Seismic monitoring of “hot and cold” heavy oil production

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ABSTRACT

Time-lapse seismology has proven to be a valuable tool in the characterization of reservoir conditions in enhanced oil recovery (EOR). Our collective research experiences with Athabasca, Cold Lake, and Lloydminster oil sands demonstrate the utility of seismic monitoring for mapping steam front zones. Due to seismic velocity decrease with increasing temperature, seismic monitoring of steam zones can be achieved by time-lapse mapping of seismic reflectivity, impedance, and amplitude variation with offset (AVO). The application of seismic monitoring in cold oil production has not been widely applied. With cold production of oil sands, there can be the development of high porosity zones known as “wormholes”. These high porosity zones are much smaller than a seismic wavelength so their detection will be extremely difficult unless several wormholes collectively create a larger effective medium with low seismic velocity. Nevertheless, it is interesting to speculate whether time-lapse seismology has a role to play in the reservoir characterization of “cold flow” as well as in “hot flow” heavy oil production.

INTRODUCTION

Time-lapse seismology has been successfully used in the mapping of steam fronts in the enhanced oil recovery from heavy oil sands. This technology has been effectively utilized for almost two decades, following the studies by Nur et al. (1984), which showed that steam injection into oil sands could cause dramatic decreases in seismic P-wave velocity. In Western Canada, there have been seismic monitoring studies in the oil sands of Athabasca (Matthews, 1992), Cold Lake (Eastwood et al., 1994) and Lloydminster (AOSTRA Project Report #1296). All have shown that repeated seismic surveys can detect the decrease of seismic P-wave velocities that occur due to steam injection. In this sense, time-lapse seismology indirectly acts as a “thermometer” for the oil sands and can aid reservoir engineers in the scheduling of EOR steam injection. In addition to seismic monitoring of steam injection processes, there is also the question of whether seismic responses can detect porosity changes in cold production.

SEISMIC MONITORING OF “HOT FLOW”

During the last two years, CREWES has been involved in a study at Husky’s Pikes Peak field east of Lloydminster, on the Alberta-Saskatchewan border. The results of this research have been summarized by several papers in the CREWES reports of 2000 and 2001 and in the final report of AOSTRA project #1296. At Pikes Peak, various seismic attributes can be used to define steam zones including:

1. Seismic reflectivity (Watson and Lines, 2001)

2. Seismic traveltimes (Matthews, 1992)

3. Seismic acoustical impedance (Watson and Lines, 2001)

4. AVO (Downton and Lines, 2001; Russell et al., 2001)

5. V_P/V_S ratio changes with temperature (Watson and Lines, 2001).

All of these seismic measurements show promise as means of detecting temperature changes in the reservoir due to steam injection. As yet, it is not clear as to which of these measures is best for seismic detection. Each has its own advantages and disadvantages.

The differencing of seismic reflectivity is the simplest and most direct approach. It would generally be used first as a basic test of the acquisition and processing. If the time-lapse reflectivity estimates did not show significant differences, then time-lapse versions of impedance inversions would not show significant differences. In obtaining time-lapse reflectivity estimation, one would hopefully have used acquisition and processing that showed virtually no change in seismic response for zones unaffected by steam injection while showing pronounced differences in zones where seismic velocity was affected by steam injection. For the Pikes Peak data, we can refer to Figure 1, from Watson and Lines (2001). The largest differences in seismic amplitudes are shown in the middle of the section between 0.6s and 0.75s, in the zone of recent steam injection.

