Fluid and Rock Property Controls On Production And Seismic Monitoring Alaska Heavy Oils

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Final Report

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Prepared by Principal Investigators:
Matthew Liberatore[1] (PI, point of contact)
Andy Herring[1]
Manika Prasad[2]
John Dorgan[1]
Mike Batzle[3]

[1]Chemical and Biological Engineering Department
[2]Petroleum Engineering Department
[3]Geophysics Department
Colorado School of Mines
1613 Illinois St (435 Alderson Hall)
Golden, Colorado 80401
Phone: 303-273-3531
Fax: 303-273-3730
email: mliberat@mines.edu

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Executive Summary

Goal

The goal of this project is to improve recovery of Alaskan North Slope (ANS) heavy oil resources in the Ugnu formation by improving our understanding of the formation's vertical and lateral heterogeneities via core evaluation, evaluating possible recovery processes, and employing geophysical monitoring to assess production and modify production operations.

Performers

Colorado School of Mines, Golden, CO 80401

University of Houston, Houston, TX 77204

Earthworks, Newtown, CT 06470

BP, Anchorage, AK 99519

Background

Although the reserves of heavy oil on the North Slope of Alaska are enormous (estimates are up to 10 billion barrels in place), difficult technical and economic hurdles must be overcome to produce them. The Ugnu formation contains the most viscous, biodegraded oils and standard production methods are ineffective. Numerous alternative techniques for heavy oil production have been proposed (e.g., steam injection). However, the overall effectiveness of these methods is much lower than either modeling or laboratory tests suggest. A prime factor limiting the efficiency of heavy oil recovery is the heterogeneity of the system. Heavy oils are viscoelastic materials with varying resin and asphaltene contents. The rocks containing the fluids have porosities, permeabilities, connectivities, and mineral contents that vary over short distances. Seismic attributes could be used to monitor how well a recovery technique is sweeping the reservoir and where there are complications. Seismic responses from pre-production of the reservoir could be used to illuminate the local geology, which could assist in designing well trajectories that would enhance productivity.

This project characterized the fluids and rocks on a fine scale to ascertain the range and distribution of physical properties and evaluate the various proposed recovery processes in light of these distributions; design a geophysical monitoring program to continually assess the progress and effectiveness of production; and develop feedback procedures using monitoring results to update and modify the production procedures.

Impacts

A state-of-the-art seismic monitoring program based on chemical and physical characterization of core samples and simulated production experiments has potential to improve the technological and economic hurdles slowing development of the vast heavy oil resource on the North Slope of Alaska. The project generated significant amounts of new public data on heavy oil fluids, rocks, and the seismic attributes of ANS oils and reservoir rock. This work, when applied, is expected to improve seismic resolution through permafrost and the ability to evaluate heavy oil reservoirs. Successful completion of the project will result in the capability to monitor, over time, the progress of a heavy oil recovery process by seismic measurements.

Accomplishments

Heavy oils can be viscoelastic fluids. Thus, it is critical that we understand the properties of the heavy oils we are trying to produce *before* the geophysical model and modeling plan can be completed. The organization of the accomplishments and the rest of the report begin with chemical and physical property characterization and conclude with the geophysical studies.

Researchers collected samples that included approximately a dozen dead oil samples, 5 gallons of dead oil, 5 gallons of oily sand, and several well logs. In addition, samples from two different cores have been sampled. Several types of molecules were observed by MBMS, and NMR in the heavy oil samples including alkanes, alkynes, aromatics, as well as a small amount of other type organic molecules. These molecules vaporize in the sequence of alkynes, alkanes, and aromatics as the temperature increases. The average detected molecular weights vary between 140 and 300 Daltons. Azeotrope of water and alkyne or cyclohexenetype molecules has been detected by the congruent of water clusters and the olefin MS peaks between 200-300 ºC.

Saturate-Aromatic-Resin-Asphaltene (SARA) fractions have been measured on site and by an outside laboratory. The SARA technique has large experimental variation when used to measure heavy oils. Asphaltene content varied from 3 to 9% in the same sample measured by CSM and an outside laboratory. More powerful chemical characterization techniques are being pursued.

The oils (including more than 18 oil, oil/sand, oil/water, and oil/sand/water mixtures) exhibited non-Newtonian characteristics, including shear thinning and a non-zero shear modulus. The complex viscosity of the dead oils has been found to be as high as 7,000 Pa-s and a shear modulus at -10^{o}C above 10,000 Pa (and frequency dependent). A complete set of “live” oil rheology experiments were completed. A large range of temperatures (-10 to 60^{o}C) and pressures (15 to 2000 psi) were controlled and viscosity measured in novel high-pressure rheology setup.

A large number of experiments have been completed, including molecular beam mass spectroscopy (MBMS), optical and scanning electron microscopy, x-ray CAT scans, acoustic microscopy of simulated water floods, and laboratory seismic measurements. For example, the microscopy has allowed the sand grain size to be determined (~5µm diameter) as well as the grain chemistry (nearly pure silica). Chemistry signatures are being used in the analysis of the MBMS and SARA data have been correlated with the viscosity of the heavy oils.

Seismic monitoring of heavy oil recovery can lead to a more efficient process with higher recovery factors. However, in order to interpret the results of any monitoring process, we must know the state or phase of the reservoir fluids, condition and history of production, and physical properties reservoir and fluids. As important, the process that is being used to enhance oil recovery must be known in order to interpret the resulting geophysical data. In this project, we have examined both the near-term process CHOPS (Cold Heavy Oil Production with Sand) and longer term thermal flooding.

Seismologists can monitor Cold Heavy Oil Production in-situ in two ways: (a) low-definition imaging of the phenomenological behavior of the formation, and/or (b) high-definition imaging of the detailed configuration. In both cases, the appropriate solution depends strongly on a comprehensive understanding of the material-property changes involved. This study modeled these two cases based on oil and sediments properties measured in the laboratory.

In the low-definition imaging case, low-frequency (30 to 100Hz) waves sense the spatial and temporal property variations of the composite material on average. Only a portion of the formation reacts producing wormholes. The low-frequency wave detected only the effect of the limited volume on the overall formation response. In the high-definition imaging case, the short range imaging at 100-1000Hz waves can illuminate individual wormhole features. At the wormholes, the frame fails and the heavy-oil moduli drop such that the shear wave velocity vanishes and the compressional-wave velocity diminishes 66%. At 300Hz, features on the order of inches can be detected. We propose a monitoring configuration that minimizes cost and maximizes acquisition. The working range is roughly 300-500ft.

The consideration of electromagnetic properties might be helpful to invert the measurements into intrinsic properties such as porosity, oil saturation, and oil density. In the same vein, monitoring of the ultrasonic properties of the product as is extracted from the borehole would reveal the concentration of solids, heavy oil, and gas bubbles exsolved from solution and the high-frequency velocities of the mixture. The breakdown of the frame causes microearthquakes that may be located in way that wormhole creation could be mapped. Of course, this is a short-range measurement that could be obtained with the short range array that we propose. BP has pointed out that the behavior of the unconsolidated frame controls the log interpretation. We determined that the Ugnu formation requires a more particular description than the simplest general equation.

Measured velocity-temperature trend on heavy oil sands suggests that the thermal damage of sand frame is caused by thermal pressure of heavy oil and mainly deteriorates the heavy oil contribution to strength sand frame and reduce velocities. It is a quasi-static processing and not counted as frequency dependent. Thermal damage mainly occurs at low temperature and reduces with increasing temperature. The thermal damage is limited by rock texture and degree of compaction. Analysis of measured data suggests that Gassmann's model work well for heavy oil sands at temperature higher than the liquid point. The thermal damage effect on sand frame will need to be accounted for when modeling velocity-temperature trend of heavy oil sands.

The Project Management Plan (PMP), Technological Assessment, and Project Summary have been completed in cooperation with NETL. A number of trips to Alaska (January 2009, August 2010, November 2010, March 2012) were undertaken to coordinate sample/core retrieval, discuss objectives, and complete a sample testing plan with BP. Two talks by the group were made at the BP Heavy Oil Symposium in November 2010 with 150 people (from industry, academia, and government) attending in Anchorage, AK. Team gave over 15 presentations at technical meetings (e.g., SEG, ACS, etc.). Five students completed graduate degrees and theses (2 Ph.D. and 3 M.S.), 2 additional students still finishing thesis work. Two peer reviewed papers published, several under review, several more being completed in last weeks of project. Results of the rock physics model, and algorithms developed for modeling seismic data at a high frequency range were presented at the 1st International Rock Physics Symposium in Colorado (August 2011).

Project Start: October 1, 2008

Project End: June 30, 2012

Accomplishments summary

The characterization of properties of Alaska heavy oils is discussed first and is leveraged in the discussion of the geophysical model and modeling plan.

