, out of a total 120 samples from 6 cores. The analysis methods used here include solid phase extraction (SPE) techniques (Bennett et al, 2000) followed by gas chromatography-mass spectroscopy (GC-MS), and are discussed following.

The Peters and Moldowan (1993) biodegradation scale (Figure 7) lets us compare how the chemical composition of the petroleum changes spatially within the reservoir and how it compares to other heavy oil reservoirs. The PM scale describes the characteristic sequence of compound destruction during biodegradation of petroleum.

Figure 7 – Modified from Peters and Moldowan biodegradation ranking based on compound classes (1993).

Methods

Approximately 300 grams of oil sand was homogenized using a mortar and pedestal. Solid chunks of dark brown-black oil/sand/cement were broken and mixed. Samples were generally weakly-moderately consolidated with 5-15 % hard chunks, although this may be due to analysed core being stored from 5-35 years. Approximately 0.1 gram of mortared oil sand was washed with dichloromethane (DCM) to extract the bitumen from the sand while taking care not to transfer clays and fines. Duplicates, repeats and blanks were also analysed. Extract weights were calculated by drying a fraction of extract under nitrogen. An aliquot of core extract dissolved in DCM was cleaned using a Florisil solid phase extraction (SPE) cartridge, to remove NSO compounds like asphaltenes and resins from the mixture. This cleaned mixture was then separated again using a C18 SPE cartridge to separate the carbazole fraction using hexane, from the aromatic and aliphatic fractions using DCM.

The samples were then analysed with an Agilent Technologies 5973 GC-MS mass selective inert detector, using selected ion monitoring and split-less injection. The GC-MS was run at 70 eV and at 40-300 $^{\circ}$C increasing at 4 $^{\circ}$C/min. Quantification of

individual compounds in the core extract bitumen was done by injecting 4-8 μl of several deuterated and non-deuterated chemical standards into the DCM+bitumen mixture following extraction from the sand core.

Results

Figures 8-9 show GC-MS total saturated ion chromatographs for five samples versus depth for two wells at Plover Lake approximately 6 km apart. The relative abundance of the saturated hydrocarbon compounds can be measured from the relative areas under each peak, compared to the injected standard of similar chemical structure (see Figure 10). Varied chemical structures (e.g. aliphatic versus cyclic) will have slightly different response factors when measured with the mass spectrometer. Concentrations were all calculated assuming a response factor of 1 for all ions.

Figure 8 – Total ion chromatographs for saturated hydrocarbon compounds from the Bakken Formation at Well #1, Plover Lake.

Figure 9 – Total ion chromatographs for saturated hydrocarbon compounds from the Bakken Formation at Well #2, Plover Lake.

Each peak on the chromatograph represents a different compound or stereo-isomer, and each falls into a number of mass:charge ion groups. Figure 10 shows two such groups, the 85 m/z ion (n-alkanes) and the 206 m/z ion (dimethylphenanthrenes) chromatographs for wells #1 and #2, and illustrate how the concentration data is calculated. Figure 11 shows calculated concentration profiles of selected n-alkanes with depth through the oil column. Decreasing concentrations indicate more severe biodegradation is occurring is these zones of the oil column.

Figure 10 – 85 m/z and 206 m/z ion chromatographs for well #1 and #2.

Figure 11 – n-alkane distribution in core extract bitumen versus depth for well #1.

Figures 12-13 show total concentration profiles with depth at wells #1 and #2, for five compound classes including total n-alkanes, isoprenoids (C18-C20), naphthalenes (C1&C2), phenanthrenes (C1&C2), and hopanes. These compounds are considered good indicators of biodegradation because they designate Peters and Moldowan level 1 to 5. These concentration profiles allow us to see chemical and biodegradation gradients in the reservoir and make estimates of fluid properties.

Figure 12 – Concentrations of total n-alkanes, isoprenoids (C18-C20), naphthalenes (C1&C2), phenanthrenes (C1&C2), and hopanes in core extract bitumen versus depth for well #1.

Figure 13 – Concentrations of total n-alkanes, isoprenoids (C18-C20), naphthalenes (C1&C2), phenanthrenes (C1&C2), and hopanes in core extract bitumen versus depth for well #2.