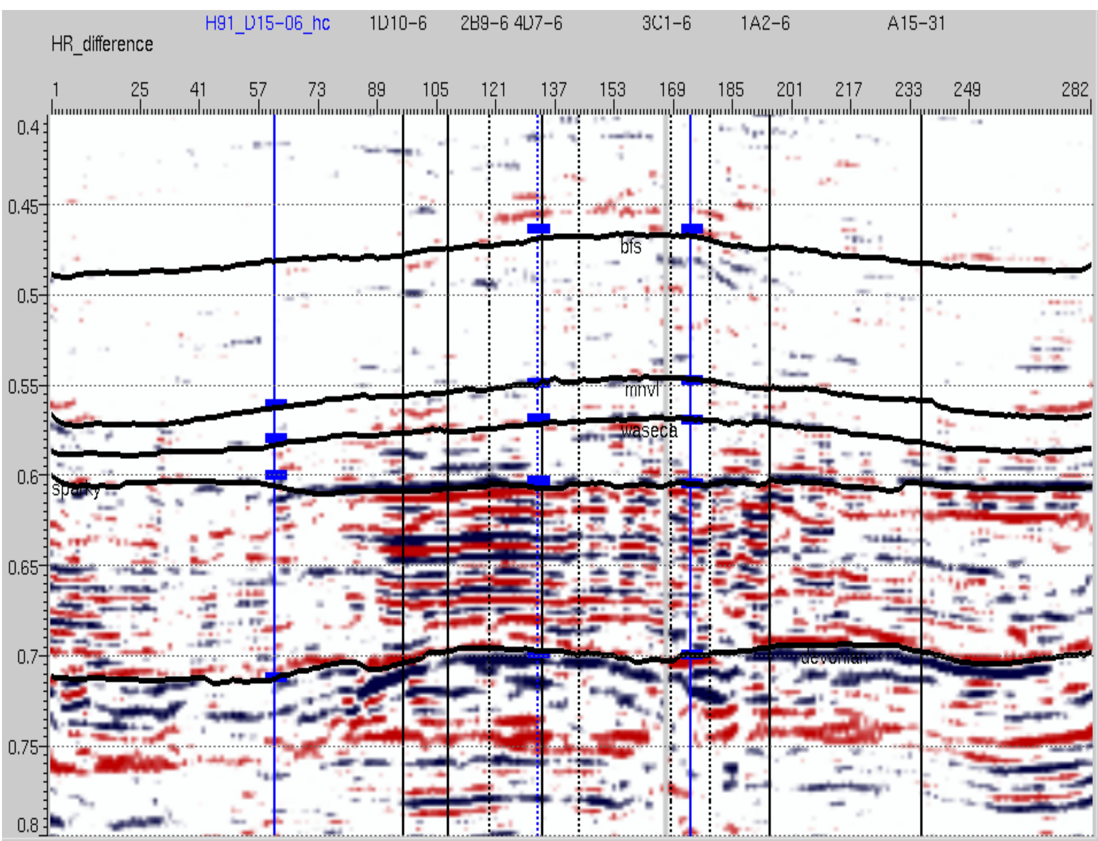

FIG. 1 Seismic amplitude difference section from Watson and Lines (2001). Time window is from 0.4 to 0.8 s over a distance of 2.81 km with trace spacing of 10 km.

In addition to monitoring changes in seismic amplitudes, we can monitor seismic traveltime changes. This has been tested with Athabasca oil sands at Gregoire Lake, Alberta by Lines, Jackson, and Covey (1990) and by Matthews (1992). Although seismic arrivals are delayed by a few ms after steaming, this is a detectable amount. Traveltime delays can be indications of steam zones.

Since impedance estimates from trace inversions include integrated seismic reflectivity and well log information, one would expect to see changes in the impedance at the same locations as zones of reflectivity difference. The advantage of using impedance estimates rather than reflectivity is that the estimated impedance (product of density and seismic velocity) is a more direct indicator of rock properties than the seismic amplitude. Watson and Lines (2001) show the time variation of impedance for Pikes Peak data.

AVO is another indicator of time-lapse changes in the reservoir. AVO involves the analysis of seismic amplitudes in their unstacked (or partially stacked) form. This has the advantage of illuminating lithology changes and fluid property changes in the reservoir and the disadvantage that unstacked data generally contains more noise than stacked data. It is difficult to correctly perform AVO analysis for at least three reasons. First, one has to be very careful to not distort the “true amplitude” nature of seismic amplitude variation in processing and since almost every step in seismic processing can distort amplitudes, this is not an easy task. Second, there is generally more noise in unstacked data. Third, AVO is an inversion process in which there are ambiguities or problems with nonuniqueness since we can correctly model the data with models that may be inaccurate. Nevertheless, despite these disadvantages, AVO can be useful. This was demonstrated for the Pikes Peak data by Downton and Lines (2001) and by Russell (2001). The paper by Downton and Lines (2001) showed that the “fluid stack” (indicator of steam) and the “delta lambda” stack (change in Lame parameter, lambda) show anomalies resulting from steam injection. Russell (2001) shows that changes in AVO attributes of intercept and gradient can serve as indicators of changes in porosity, temperature, water saturation, and pressure.