Geochemical Characterization

The routinely used method for HO characterization in the oil industry is SARA fractionation, and the Resin and Asphaltene components correlate with viscosity [i,ii iii,iv v]. However, large errors exist in SARA fractions from commercial labs. We have established a standard procedure for SARA analysis, identified sources of errors, and assessed repeatability of the measurements[vi,vii,viii]. We find that upon enforcing meticulous accounting for all fractions including weight loss with drying, we can reduce errors and have a repeatability within 5% that can be corroborated by separation by identifying chemical fractions with Fourier Transform Infrared Spectrometry (FTIR)

Rheology

A high-pressure rheology apparatus for the study of live oils up to 2000 psi and temperatures from -10°C to 150°C has been constructed [ixx.xi]. Viscosity, μ, of the Ugnu oil saturated with methane was measured from temperature of 0°C to 60°C, pressure from 15 psi to 1800 psi, and shear rate of 0.1 s^{-1} to 500 s^{-1}. In all studied conditions, the Ugnu oil reveals Newtonian behavior. A two-variable correlation $\mu(T, P)$ was developed using 48 shear-rate averaged points on a (p,T,μ) diagram (**Figure 2**). The influence of temperature, pressure, and methane concentration was analyzed. Methane saturation has a dramatic effect on the oil viscosity: e.g., the viscosity of the Ugnu oil saturated with methane at the average temperature and pressure of the reservoir – 1400 psi and at 10°C – is about 20 times lower than that for the dead oil. Temperature has an even more pronounce impact: an increase in temperature from 0°C to 60°C leads to a three order of magnitude decrease in Ugnu oil viscosity. At the same time, bare pressure without any saturation with gas just slightly increases the oil viscosity (2 times for the rise of Δp = 1500 psi) due to liquid compression. The iso-compositional rheological measurements allowed estimating the enthalpy of solution of methane in the Ugnu oil to be 2 $kJ \cdot mol^{-1}$. Since the produced oil is always accompanied by sand and water, their influence on the viscosity of the Ugnu oil saturated with methane at 1500 psi was also evaluated. The relative viscosity of the Ugnu oil + water system at temperatures from 2 to 60°C was shown to increases almost linearly with increasing water concentration from 0 to at least 20 wt% following the Einstein viscosity model for dispersions with a slope of 2.5. Due to rapid sand particle sedimentation in the methane saturated Ugnu oil during pre-measurement stages (loading and equilibration), the exact impact of sand concentration on the live oil viscosity has not been evaluated. However, it is expected to be similar to that for the dead oil. The presented research created a basis for simulating a more realistic behavior of the Ugnu oil in situ.

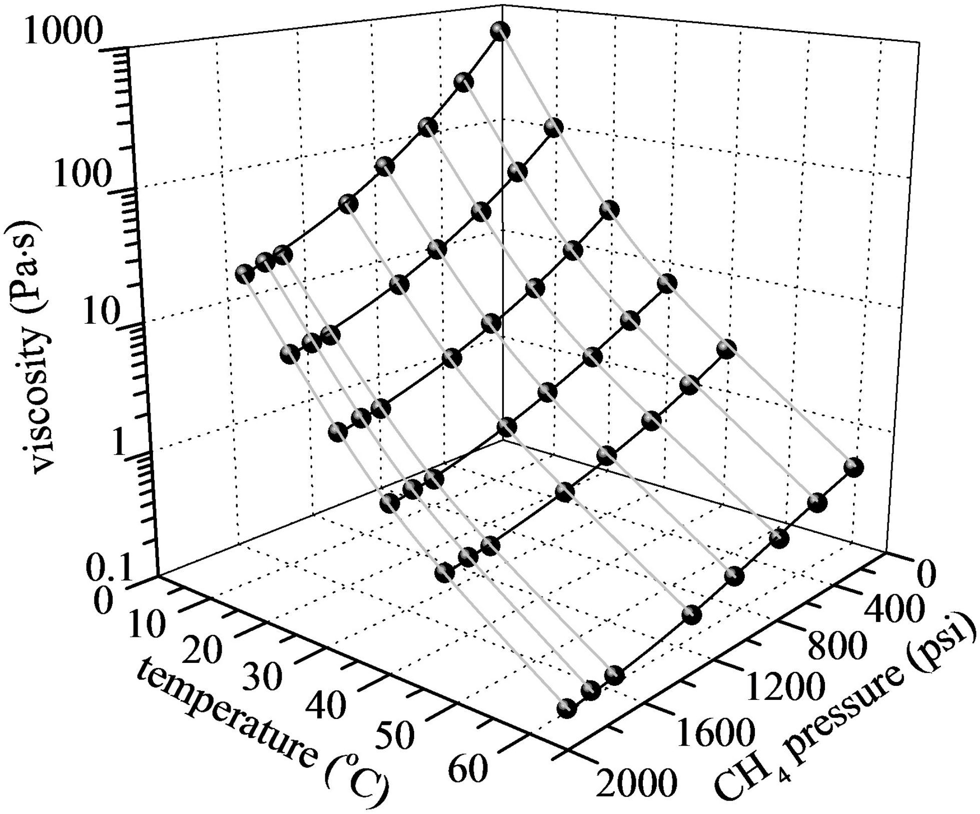

Figure 2. Pressure and temperature dependence of methane saturated Ugnu oil MPS-41: black lines, isotherms; grey lines, isopleths

Detailed Chemistry

The following samples were tested in the chemistry study part of heavy oil [xii,xiii,xiv]. The primary studies were on nine heavy oil samples taken in September 2009 from the Ugnu formation on the Alaskan North Slope in one production well (after sand separation). Additional studies compared other heavy oils to the Ugnu including six Canadian McMurray formation heavy oils at different depths by perforation in different wells of the same heavy oil reservoir; two tar samples from Utah Asphalt Ridge and Gulf of Mexico, asphaltene samples taken from the eastern Utah Gilsonite deposit, and Bonanza asphaltene which is the n-heptane solvent extracted asphaltene fraction from the Gilsonite.

Major results for the heavy oil chemistry study can be summarized as mainly two parts: a) the fundamental understanding of more detailed heavy oil components using combined powerful CSM facilities in addition to previous SARA classifications. Time-resolved screening methods were developed to seek out major compounds; and b) preliminary statistical models have been established to relate the obtained complex chemical information to heavy oil physical behaviors, specifically viscosity values. The fast and comprehensive statistical method provides a way to find the role of each mass that is within the detection range in the change of viscosities.

Two technical papers have been accepted by peer reviewed journals *Fuel* and *Energy & Fuels.* The papers are about eleven Alaskan Ugnu heavy oils of different production days in 2009 with a small viscosity variation (20-60 Pa-s) and Canadian McMurray Formation at five different depths (391-434 m) of large viscosity differences (400-2000 Pa-s).

Technically, several representative compound types including water, straight/cyclo alkanes, alkenes, aromatics, heteroatom hydrocarbons, and specific compounds with their homologues such as sec-hexadecyl naphthalene, 2,2',5,5'-tetramethyl-1,1´-biphenyl, 1-methylanthracene, and cyclopentylcyclopentane, etc. were found in Ugnu or McMurray heavy oils. Azeotropic behavior when co-evaporation of molecules of water and decalins occurs was observed between 100-250 °C. Change in aliphatic chain and aromatic core ratio was found as a function of depth. In the same well, production day has a small effect on viscosity; molecular weight plays a major role in viscosity change. The partial least squares correlation between molecular masses and the viscosity for the small viscosity variation Ugnu heavy oil shows that water, alkylbenzene, and molecules with higher masses have positive correlations to the viscosity, but that the aliphatic molecules were anti-correlated (**Figure 3**). In the same reservoir, viscosity changes largely with depths. The correlation models for the large viscosity variation McMurray heavy oil found water as one of the primary predictors and is anti-correlated to viscosity.

As the two data sets both represent a limited number of samples and oil chemistries, and the initial investigation tools are of limited resolution and detection capability, a further investigation of heavy and viscous oils representing a larger variation with newly coming instruments of more robust capability will be necessary and worthwhile. Nethertheless the results achieved here are still valuable to the heavy oil resource development, as production moves from surface accessible site to sites with considerable overburden necessitating drilling technologies. Besides the above heavy oil work, observation of unusual intense vibrational modes of heavy oil leads to discovery of features related to asphaltene and an exploration of asphaltene structures is in progress, which is of broad research interest aiming to aid better transportation and upgrading process controls.

