Time-lapse multi-component seismic modeling of CO_2 fluid replacement in Redwater Leduc Reef, Alberta

Taher M. Sodagar and Don C. Lawton, University of Calgary*

Summary

Common shot multi-component ray tracing modeling was undertaken to evaluate variations in the seismic response of the Redwater reef along the 2D line across the southern margin of the reef as well as with CO_2 saturation in the Upper Leduc interval zone. The input geological model was based on well data and depth-converted seismic data from the interpretation of 2D seismic lines in the area. P-wave and P-S wave Ray tracing synthetic seismic sections demonstrate similar seismic attributes for the Mannville, Nisku, Ireton, Cooking Lake, and Beaverhill Lake Formations. The Cooking Lake and Beaverhill Lake formations display positive structure below the reef in time sections due to the lateral velocity change from on-reef to off-reef, but corrected in the depth sections.

Terminations and the lateral position of the Upper Leduc and Middle Leduc events are obvious on the pre-stack time-migrated section and a modest improved on the depth-migrated section. Higher amplitudes at the base of Upper-Leduc member are evident near the reef margin due to the higher porosity of the foreslope facies in the reef rim compared to the tidal flat lagoonal facies within the center of the reef. Time-lapse seismology proved showed amplitude and traveltime differences for the seismic data before and after CO_2 saturation. A fairly good contrast reflection occurring at the top of upper-Leduc, top of the rim, and base of upper-Leduc near the reef edge was strong evidence to observe and monitor CO_2 saturation with seismic data.

Introduction

The main objective of the study was to create a 2D geological model of the Redwater reef, from the reef center to off-reef, across the southern margin of the reef. Seismic modeling was then undertaken to generate 2D P-P and P-S converted wave synthetic seismic data to map facies variations within the reef, based on seismic character, and to characterize the reef members and formations below the reef. Another objective was to build same model of the reef, with CO_2 saturation in the Upper Leduc member zone. Fluid substitution seismic modeling was then undertaken to generate a 2D P-P and P-S synthetic seismic data with same parameters to trace the consequences of CO_2 saturation on the reef formation facies.

The study area is located in the Redwater region of Alberta, northeast of Edmonton (Figure 1). The Leduc reef at Redwater is one of the largest Devonian Leduc reefs in the Western Canada sedimentary basin (WCSB). The Redwater reef is in the Heartland area close to large sources of CO_2 in the Redwater-Fort Saskatchewan-Edmonton region (Gunter and Bachu, 2007). In map view, the Redwater reef complex has an approximate triangular shape (Figure 1) with an area of about 600 km^2. It occurs at a depth of about 1000 m, and has a thickness of 160 to 300 m. The Redwater reef is currently under the last stages of water flood for oil production, and this depleted oil reservoir is currently used for water disposal (Bachu et al., 2008).

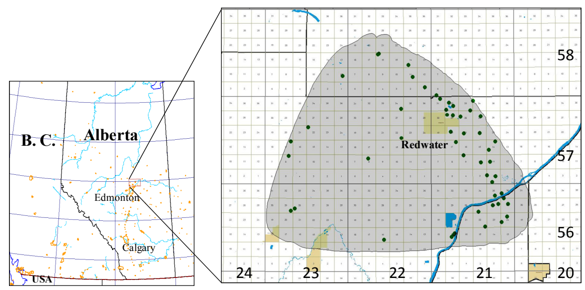

Figure 1: Alberta map showing the location and outline of the Redwater Reef, and wells penetrating the Lower Leduc Formation.

Methods

A large number of wells penetrate the Upper Leduc Fm, especially along the eastern margin of the Redwater reef, but only a small number of wells penetrate the Cooking Lake Formation and few of these have sonic and density logs. Three wells inside the reef and six wells off-reef that penetrate the Cooking Lake Formation in the general study area. Of these, three on-reef and four off-reef wells were used to assist in the generation of the velocity and density model used for the seismic modelling project.