A fifth measure of temperature variation involves monitoring V_P/V_S ratio changes in the reservoir. This approach is demonstrated in the CREWES 2001 report by Watson et al. This method relies on the fact that in heavy oil sands, both P-wave and S-wave velocities decrease with increased temperature, but that the P-wave velocity decreases more than the S-wave velocity. (See the Core Laboratory results presented by Watson et al., 2001). Based on the rock property measurements, one would expect to see a significant decrease in the V_P/V_S ratio in zones of steam injection. At Pikes Peak, reductions in the V_P/V_S ratio coincide with zones of steam injection. In contrast to the other three methods, this method of time-lapse monitoring makes more complete use of the multicomponent data measurements of the elastic wave field.

The use of time-lapse seismology to characterize heavy oil reservoirs with steam injection has shown considerable progress over the past two decades. We have seen research and development within our own AOSTRA Project #1296 and other projects in Alberta and Saskatchewan. In addition to “hot flow” projects in oil sands, interest is also emerging in “cold flow” projects.

SEISMIC MONITORING OF WORMHOLES

In addition to the production of heavy oil from the steam injection in Pikes Peak field, there is production from cold flow heavy oil fields in the surrounding areas. In the cold flow production process, oil and sand are simultaneously produced in unconsolidated heavy oil reservoirs by using non-thermal extraction. Tremblay et al. (1999) give a lucid review of cold production processes. One of the phenomena in oil sand production is the development of wormholes. Wormholes are permeable sand tubes of very high porosity (over 50% in some cases) which extend out from the borehole and which develop during oil sand production. The high viscosity of oil sands gives the sand a higher compressive strength when dilated due to pore suction. In the lab simulations, it is seen that wormholes develop within the weaker, cleaner sands with the highest oil content. Given the higher porosity (and lower seismic velocity) of wormholes, there is the question of seismic detectability. Can wormholes be detected by seismic experiments?

Seismic detectability will undoubtedly be a function of the wormhole diameter and the seismic frequencies achievable in an experiment. In order to answer these questions, one could use modeling – both numerical and physical. If models demonstrate feasibility, then one would try field experiments.

We can test feasibility with numerical computations such as finite-difference wave equation modeling. Figure 2 shows the shape of a wormhole similar to that illustrated by Tremblay et al (1999). This model contains 60 rows and 60 columns of 10 m square cells. The model contains velocities of highly porous sands (1677 m/s) and porous sands (1923 m/s), overlying a carbonate with velocity of 2500 m/s. The zero-offset seismic response for this model is shown in Figure 3. The arrivals differ from the case of a single flat reflection event that would occur for the case of no wormholes.

However, Figures 2 and 3 may represents the case of a ridiculously optimistic “mega-wormhole”, since individual wormholes are at least two orders of magnitude smaller than this case. So unless this model is a valid “effective medium” containing several adjacent wormholes over several meters, we would have to consider a scaled version of this model. Instead of ms samples in our seismogram, we would need to consider 10 microsecond samples. Instead of a seismic wavelet with a dominant frequency of 35 Hz, we would need a frequency of 3500 Hz. The only situation in which we could even approach frequencies of this magnitude would be with borehole piezoelectric seismic sources. Even in using these sources, we would need wave propagation through rocks with very high Q (low absorption) in order to maintain high frequency content. Seismic detection of wormholes is an important, but difficult, problem in reservoir characterization of heavy oil production. More research is needed.