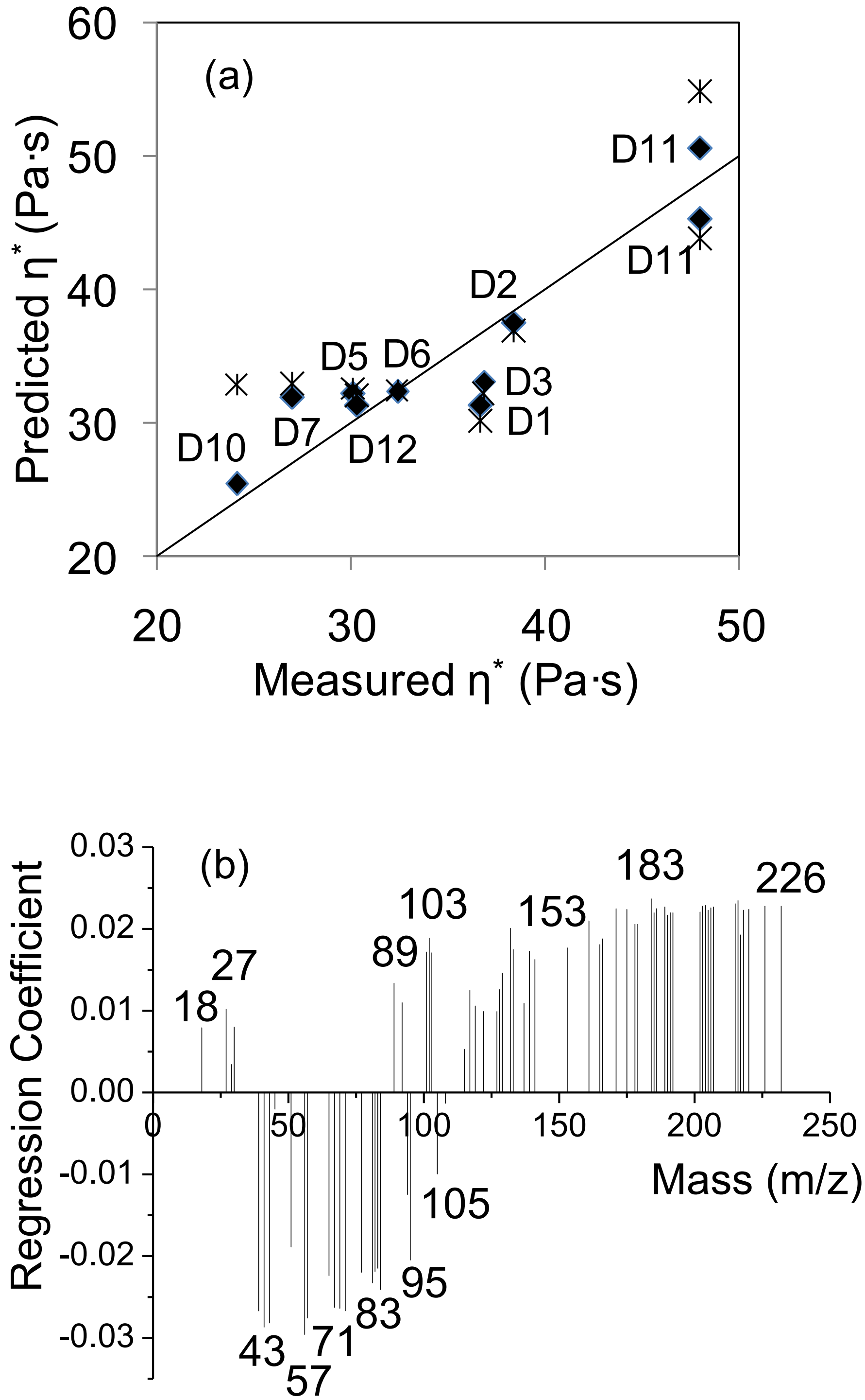

Figure 3. (a) Measured viscosity (20 °C, 1 Hz) versus model predicted viscosity values. The coefficient of determination is 0.85 for the full sample set (solid diamond) using two main

principle components, and 0.65 for the cross validation (cross star); (b) Correlation coefficient of MBMS variables with viscosities, resulting from partial least squares regression analysis.

Seismic Monitoring of Heavy Oil Recovery Techniques

Seismic monitoring of heavy oil recovery can lead to a more efficient process with higher recovery factors. However, in order to interpret the results of any monitoring process, we must know the state or phase of the reservoir fluids, condition and history of production, and physical properties reservoir and fluids. As important, the process that is being used to enhance oil recovery must be known in order to interpret the resulting geophysical data. In this project, we have examined both the near-term process CHOPS (Cold Heavy Oil Production with Sand) and longer term thermal flooding.

Heavy Oil Characterization

It is critical that we understand the properties of the heavy oils we are trying to produce in order to predict the geophysical signature. Heavy oils can act viscoelastically. At low temperatures, the oil has an effective shear modulus. This will be important not only for converted shear waves, but also for the effective cementation that will increase the compressional waves beyond what is expected. Figure 4, shows the shear modulus derived from rheometer measurements as a function of frequency. Note that there are three frequency bands indicated: surface seismic (10 – 100 Hz), borehole acoustic (10,000 Hz), and standard laboratory ultrasonics (Mega Hz). It is obvious that at lower temperatures, laboratory measurements will not equal sonic log values, which will not equal seismic values.

This kind of behavior is translated into frequency and temperature related rock properties. For seismic monitoring, Vp (compressional velocity), Vs (shear velocity), and ρ (density) are the controlling factors. These, in turn, depend on the rock properties, bulk modulus (K) and shear modulus (G)

$$Vs = (G/\rho)^{1/2}$$

$$Vp = ((K + 4/3G)/\rho)^{1/2}$$

Figure 5 shows the expected dependence of K and G as a function of temperature. At low temperatures, typical of cold production, the moduli are also strongly frequency dependent. This is important from our modeling point of view. Gassmann (1952) substitution is the standard technique used to interpret changes in fluid content in terms of seismic properties. But as Figure 5 indicates, this standard technique is only valid at high temperatures.

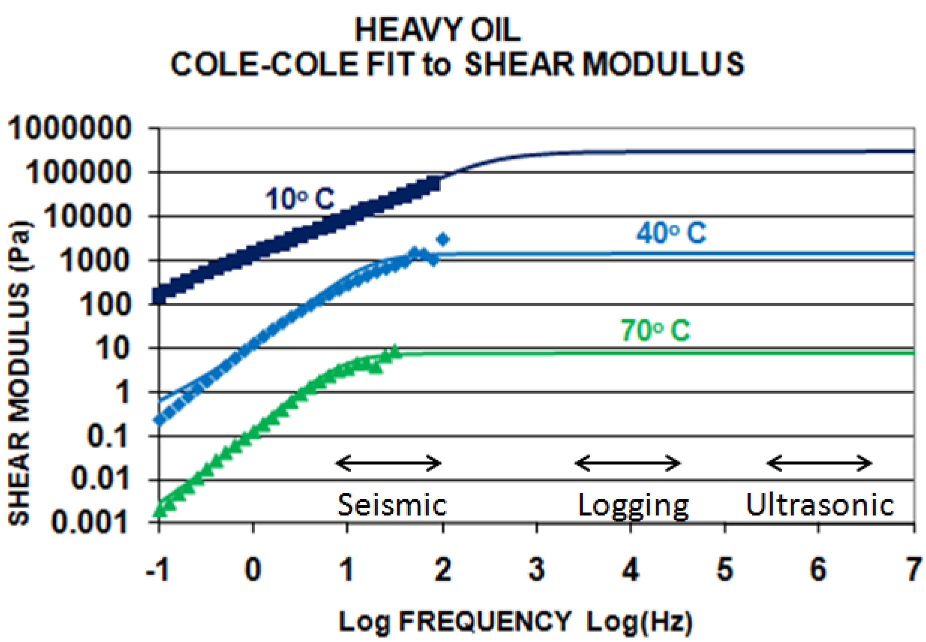

Figure 4. Heavy oil shear modulus as a function of frequency with measurement bands indicated.

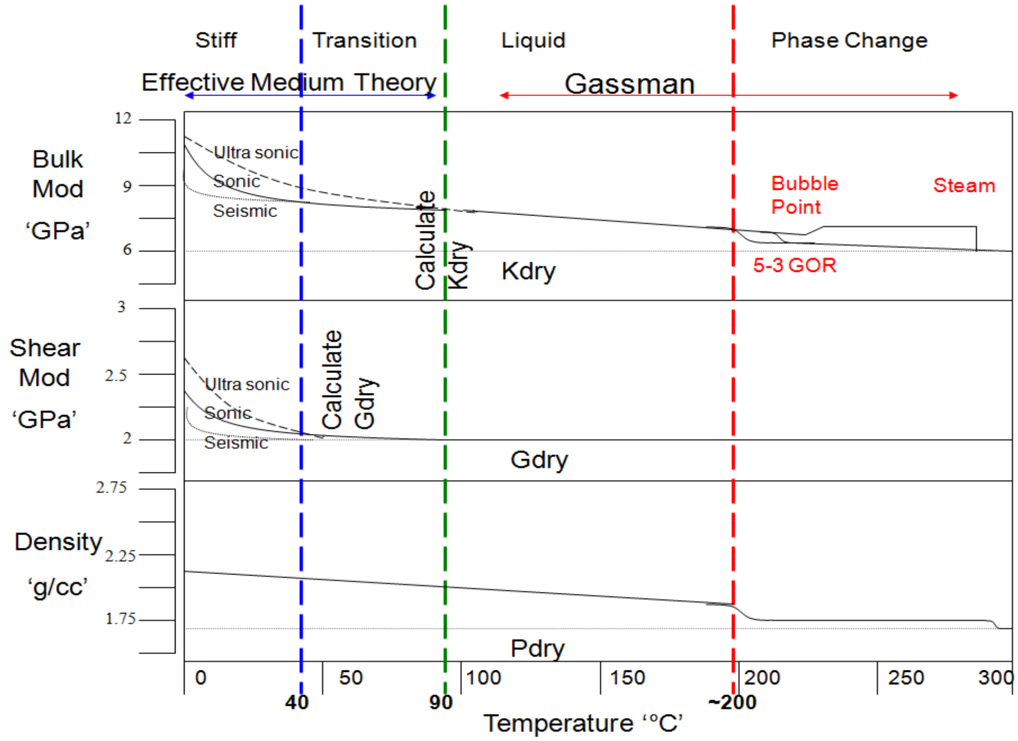

Figure 5. Expected seismic response of rocks containing heavy oil as a function of and temperature. Note that at the lower temperatures, frequency also has a strong influence.

The method used routinely for HO characterization in the oil industry is SARA fractionation, and the Resin and Asphaltene components correlate with shear modulus and viscosity. However, large errors exist in SARA fractions from commercial labs. We have established a standard procedure for SARA analysis, identified sources of errors, and assessed repeatability of the measurements. We find that upon enforcing meticulous accounting for all fractions including weight loss with drying, we can reduce errors and have a repeatability within 5% that can be corroborated by separation by identifying chemical fractions with Fourier Transform Infrared Spectrometry (FTIR). Results were published recently by the SPE (SPE #146107-MS).