Discussion

Comparing relative concentrations of non-degraded, standard Exshaw oil to the core extract samples of Plover Lake bitumen indicates light to moderate degradation at 3-4 on the Peters & Moldowan scale (1993). This conclusion is consistent with Obermajer et al (2004) observations that in Bakken reservoirs near Kindersley, Sask., n-alkanes, isoprenoids, alkylbiphenyls, and methylated naphthalenes are microbially degraded while terpane and sterane biomarkers are not. In the present study, concentrations of indicator compounds in Plover Lake bitumen are shown to vary up to x4 between wells and with depth. Miller et al (2006) also noted viscosity measurements from produced oils varied by x4 at Elk Point, Alberta. The core extract data indicates that the oil column is heterogeneous and there appear to be trends related to permeability, grain-size, and water-leg distributions.

Figure 10 shows n-alkanes (85 m/z) and dimethylphenanthrenes (DMP) (206 m/z) concentrations in core extract bitumen for two wells. There is considerable n-alkane biodegradation in both wells while DMP is predominantly non-degraded. Figure 11 shows the major n-alkanes through the oil column. The removal of some compounds (e.g. C20 & C19) above –87m SS represents a classic degradation profile in the upper Bakken sand column. It is important to note that the top meter of the upper Bakken sand for both wells, were missed or lost while coring. And leaves open the possibility of a more pronounced down-ward decreasing trend of biodegradation toward the oil-water contact.

The profiles in Figures 11-13 show above-average concentrations in a thin zone at the base of the column indicating less severe degradation. This lower zone is separated from the upper Bakken, by thin, silt-sand interbeds. The silty interbeds also appear to be partly wet, indicated by core measurements of water saturation levels exceeding 50% versus oil saturations. All compound groups in Figure 12-13 except phenanthrenes, show systematic concentration increases in this lower isolated zone. Increasing proportions of resistant compounds may be associated with a concentration affect resulting from biodegradation, however this is unlikely here because n-alkanes also increase. The lower zone could represent active oil-charge into a previously degraded zone in the reservoir. This suggestion follows from studies by Obermajer et al (2004) on regional geochemistry around Lloydminster to Kindersley, Sask., that also indicate present day oil-charge is possible.

Figures 12-13 show biodegradation is more severe in well #1 compared to well #2. This is observed by differences in the UCM (unresolved complex mixture) 'hump' that is characteristic in biodegraded oils. And, by the disappearance of the 'light-end' component peaks in well #1. Overall, the concentration of n-paraffins in Plover Lake

bitumen is generally low, and isoprenoids are low-moderately degraded. In well #2 the alkanes and isoprenoids are roughly twice as high in some zones compared to well #1. These high and low concentration zones within the oil column could be defined as 2 and 3 respectively on the PM scale. The naphthalene and phenanthrene aromatics tend to be higher when n-alkanes and isoprenoids are low. This may be the result of concentration affect due to biodegradation or may reflect a complex charging history. The lower zone of well #2 is reduced in C1 and C2 naphthalenes and indicates moderate biodegradation (3) on recent adapted versions of the PM scale by Head et al (2003).

The application of chemical proxies is a useful correlation tool for fluid properties like viscosity (Larter et al, 2006). Figure 14 shows there is good agreement between naphthalenes and phenanthrenes concentration in core-extracted bitumen compared to viscosity measured from spun oils for a Peace River reservoir. Applying this relationship to the Plover Lake field, it appears that viscosities would be greatest in the lower isolated zone of well #1 (bottom of Figure 11). More data is needed for the current study to make conclusive viscosity predictions based on chemical proxies. However, assuming the Peace River tar sand data from Figure 14 is analogous to Plover Lake, we could expect viscosity to vary by an order of magnitude between wells and throughout the oil column.

Figure 14 – Modified from Larter et al (2006) showing phenanthrenes & C2+C3 naphthalenes concentration and measured & predicted viscosity versus depth for a Peace River heavy oil reservoir. Chromatographs show progressive removal of dimethylnaphthalenes towards the oil water contact.

Geochemistry enables us to map out the biodegradation process and understand how fluid composition is distributed within the reservoir. Figure 14 illustrates the major processes influencing biodegradation and fluid property heterogeneity, and summarizes why we see biodegradation trends at Plover Lake. This information is important for selecting extraction methods. And can also be used to history match to simulations because produced fluids can be allocated to specific zones in the reservoir. As part of the CHORUS project, this geochemistry information will be used in reservoir simulations, and may have possible links with seismic and rock physics studies to provide an integrated characterization of the Plover Lake reservoir.

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