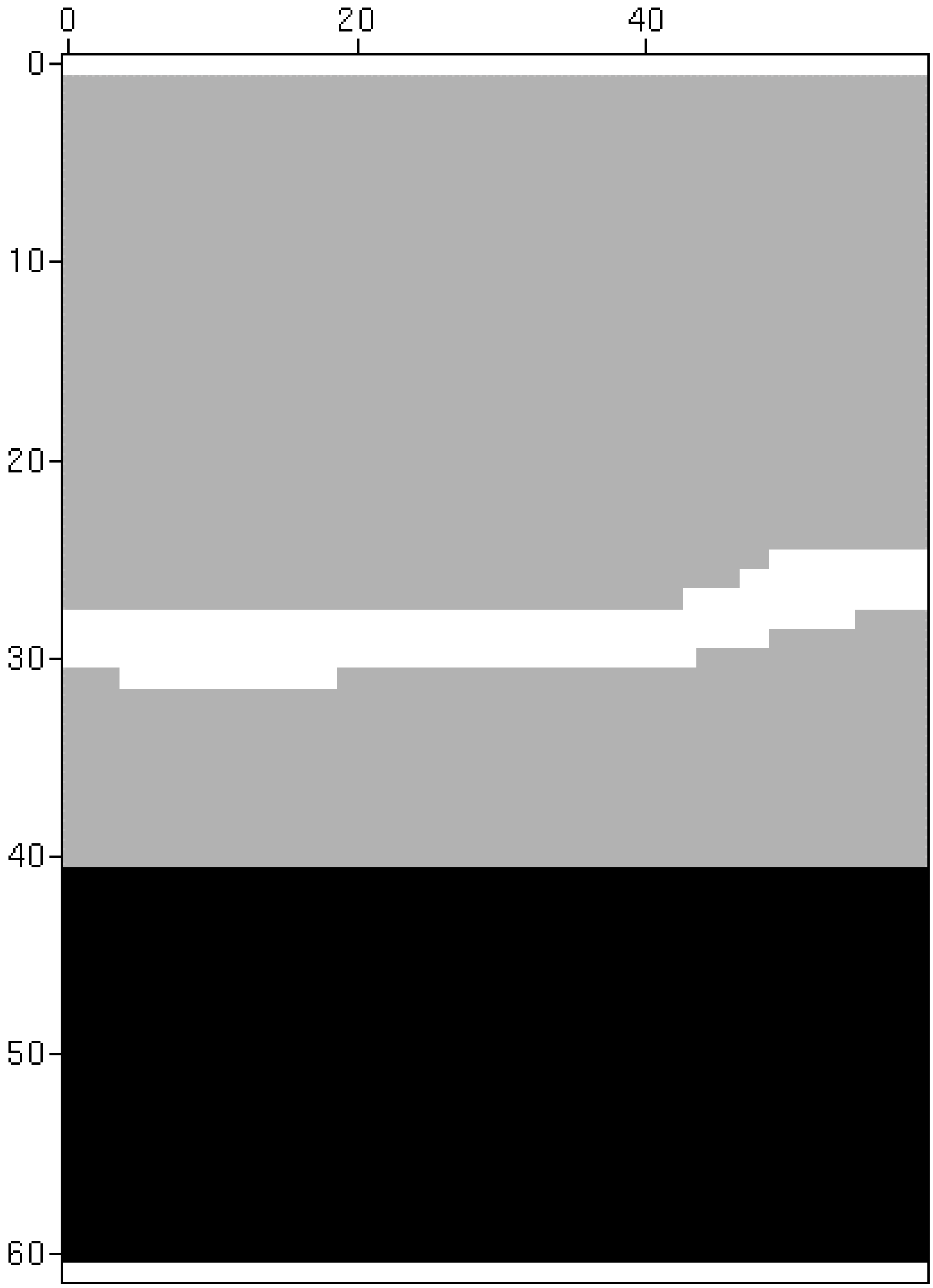

FIG. 2. Velocity "mega-wormhole" model for a highly porous sand with low velocities of 1677 m/s (white), embedded in porous sands of 1923 m/s (grey), overlying a carbonate of 2500 m/s (black). The model is a 60 by 60 array of cells of size 10 m by 10m.