CHOPS (Cold Heavy Oil Production with Sand)

Being a cold production technique, the oil and rock properties will fall in the range where the oil shear modulus is significant. During CHOPS production, substantial matrix material is produced with the heavy oil. "Worm holes" are developed in the sand matrix, propagating away from the borehole. Figure 6 shows schematically, how the CHOPS process develops. This process results in increasing the effective porosity in the region around the producing well.

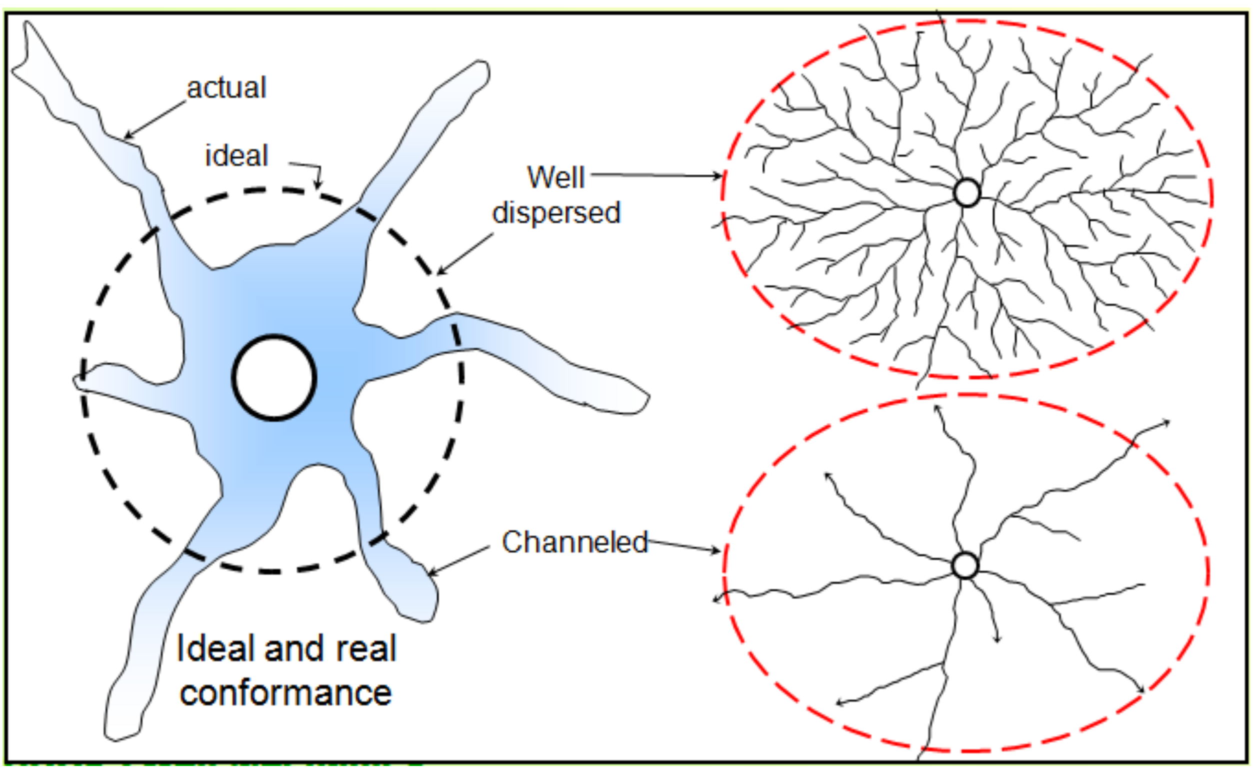

Figure 6. Schematic growth of "wormholes" during CHOPS production (from Maurice Dusseault , personal communication)

As a direct result of the oil/sand production, pore pressure decreases, the can oil drop below the bubble point, and gas will be produced. The combination of increased porosity and gas content enhances the geophysical time-lapse signature of CHOPS production.

A simulation cell was constructed for use with the Scanning Acoustic Microscope (SAM) to document the changes in acoustic properties during heavy oil production. Figure 7 shows the cell set up with heavy oil saturated sand.

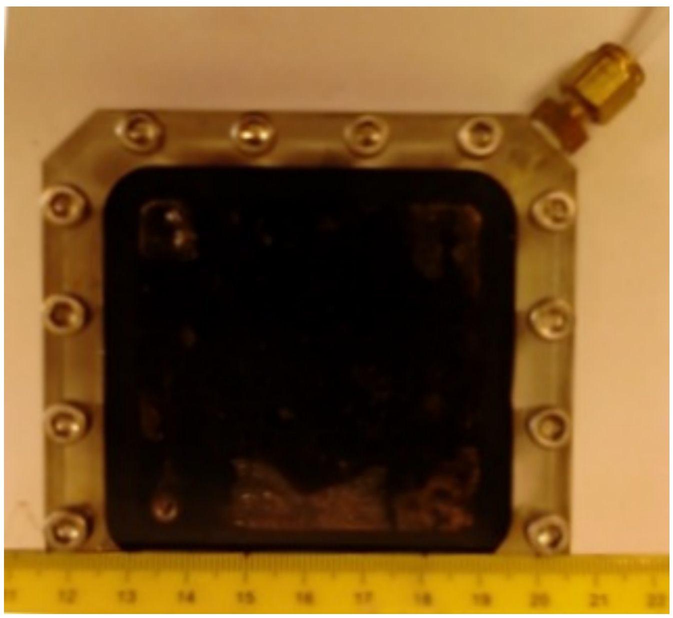

Figure 7. Flow cell to use with the Scanning Acoustic Microscope to monitor acoustic properties under simulated production schemes. Scale is in cm.

As a result of fluids crossing the bubble point during production, a free gas phase can develop, which has a dramatic influence on the seismic properties. An example is shown in Figure 8. The results of water-gas substitution shows a clear change in signal amplitude. Note in cross sections

(2), (3), and (4) how the signal is much stronger in the gas saturated region. This would be the effect we expect to see with seismic monitoring.

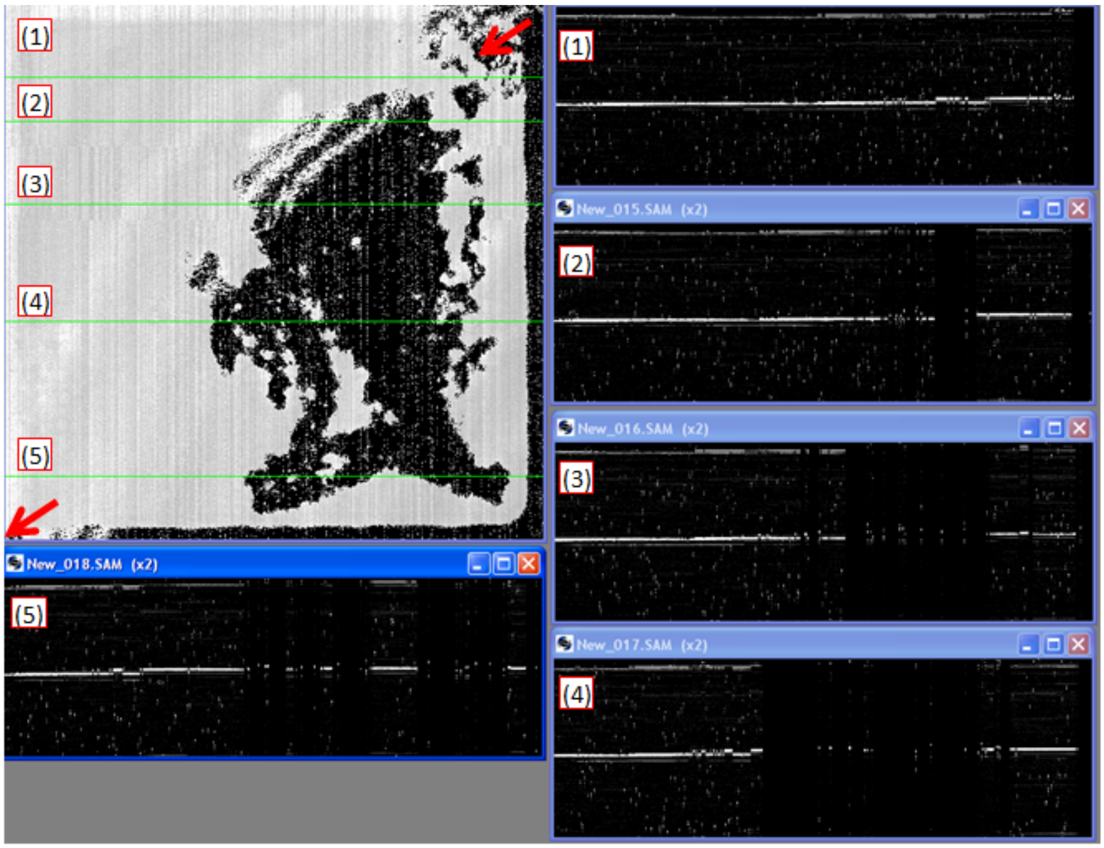

Figure 8. Cross sections collected with the Scanning Acoustic Microscope demonstrating the change in signature with changing phase. Red arrows indicate flow direction. (1) through (5) are the two dimensional acoustic images indicated by the green lines in the optical image to the upper left.