A 2D geological model of the Redwater reef area was constructed and 2D P-P and P-S seismic modeling using common shot ray tracing method was undertaken to produce field survey shot gather seismic data. The model section is oriented in north-south direction and extends from the lagoonal facies within the central region of the reef to off-reef. The 2D geological model was extracted from the interpretation of the existing 2D surface seismic data, particularly 3D gridded time structure maps of geological formations including Mannville, Nisku, Ireton, Leduc, Mid-Leduc, Cooking Lake and Beaverhill Lake (Lawton et al., 2009; Sodagar et al., 2009). These time structure maps were converted to depth maps using a gradient velocity at the well locations. Errors in the calculated depth were within 1m at the well locations for all formations picked for the geological model.

The 2D geological model developed is shown in Figure 2. Interfaces in depth were transformed to event blocks and then P-wave velocities and densities were assigned to these blocks using average values from the wells. These properties of the model are shown in Figures 2 and 3. S-wave velocities were assigned assuming Vp/Vs = 1.9. The reef rim region was modeled as a separate block. In this block, the velocity and density values had a lateral gradient associated with an average porosity of 4% in the tidal flat lagoonal facies to an average porosity 9% in the foreslope facies at the rim of the reef (Figures 2 and 3). Leduc formation original fluid (100% water) was replaced by 40% CO_2 saturation because no significant variation happens from 40-100% of CO_2 saturation (Lawton and Sodagar, 2009) in the Upper Leduc member zone. The velocities and densities were recalculated using Gassmann (1951).

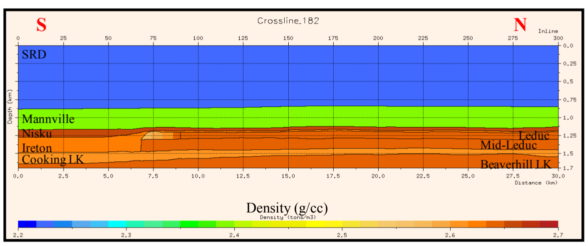

Figure 2: 2D geological model across the southern margin of the Redwater reef, showing densities of the various formations.

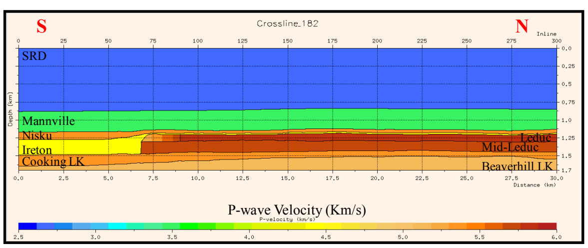

Figure 3: 2D geological model across the southern margin of the Redwater reef, showing P-wave interval velocities of the various formations.

Common shot ray tracing for primary P-P and P-S events was performed with a shot interval of 40 m and receiver interval of 10 m from a SRD (Seismic Reference Datum) of 750 m above sea-level. The survey was undertaken with 150 receivers each side of the source points. The shot gather seismic data was generated by convolving the computed arrival time with a zero-phase 20 Hz Ricker wavelet and S_v mode pulse.

The synthetic shot gather seismic data were processed and migrated to improve the imaging of the reef margin and the internal reef facies. This processing involved converting the trace headers from shot point to CDP (Common Depth Point) for P-P and ACP (Asymptotic Conversion Point) domain for P-S and polarity reverse for the left traces in the shot gathers, followed by Kirchhoff pre-stack time migration (PSTM), and pre-stack depth migration (PSDM). The velocity model used for the migration was created by converting the interval velocities from the input geological model into rms velocities in time.

