

Monitoring active steam injection through time-lapse seismic refraction surveys

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Introduction

Steam-assisted gravity drainage is an effective recovery method employed in shallow heavy oil reservoirs to increase the amount of recoverable oil. To ensure effective recovery, seismic monitoring of an active steam flood is essential in delineating the location of stimulated reserves. Typically, large and dense 4D reflection surveys are recorded to trace the motion of the steam flood, observable in terms of time-shifts and amplitude differences. However, it is proposed that time-lapse refraction profiles can be employed to monitor the movement of an active steam flood within a reservoir in a manner similar to that of 4D reflection profiles. Through reciprocal traveltimes analysis, refraction profiles can delineate significant time-shifts within a monitor survey due to the injection of a steam flood. Observed time shifts values are dependent on steam chamber dimensions, reaching as high as 25 ms for a 60 m thick steam chamber.

This study will outline the basis for 4D refraction surveying through simple numerical modeling of a shallow, heavy-oil reservoir. Modified from an original design proposed by Hansteen et al., (2010), this method provides a way to compensate for traveltimes differences that might be caused by different shot statics between monitor and baseline surveys, hence reducing the uncertainty in the source of observed time-shifts recorded at the geophones.

Method

Time-lapse refraction surveys were numerically modeled over a schematic reservoir undergoing active steam assisted recovery. For simplicity, surveys were modeled over layer-cake geometry with average formation thickness and depth appropriate for a shallow oil sands deposit (Figure 1). The velocity structure of the McMurray Formation reservoir is an ideal candidate for a refraction analysis due to the large velocity contrast between the McMurray Formation and the underlying high-velocity Devonian rocks. The McMurray Formation reservoir was assigned a P-wave velocity of 2200 m/s, and the underlying Devonian carbonates a P-wave velocity of 5500 m/s. All formations overlying the McMurray formation are referred to as overburden, with a thickness of 20m and an average P-wave velocity of 1900m/s. (Lines et al., 1990; Bianco, 2008; Eastwood, 1993; Forgues et al., 2006).

The refraction survey modeling consists of a single refraction line with reciprocal shot points and a series of single component geophones within the center of the array. To provide sufficient areal coverage, 2D refraction lines are recorded in a radial pattern, every 11 degrees. This pattern will simulate a large and dense pad of geophones occupying the center portion of the array, overlying the steam chamber. Figure 1 shows a schematic model and survey design, and projected ray paths for refractions from the underlying Devonian carbonate.

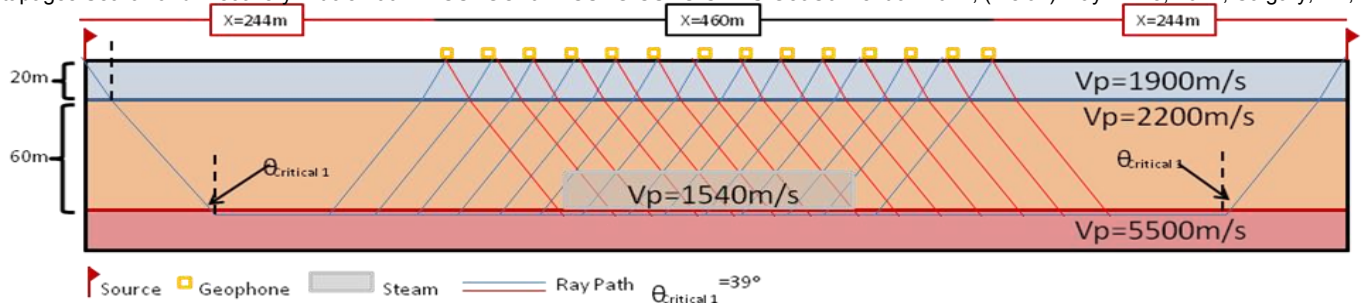


Figure 1. Geological model and survey design. Note that each source location also contains one single component geophone. Projected ray paths show both the forward (blue; from shot point A to B) and reverse (red; from shot point B to A) refraction profiles.