Seismic Modeling

The rock physics model continued with the CHOPS hypothesis and estimation of the properties of the wormholes for the Ugnu formation. Figure 9 shows initial modeling results using the CHOPS hypotheses parameters (Table 1) The first experiment focus on the transmission effect. The source is located in the borehole at 300 ft below the Ugnu formation, the receivers are at the top of the formation.

Figure 9 through Figure 11 displays the initial results, and the results of wormhole in the early starges of development. The bottom panel shows the amplitudes of the first arrival for this model. The absorption due to the presence of the wormhole is evident, suggesting the possibility of detecting small changes in the reservoir, and the capacity of imaging such changes both in the amplitude spectrum and the image space.

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Table1. CHOPS hypothesis – rock physics model

	Density (kg/m^3)	P-Velocity (m/s)	S-Velocity (m/s)	a(m)
Strata at t=0	1,950	2,470	1,050	10.00
Wormhole min	1,100	600	0	0.01
Wormhole max	990	360	0	1.00

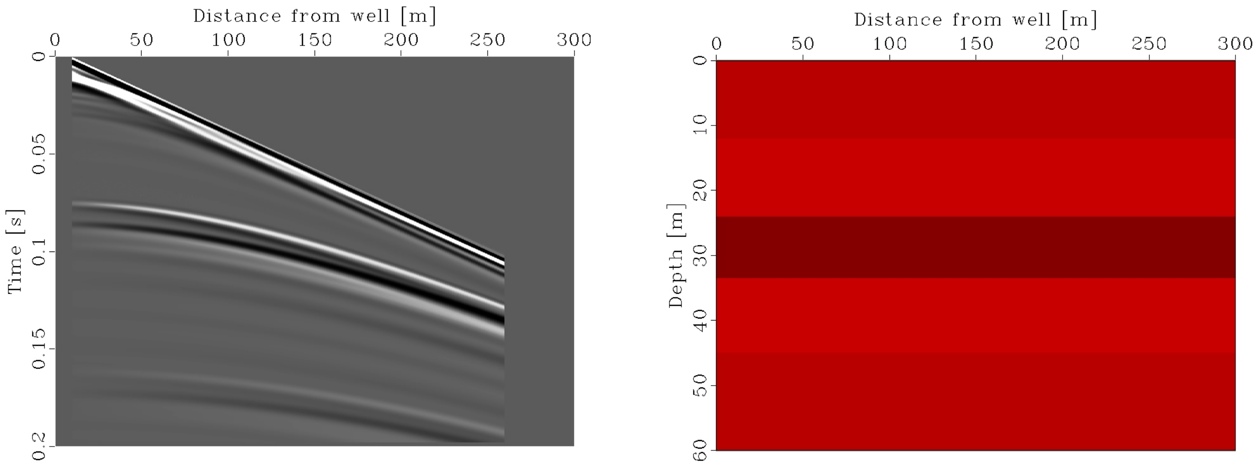

Figure 9. Initial model. Calibration from Ugnu formation.

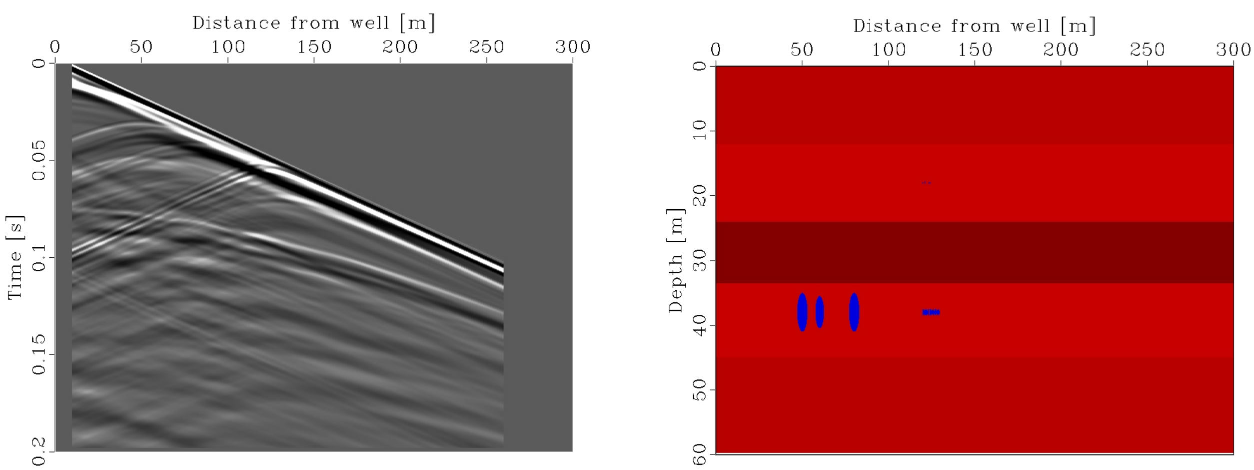

Figure 10. Ideal individual pattern, perfect circles (VE . 2).

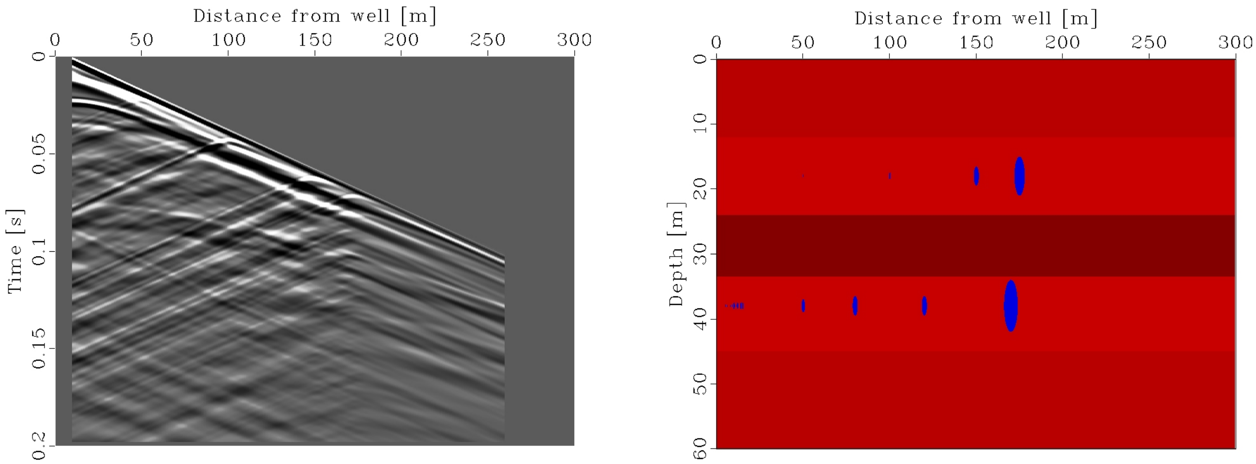

Figure 11. 2D wormholes distribution.

The figures display the initial results, and the results of wormhole in the early starges of development. Figure 11 shows the amplitudes of the first arrival for this model. The absorption due to the presence of the wormhole is evident, suggesting the possibility of detecting small changes in the reservoir, and the capacity of imaging such changes both in the amplitude spectrum and the image space.

Thermal Stimulation

In the long term, some kind of thermal stimulation is envisioned to sustain production in the heavy oil sands. Steam is normally applied in this process. Even without developing a separate steam phase, the seismic velocity of the heavy oil-saturated sand drops dramatically with increasing temperature. Direct measurements show around a 25% decrease in both compressional and shear velocities due to temperature changes alone. Introduction of a separate steam phase drops these velocities much further. Figure 12 shows the measured temperature profile developed in a SAGD (Steam Assisted Gravity Drainage) stimulation project in a heavy oil reservoir (measured in a vertical observation well adjacent to the injector).