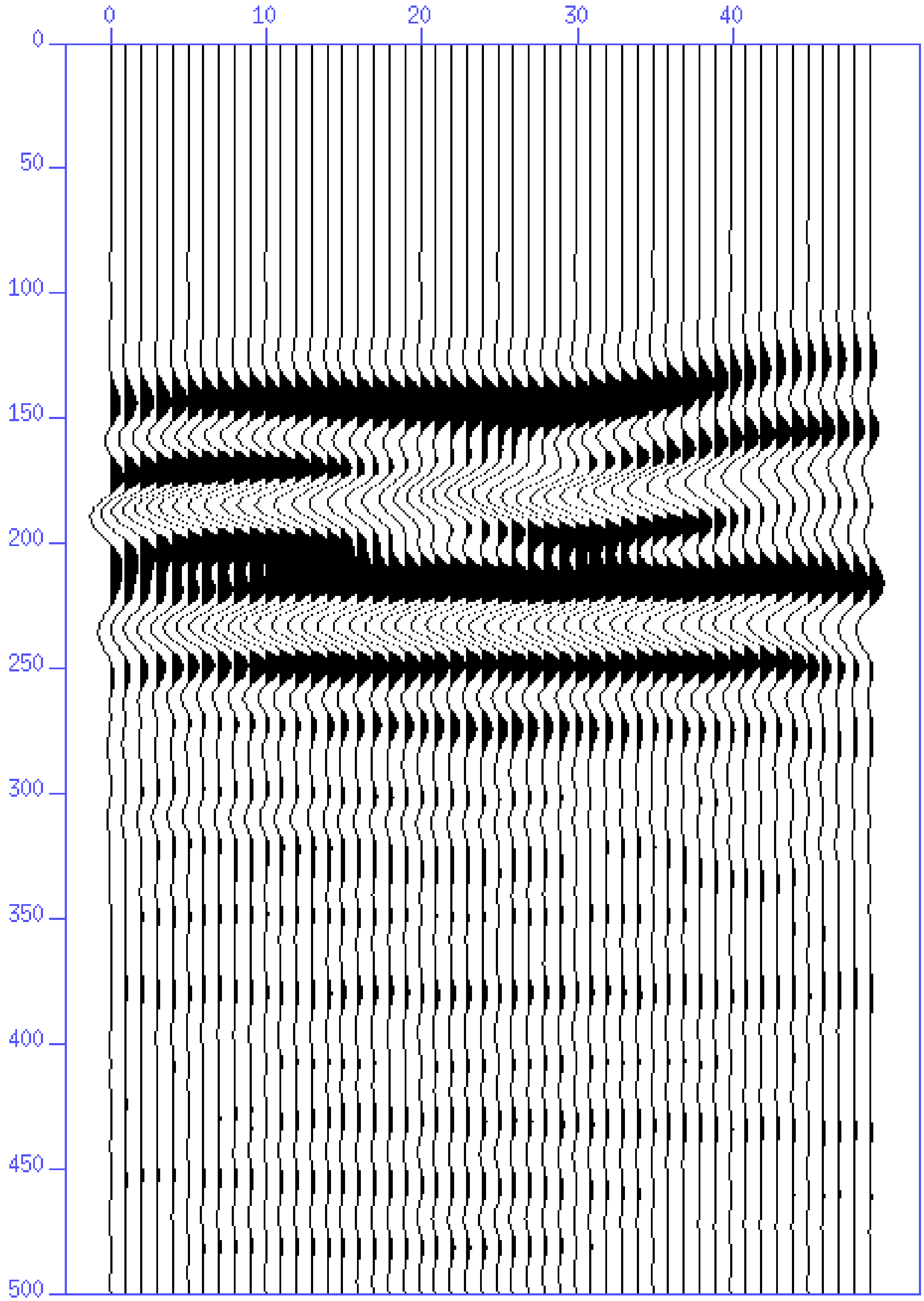

FIG. 3. Zero-offset seismic section for the wormhole model. Traces are at 10 m spacing and at offsets 50 m to 550 m and the vertical axis is in ms. The dominant frequency is 35 Hz.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The applications of time-lapse seismology to hot flow heavy oil production are well known and widely used in the heavy oil fields of Alberta and Saskatchewan. Useful tools include reflectivity differencing, traveltime differencing, impedance differencing, AVO, and the estimation of V_P/V_S ratios. All attributes show some potential for mapping steam fronts in EOR. The time-lapse monitoring of cold production phenomena such as wormholes may be a much more difficult challenge. Future research will include both modeling and real data analysis to test feasibility.

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