Refraction surveys are employed pre and post steam injection to record a baseline and monitor survey, and for modeling different sized steam chambers. Recorded travel time differences due to the presence of steam are observable as time-shifts recorded on first-arrival head waves, and observable through the subtraction of baseline survey traveltimes from those recorded by the monitor surveys. By placing a geophone at each shot point location, ambiguity is removed from observed time-shifts through the subtraction of travel times on the source side of the array, leaving only time-shifts due to steam injection. Figure 3 is an example of time shifts due to a 60m thick steam chamber.

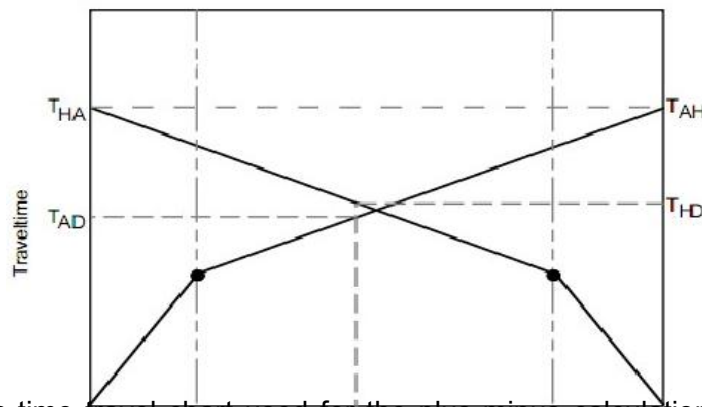


Figure 2. (a) Schematic time travel chart used for the plus-minus calculations. D = common receiver (Chen, 2009).

Data Interpretation

To quantify the changes due to simulated steam injection, traveltimes values from the baseline survey were subtracted from values in each monitor survey, leaving only time-shifts within the reservoir. However, this simplistic approach requires further consideration. Traveltimes changes observed on a monitor survey may be caused by time differences on the source side rather than the presence of a steam chamber on the receiver leg of a refraction raypath. For instance, changes on the source side of the array, potentially introduced through issues such as changes in source statics, may introduce slight time shifts which may be wrongfully attributed to changes within the reservoir. To mitigate this, we calculated and removed the traveltimes of the downgoing transmitted wave field from the source point, leaving only traveltimes for the headwaves refracting along the Devonian carbonates and propagating upward through the reservoir. Removing this component of the traveltimes plot decreases the likelihood that traveltimes changes are due to sources other than steam injection within the reservoir. These travel times can be quantified through a calculation of the T^+ component, where $T^+ = T_{AD} + T_{HD} - T_{AH}$ (Figure 2). In a time-lapse sense, we are comparing differences in T^+ traveltimes. Hence, we can effectively determine the traveltimes for the downgoing portion of the wavefield for each monitor survey, resulting in time differences attributable only to the upgoing wavefield through the steam zone

Results

Observed traveltimes changes along a modeled 2D refraction line were projected into 3D in an azimuthal distribution and plotted in map view (Figure 4a). Due to the symmetry of the model and the applied velocity taper, observed time-shifts form a bull's-eye pattern, showing the extent of the steam chamber as well as the reduction in heat with increasing distance from the injection location.

Our modeling was extended from a vertical injector well to a simulate heating via a horizontal SAGD well pair. Due to this new geometry, observed traveltimes did not form a bulls-eye pattern, but instead reflected the geometry of the horizontal injection well in the area of steam injection (Figure 4b).