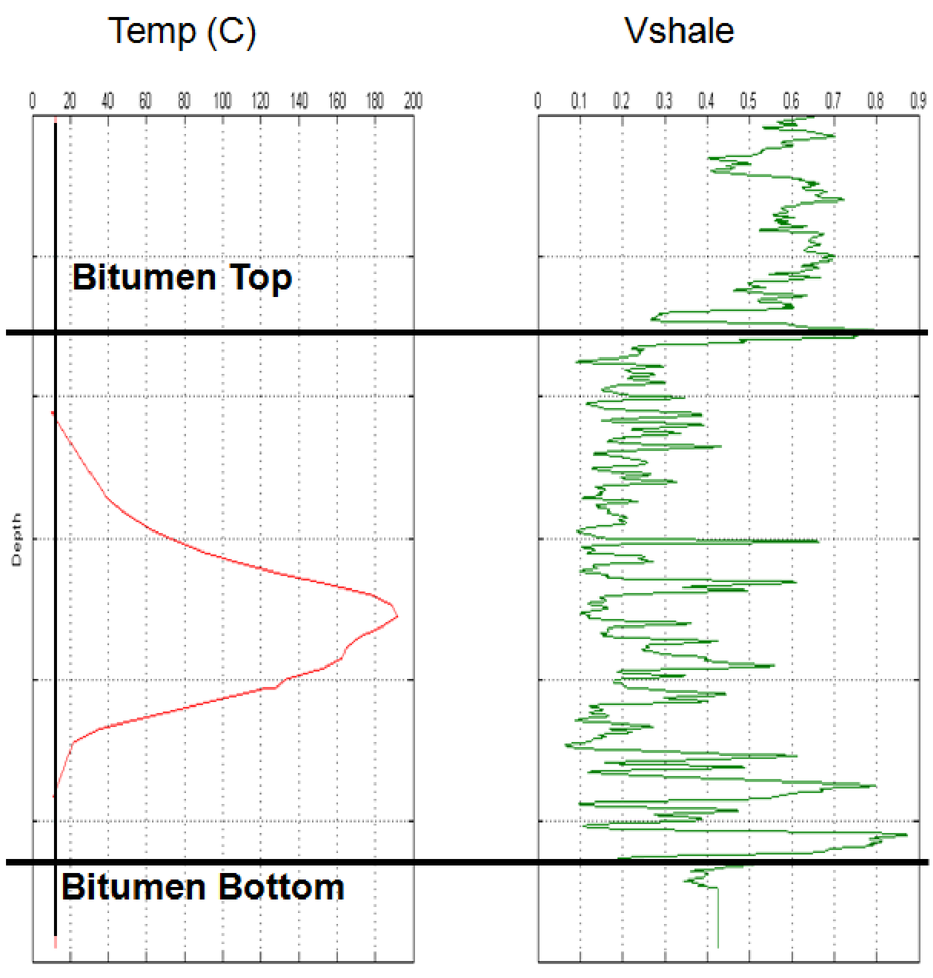

Figure 12. Temperature profile and gamma ray log (lithology) from a thermally stimulated well similar to the Ugnu sands. In this SAGD process, the high temperature zone starts near the middle of the reservoir zone (from Das, 2010).

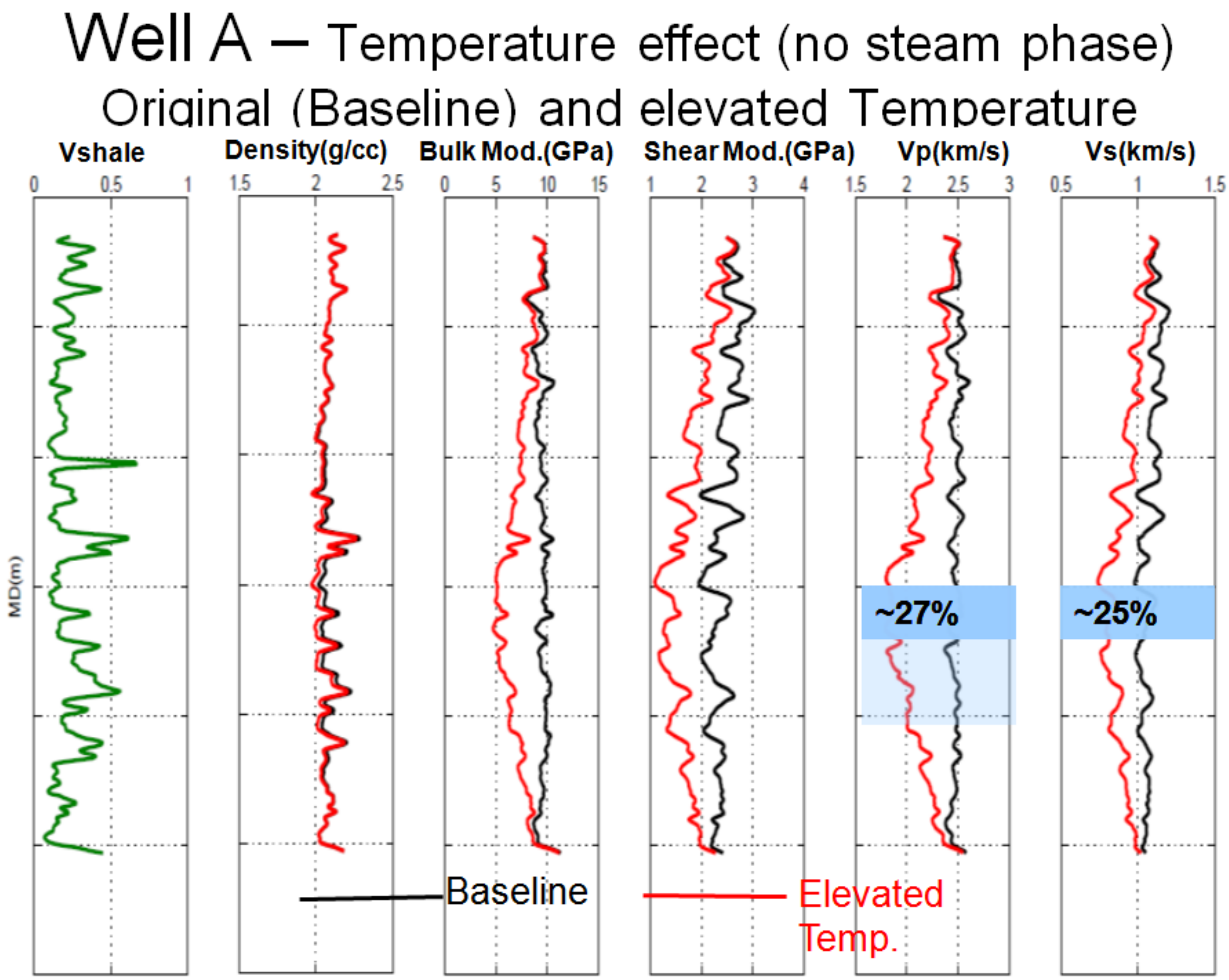

Figure 13. Measured baseline velocities before thermal stimulation and after stimulation through a heavy oil zone. Although no steam phase was introduced, the velocities dropped significantly (from Das, 2010).

In this well (well'A') we know the velocities and densities both before and after thermal stimulation. This allows us to calculate the expected seismic signature before and after stimulation. Figure 14 shows the synthetic seismic traces calculated using the original logs and the logs adjusted for the increased temperature. The change is substantial and indicates that monitoring a thermal process should be viable. Note that no separate steam phase was introduced to make this calculation.

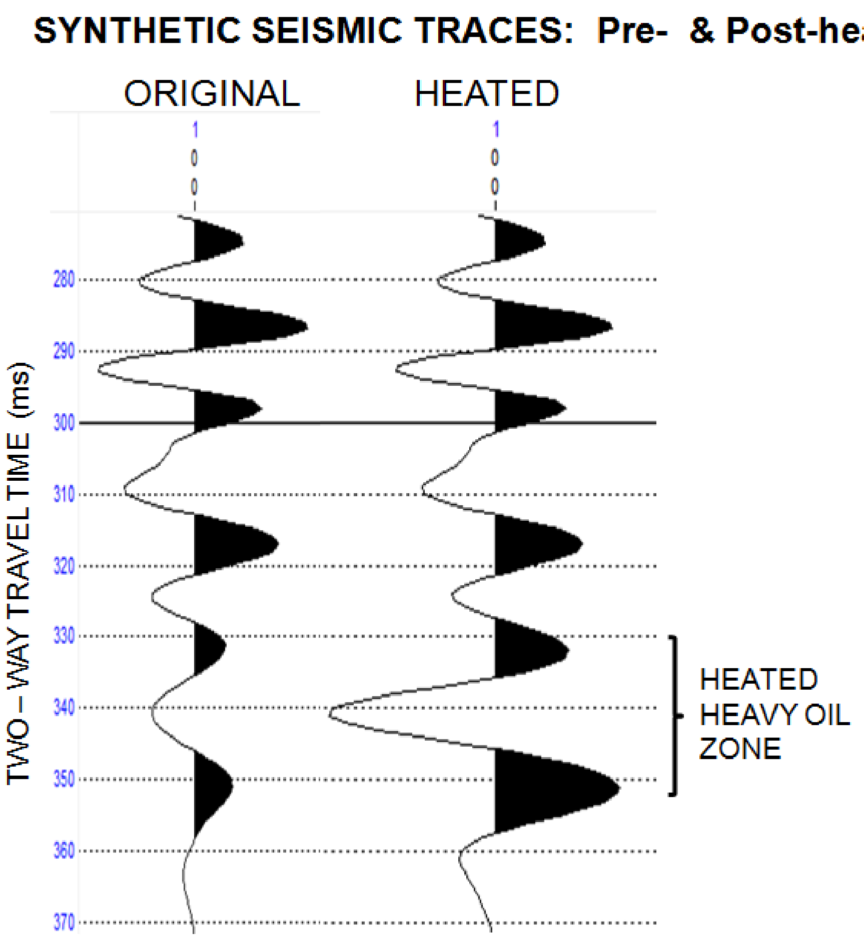

Figure 14. Synthetic seismic travel times pre and post thermal stimulation (from Das, 2010).

Lessons Learned

The accomplishments from the previous project include:

- Seismic Modeling: Both active modeling and passive monitoring studies are progressing under the direction of subcontractor Earthworks (E4Sciences). Signatures of wormholes developed during CHOPS are being observed.
- Rock Properties: Acoustic Imaging of fluid movements during flooding front: The fluid cell is constructed and initial measurements show a good acoustic contrast. Currently, we are importing the acoustic imaging data into standard seismic interpretation software to make laboratory scale fluid maps.
- Rheology: The Ugnu heavy crude sample viscosities were highly temperature dependent and reproducible over a long period of time. A significant contribution of the Elastic Modulus to its viscoelastic behavior was also observed with G' values as high as 3×10^5. A high-pressure experiment has begun to simulate reservoir conditions by reconstituting the gas components in the crude oil samples to account for phenomena such as live oils and foamy oils.
- Chemistry: Chemical characterization of Ugnu heavy oil identified about seventy maltene species. Partial linear squares regression models give correlation and prediction of heavy oil compound class and weights to shear viscosity. Laser pyrolysis molecular beam and MALDI-TOF mass spectrometry, high field NMR, and other techniques are examined to give more detailed chemistry about the heavy oil and its constituent asphaltenes. Additionally, our improved heavy oil fraction (SARA) separations yields results with 5% repeatability.
- Flooding: Subcontractor University of Houston is finishing thermal properties report on oil

and sands. Another set of experiments would be needed to more clearly determine the feasibility study of SAGD (or SAGD-CHOPS in combination) studies.

The CHOPS modeling by e4sciences examined:

(1) the constitutive models and constitutive properties of heavy oil sands
(2) compared the measured rock properties from borehole logs, laboratory measurements, and theoretical constitutive models
(3) the road map of processes involved in CHOPS
(4) hypothesized effect of CHOPS on seismic properties
(5) forward modeling of seismic waves as a function of frequency and wormhole diameter
(6) the possibility of electromagnetic imaging in the subsurface
(7) a simple umbrella configuration for monitoring wormholes in-situ
(8) feasibility and constraints for seismic response undergoing CHOPS dendrite or steam-flood fronts

The principle of equipresence requires that the we consider the effect of porosity, temperature, pore pressure, effective pressure, saturation, and frequency in the constitutive behavior of the Ugnu sands saturated with heavy 12° API oil. We treat the bulk and shear moduli as parallel sums of the frame and pore space moduli. The frame moduli are most sensitive to porosity and effective pressure. The pore-space moduli are most sensitive to pore pressure, temperature, partial saturation, and frequency. All of these factors are strongly interrelated in the viscoelastic behavior of the heavy-oil as demonstrated in theoretical description of the CSM laboratory experiments. In heavy oil sands, there are both bulk and shear pore-space moduli because of the finite rigidity of the heavy oil.

Seismically and sonically, the bulk and shear frame moduli drop to zero. The shear pore-space moduli drop to zero. The bulk pore space moduli drops to that of the gas/oil/sand emulsion/suspension. At the same time, the density declines from 1,950 to 990 kg/m^3 as the solid content decreases and the fluid density decreases due to partial gas saturation. The shear wave velocity goes from 1,050m/s to nearly zero, and the compressional wave velocity drops from 2,470 to 360m/s. This is a dramatic change in elastic properties and in the seismic response.

Conclusions

Monitoring protocols for cold production of Alaska Heavy Oils

Correlating chemistry, viscosity and rock properties would help tap vast domestic resource

In a project funded by the U.S. Department of Energy (DOE), the Colorado School of Mines led team, including the University of Houston and small business partner E4Sciences, has identified numerous properties of heavy oils that may lead to improved recovery of heavy oils in the North Slope of Alaska. BP Alaska has provided numerous samples of heavy oils and core for characterization by the team over the course of the project. The research could potentially enhance recovery of a resource with more than 10 billion barrels of oil in place, significantly extending the life of these oilfields.

Heavy oils are crude oils that are extremely thick (i.e., fluids have a viscosity that ~20,000 times thicker than water at room temperature), and thus production of these oils is difficult and expensive. Although the reserves of heavy oil on the North Slope of Alaska are enormous, difficult technical and economic hurdles are involved in producing these oils. The Ugnu formation contains the most viscous, biodegraded oils and standard production methods will be ineffective. Numerous alternative techniques for heavy oil production have been proposed (e.g., cold production, steam injection, etc). A prime factor limiting the efficiency of heavy oil recovery is the heterogeneity of the entire system. The heavy oils are viscoelastic materials with varying resin and asphaltene contents. The rocks containing the heavy oils have porosities, permeabilities, connectivities, mineral content, etc. that vary over short distances. Seismic attributes can monitor how well the recovery technique is sweeping the reservoir and where there are production complications.

The overall objective of the project is to advance the state-of-the-art of seismic monitoring, using chemical and physical characterization of core samples in combination with simulated production experiments, to optimize the recovery of heavy oils from Alaskan deposits. A state-of-the-art seismic monitoring program based upon chemical and physical characterization of core samples and simulated production experiments has potential to improve the technological and economic hurdles slowing development of the vast heavy oil resource on the North Slope of Alaska.

The accomplishments of the project cover a wide range of important technical areas. First, seismic modeling work under the direction of E4Sciences have identified signatures of wormholes (i.e., inhomogeneities in the rock where heavy oil is transported) developed during a simulation of cold heavy oil production with sand (CHOPS). Laboratory scale measurements of the rock properties include acoustic imaging of fluid movements during flooding. The acoustic imaging data collected will be transformed into fluid maps used to validate the seismic model. At subcontractor University of Houston, thermal properties have been measured on oil and sands to help determine the feasibility of using steam assisted gravity drainage (SAGD) or the combination of CHOPS and SAGD as a production strategy.

Additional laboratory experiments on the heavy oil fluids are identifying dozens chemical species (e.g., maltenes) and relating the chemical components with the oil's viscosity. The Alaska heavy oil's viscosity is highly temperature dependent and stable over a long period of time. The oils also show a significant contribution elastic character, which must be accounted for in the seismic models. Finally, a high-pressure experiment is providing some of the first viscosity data that directly simulate reservoir conditions (i.e., temperature *and* pressure).

The effect of CHOPS on seismic properties is strong and highly measureable. Two factors complicate the situation: very high intrinsic attenuation in the original heavy-oil sand, and the dendrites are finite objects of small cross section. Our idea is to overcome these factors and monitor wormhole development at small range and high frequency.

Seismic modeling suggests wormholes layers as small as 10cm in radios are detectable with frequencies of 100Hz and larger. The seismic effect on worhmholes is noticeable in the backscatter wavefield. Therefore, processing of data should focus on the analyses of scatters with amplitude changes in order to image wormhole changes.

Electromagnetic properties are sensitive to porosity, water saturation, and clay content. We performed a electromagnetic modeling experiment, The purpose of the electromagnetic modeling is to establish feasibility of the electromagnetic propagation and diffusion between wells. The flow zone is detectable at 400 kHz, with a >2 dB anomaly, if its resistivity is ≤20 Ω-m and its thickness is ≥2m. Models with higher-resistivity flow zones are difficult to detect, as significant anomalies occur only at large propagation distances when the absolute signal levels are very low.

The measurement will require large dynamic range (30 dB) and careful control of geometry.

Overall, the research on Alaska heavy oils may be applicable to over heavy oil resources in the United States. The program is managed by the Office of Fossil Energy's National Energy Technology Laboratory.

Potential Future Work

Viscosity mapping of Alaska heavy oil resources

The Colorado School of Mines (CSM)-led team is in unique position to perform transformative research on heavy oil resources and their impending production. The CSM team has been attempting to get support directly from BP Alaska (without success to date). Our team has unique expertise in rheology, chemistry, rock properties, and knowledge of the Alaska resources. Normally, a seismic map of an oil reservoir provides significant information on the properties of the rocks and fluids, which is subsequently used in simulators that guide production. However, a seismic map does not provide sufficient information for a heavy oil production for several reasons including accounting for the elastic character (G') of heavy oils. Thus, the team will develop a viscosity map, using conventional and novel experimental techniques (e.g., live oil rheology, **Figure 4**) and advanced statistical analysis, which will innovate how heavy oil resources are produced.

Impact of the Proposed Technology Relative to State of the Art

Although the reserves of heavy oil on the North Slope of Alaska are enormous (estimates of at least 30 billion barrels are in place), difficult technical and economic hurdles are involved in producing these oils. Developing additional production on the North Slope is important both for increasing national energy resources and to maintain the local economy that has become dependent on the energy industry. However, the Ugnu formation contains the extremely viscous, biodegraded oils and standard production methods will be ineffective. A prime factor limiting the efficiency of heavy oil recovery is the heterogeneity of the entire system and the excessive pressure at which the resource is located limiting the use of steam until later production phases. Production strategies require detailed knowledge of the resource properties and distributions. The heavy oils (fluids) are viscoelastic materials with varying resin and asphaltene contents. The rocks containing the fluids have porosities, permeabilities, connectivities, mineral content, etc. that vary over short distances. For this type of reservoir, seismic attributes are limited to monitoring how well the recovery technique is sweeping the reservoir and where there are production complications. Therefore, a novel and transformative study will produce a viscosity map of the heavy oil resource. The overall objective of this project is to advance the state-of-the-art with respect to rheological, chemical, and physical characterization of oil, rock, core and other samples from the varying geography of the North Slope of Alaska. If success, a plan for optimized, efficient recovery of heavy oils from Alaskan deposits would proceed and thus, the ARPA-E funding would provide hundreds of American jobs during the ~50 years of production.