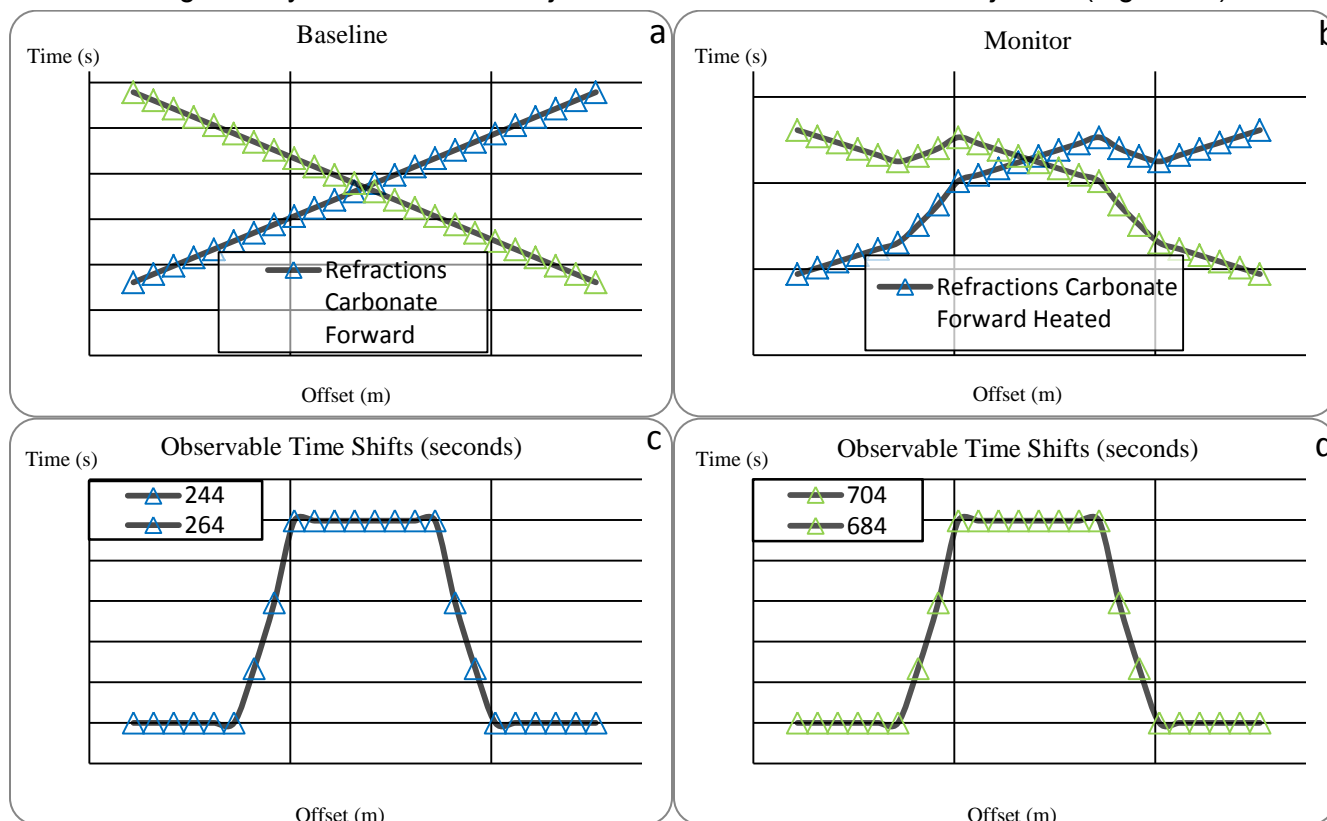