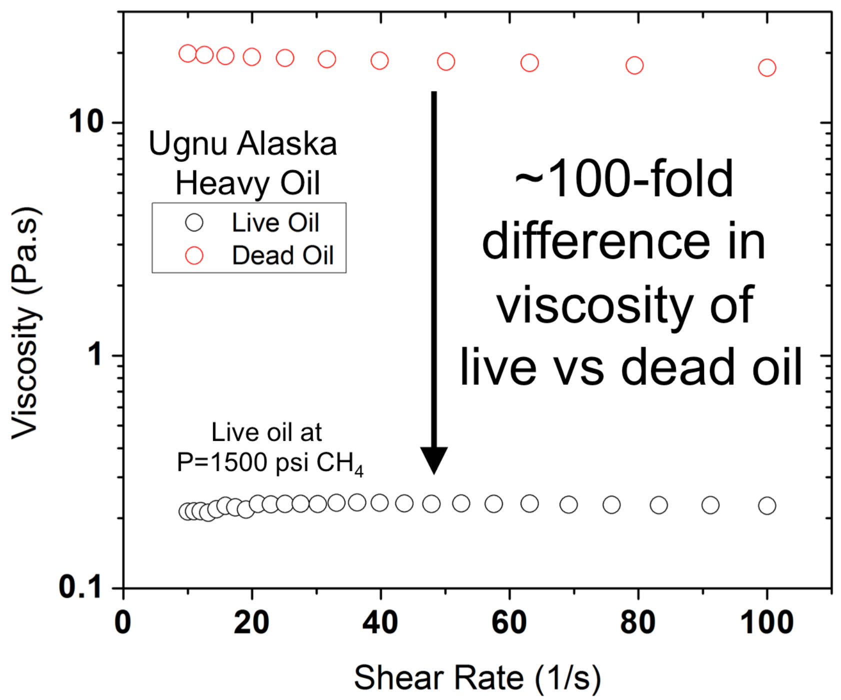

Figure 4. Viscosity as a function of shear rate for Alaska heavy oil (Ugnu) comparing live and dead oil

The unique ability of the Liberatore lab to do high-pressure rheology was recently published in *Review of Scientific Instruments* (doi:10.1063/1.3675889). This type of high-pressure rheology setup has been shown to simulate "live" oil conditions from produced heavy oil samples from Alaska (Figure 1) and the ability to quantify non-Newtonian features of oils and oil-sand slurries, which has rarely or never been completed for heavy oils. Thus, combining this unique, state of the art rheology with detailed chemical and rock properties will lead to a viscosity map and decrease uncertainty in several phases of the production of the massive Alaska heavy oil resource. Therefore, the goal of the project is to complete a viscosity map of the Alaska heavy oil resource, which will cover a number of project milestones:

- Correlating physical, chemical and rock properties of produced cores and oils. This work fits into the growing heavy oil database being constructed at CSM.

- Reformulate fluid/slurry properties for direct use in BP's simulators.
- Measurement and evaluation of oil extraction on matrix properties including strength and wormhole development
- Correlate heavy oil and heavy oil saturated sediment properties (viscosity, shear modulus) to log character (especially acoustics and NMR)

Many of our analytical techniques can be applied on heavy oils from a wide variety of locations. Our seismic-focused work on Alaska heavy oil provides an excellent case study that demonstrates the need for a viscosity map. These concepts will be expanded upon in a future proposal. BP is the obvious partner for future projects, and we will also pursue collaborations with groups at University of Texas-Austin if EOR or ASP flooding studies need to be completed.

Technology Transfer

The Project Management Plan (PMP), Technological Assessment, and Project Summary have been completed in cooperation with NETL. A number of trips to Alaska (January 2009, August 2010, November 2010, March 2012) were undertaken to coordinate sample/core retrieval, discuss objectives, and complete a sample testing plan with BP. Two talks by the group were made at the BP Heavy Oil Symposium in November 2010 with 150 people (from industry, academia, and government) attending in Anchorage, AK. Team gave over 20 presentations at technical meetings (Tabulated below). Five students completed graduate degrees and theses with others to finish at a later date (Tabulated below). Two peer-reviewed papers were published with others under review and being completed (Tabulated below).

Presentations

Authors	Title	Conference	Location	Date
M. W. Liberatore, C. Zhang, A. M. Herring, W. Wu, M. Prasad, A. Das, J. Dorgan, and M. Batzle	Rheological and chemical characterization of Alaska heavy oils	BP Heavy Oil Symposium	Anchorage, AK	11/8/2010
C. Zhang, A. M. Herring, M. W. Liberatore	Rheology and chemical characterization of Alaska heavy oils	ACS National Meeting	San Francisco, CA	3/22/2010
M. Batzle	Applicability of effective medium theories in modeling the viscoelastic properties of rocks saturated with heavy oil	The Oil Sands and Heavy Oil Technologies (OSHOT) Conference	Calgary, Canada	7/20/2010
D. Rosales, W. Murphy, W. B. Ward, B. Boyd, R. Nolen-Hoeksema	Dynamic processes in Ugnu Sands	The Oil Sands and Heavy Oil Technologies (OSHOT) Conference	Canada	7/20/2010
D. Rosales, W. Murphy, W. B. Ward, B. Boyd, R. Nolen-Hoeksema	Dynamic processes in Ugnu Sands	BP Heavy Oil Symposium	Anchorage, AK	11/8/2010
A. Das, M. Batzle	A combined effective medium approach for modeling the viscoelastic properties of heavy oil reservoirs	Soc. Exploration Geop (SEG) Annual Mtg	Denver	10/19/2010
A. Das, M. Batzle	Frequency dependent elastic properties and attenuation in heavy-oil saturated rocks	Industrial Consortium Annual Review	Golden	10/26/2010
D. Han, B. Liu, M. Batzle	Viscosity model of Heavy Oil with calibration of shear velocity data	Soc. Exploration Geop (SEG) Annual Mtg	Denver	10/27/2010
Batzle et al.	Ugnu modeling	Soc. Exploration Geop (SEG) Annual Mtg	San Antonio	7/4/2009
Han et al.	Bulk viscosity influence on heavy oil velocity	Soc. Exploration Geop (SEG) Annual Mtg	San Antonio	7/4/2009
Wu et al.	Minimizing Errors in Open Column Chromatography	Soc. Exploration Geop (SEG) Annual Mtg	San Antonio	7/4/2009
K. Li, B. Akeredolu, M. Liberatore, A. Herring, A. Renehan	Rheology and chemical characterization of Alaska heavy oils	ACS National Meeting	Denver, CO	9/1/2011
K. Li et al.	Alaska Heavy Oil Component Analysis using Molecular Beam Spectrometry: Temperature Programmed Thermal and Laser Pyrolysis	ASMS meeting	Denver, CO	6/5/2011
Michael Batzle, Matt Liberatore, Manika Prasad, De-hua Han, Bruce Ward, Daniel Rosales, Richard Nolen-Hoeksema, Beckett Boyd, Matt Art, James Trotta, and William Murphy	CHOPS Processes in the Ugnu Formation: Material Behavior of Grains and Fluids.	1st International Rock Physics Symposium	Golden, CO	08/2011
D. Rosales, W. Murphy, W. B. Ward, B. Boyd, R. Nolen-Hoeksema	Dynamic behavior of viscoelastic properties of Heavy Oil sands:A CHOPS example.	The Oil Sands and Heavy Oil Technologies (OSHOT) Conference	Calgary, Canada	07/2011
Han et al.	Core damage and velocity of heavy oil sand.	Industrial Consortium Annual Review	Houston, TX	9/25/11
M. Saidian, M. Prasad	Acoustic Monitoring of Fluid Flow in Porous Media	Industrial Consortium Annual Review	Houston, TX	9/25/11
D. Han	Thermal damage on velocities of heavy oil sands	Soc. Exploration Geop (SEG) Annual Mtg	Las Vegas	11/2012
A. Bazyleva, B. Akeredolu, M. Liberatore	Viscosity of Alaska heavy oil saturated with methane	ACS Rocky Mountain Regional Meeting	Westminster, CO	10/18/12
A. Bazyleva, B. Akeredolu, M. Liberatore	Viscosity of Alaska heavy oil saturated with methane	Society of Rheology Annual Meeting	Pasadena, CA	02/2013

Students

Name	Area of Study	Degree	Graduation Date	University
Agni Das	Geophysics	Ph.D.	December 2010	Colorado School of Mines
Wenwui Wu	Petroleum Engineering	M.S.	December 2010	Colorado School of Mines
Chenru Zhang	Chemical Engineering	M.S.	December 2010	Colorado School of Mines
Babajide Akeredolu	Chemical Engineering	M.S.	December 2012	Colorado School of Mines
Q. Yao	Geoscience	Ph.D.	June 2011	University of Houston
Milad Saidan	Petroleum Engineering	Ph.D.	December 2014	Colorado School of Mines
Fernando Martinez	Geophysics	M.S.	December 2011	Colorado School of Mines

Publications

Authors	Title	Journal	Volume	Year	Pages
Fernando J. Martinez, Michael L. Batzle and Andre Revil	Influence of temperature on seismic velocities and complexconductivity of heavy oil-bearing sands	Geophysics **77**, 19-34 (2012)			
K. Li, B. A. Akeredolu, A. M. Renehan, Y. Yang, M. Batzle, R. J. Evans, J. R. Dorgan, M. W. Liberatore, A. M. Herring	Correlation of Chemical and Physical Properties of an Alaska Heavy Oil from the Ugnu Formation	Fuel	in press. DOI: 10.1016/j.fuel.2012.07.037		
K. Li, C. McAlpin, B. Akeredolu, A. Bazyleva, K. Voorhees, R. Evans, M. Batzle, M. W. Liberatore, A. Herring.	A Rheological and Chemical Investigation of Canadian Heavy Oils From the McMurray Formation.	Energy and Fuels	in press, DOI: 10.1021/ef300608w.		
A. Bazyleva, B. A. Akeredolu, M. W. Liberatore	Viscosity of Alaska heavy oil saturated with methane	Energy and Fuels	submitted October 2012		

Acknowledgments

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