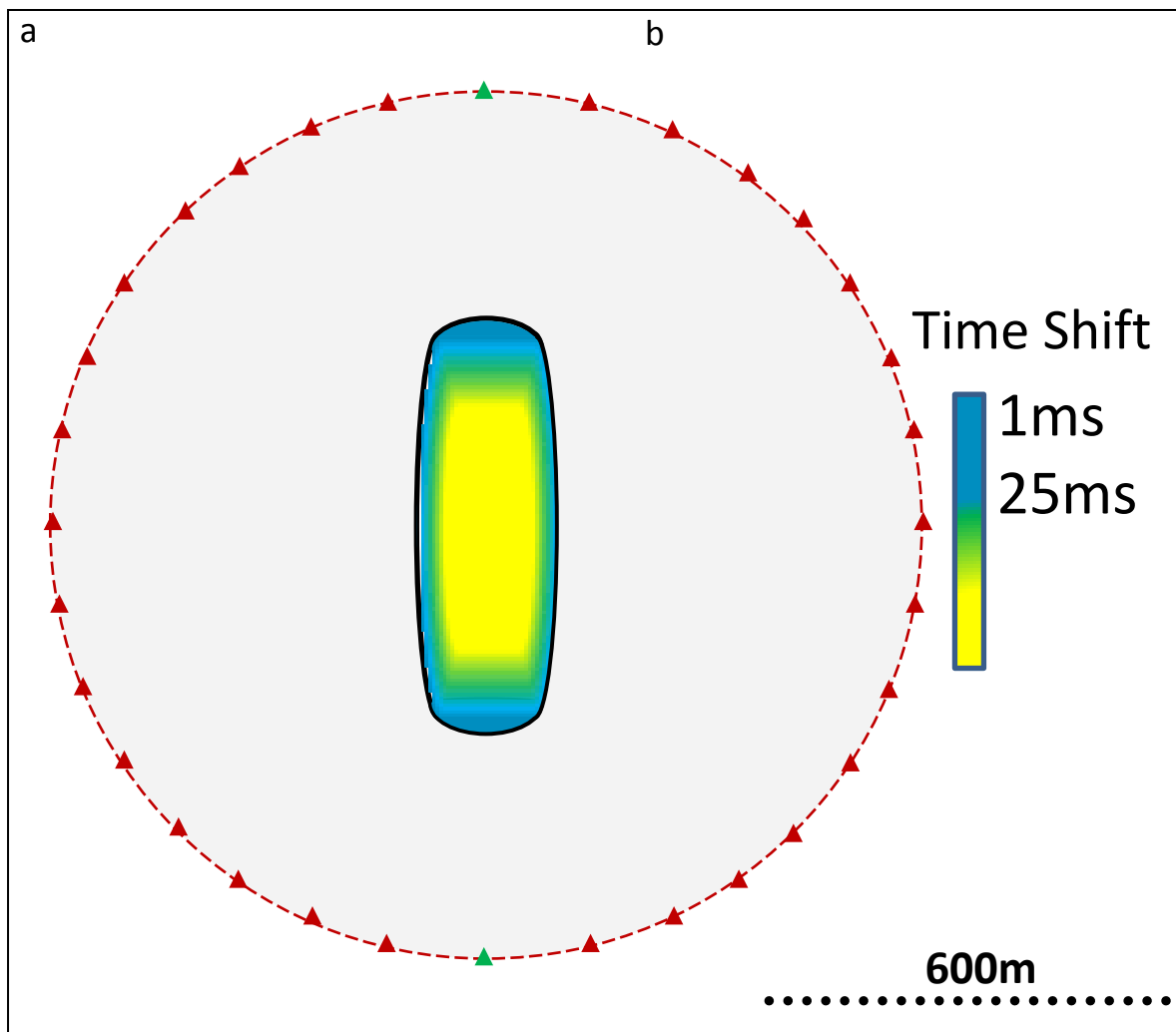


Figure 3. (a) Traveltime chart before the injection of steam. (b) Traveltime chart for a 60m thick, 140m long steam chamber after the subtraction of the downgoing wave. (c) Traveltime chart for the forward refraction profile showing the traveltime difference between the baseline and monitor survey. (d) Reverse profile for the same refraction line.



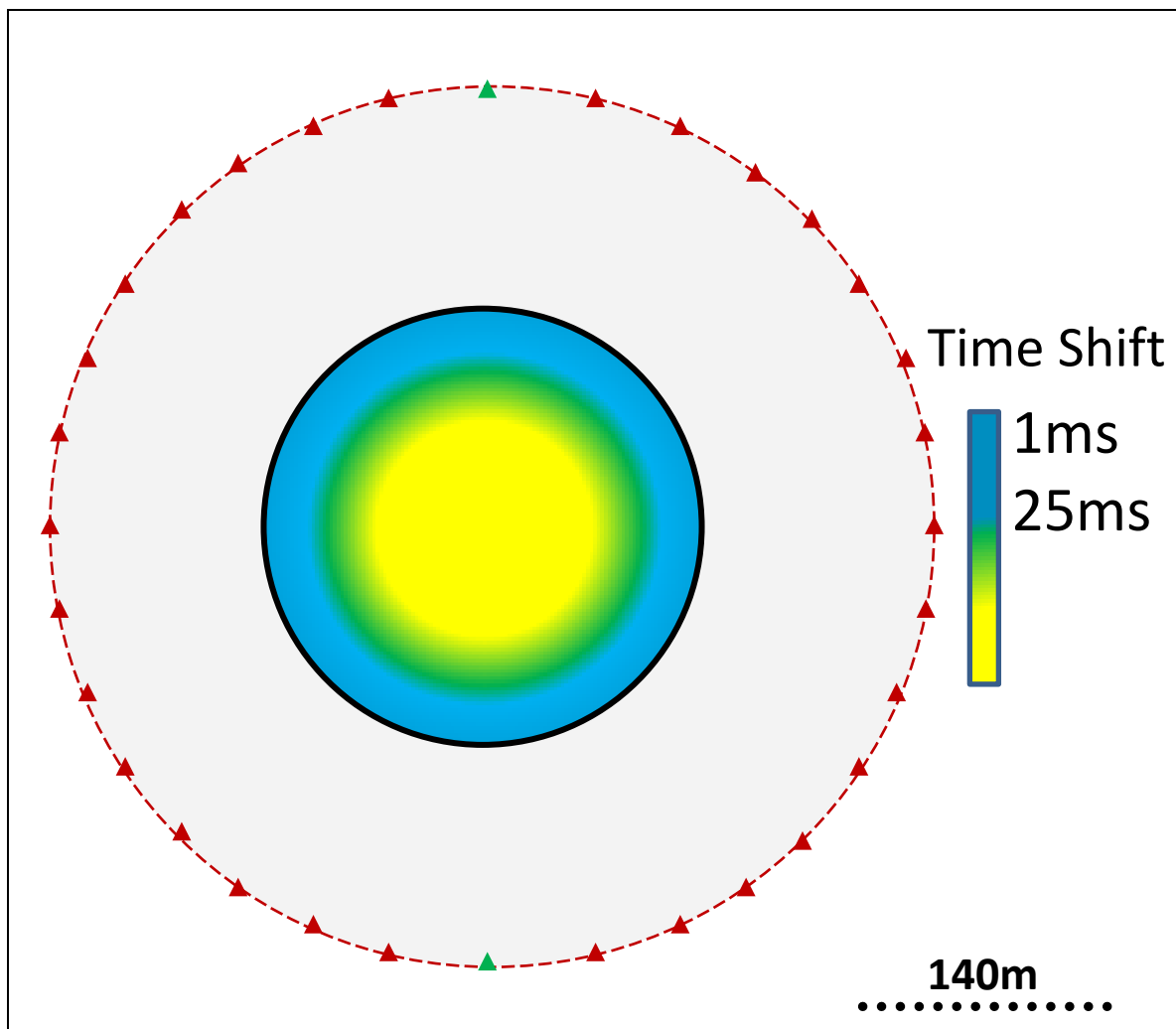


Figure 4 (a) Distribution of time-shifts due to a 60m thick symmetrical steam chamber, 140m wide. Velocity values decrease near the edges of the steam chamber due to the reduction of heat with distance from the injection location (center). (b) Distribution of time shifts due to a 60m thick asymmetrical steam chamber, representing heating through a horizontal injector well. The steam chamber is 600m long by 200m wide.

Conclusions

SAGD is an effective recovery method employed to shallow heavy oil reserves to increase the amount of recoverable oil in place. However, to ensure effective recovery, seismic monitoring of an active steam front is essential in delineating the location of stimulated reserves. Time-lapse refraction profiles can be employed to monitor the movement of an active steam front within a reservoir similar to that of 4D reflection profiles. This technique has been previously developed by Hansteen et al., in 2010, but has been modified by removing the traveltimes of the downgoing wavefield on the source side of the array, effectively reducing the uncertainty associated with observed time-shifts. Error values of the calculated plus and minus traveltimes are in the range of +/- 1.0 ms, a considerable amount less than observed time-shifts from steam injection.

Acknowledgements

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References

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