Results

Figure 4 presents the 2D processed field data showing the reef edge and interfaces. Figures 5 and 6 illustrate the pre-stack time-migrated (PSTM) seismic sections for P-P and P-S respectively using the ray tracing numerical method. In these sections, the Mannville event is a strong peak, the Nisku event is also a moderate to strong amplitude peak, the Ireton shale event is a trough and the Cooking Lake Formation correlates to a moderate amplitude trough on-reef but has higher amplitude peak off-reef. This is because the Cooking Lake carbonates, when overlain by Ireton shale, yield a large impedance contrast and a high-amplitude reflection. The Beaverhill Lake event is fairly weak trough due to the small impedance contrast at the interface between the two carbonate units.

Reflections from the Cooking Lake and Beaverhill Lake formations exhibit positive time structure below the reef on the time sections. This velocity pull-up is due to a lateral velocity change from the on-reef carbonate strata (Leduc Fm.) to the adjacent, lower velocity off-reef shale strata (Ireton Fm.). Both formations are essentially flat in the depth model (Figures 2 and 3). This velocity pull-up is corrected to nearly flat in the pre-stack depth-migrated data. Terminations of the Upper Leduc and Middle Leduc events are clear on the 2D synthetic seismic sections at the reef margin (Figures 5 and 6).

The Upper Leduc event shows the rim build-up in both sections but it is more pronounced on the P-S sections. A high- amplitude reflection at the base of upper-Leduc member is evident near the reef margin and but this event becomes weaker and diminishes toward the interior facies. This is because of the porosity differences and consequently velocity and density differences between the foreslope facies in the reef rim and lagoonal facies within the central region of the reef (Figures 5 and 6). It is noteworthy that this event on the modeled seismic data is similar to that observed on the processed field data in this part of the reef (Figure 4), and thus may be a possible higher porosity indicator. Also, it is worth mentioning that these seismic attributes and character on the P-S modeled seismic data are comparable to that P-wave modeled seismic data in this part of the reef, and thus may be a confirmation and support of possible higher porosity indicator. All the horizons dip gently to the south on the 2D synthetic seismic section.

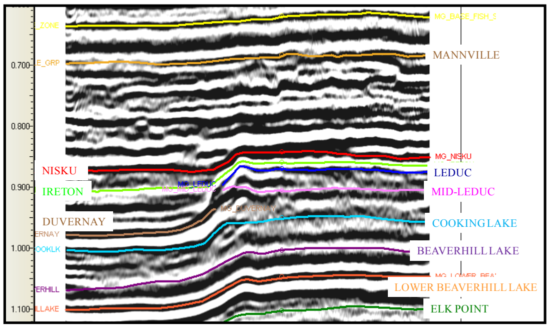

Figure 4: Interpreted seismic section across the reef margin.

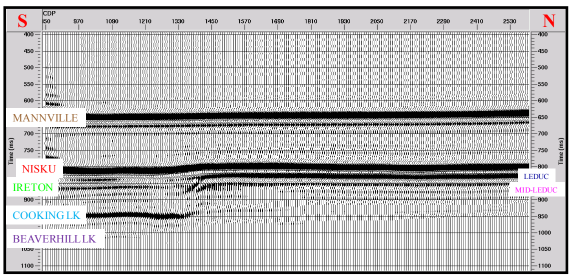

Figure 5: 2D P-P ray tracing numerical seismic data after pre-stack time migration from the Redwater Reef model, with interfaces identified.

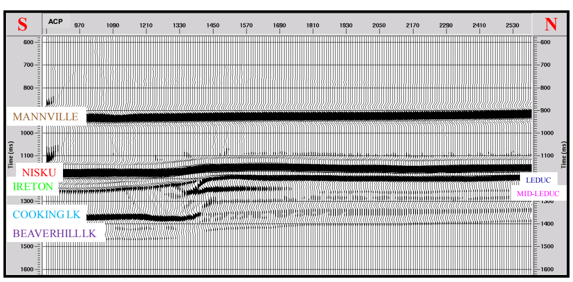

Figure 6: Radial P-S converted wave 2D ray tracing numerical seismic section after pre-stack time migration from the Redwater Reef model.

CO_2 saturation in the Upper Leduc member

The 2D geological model developed with CO_2 fluid substitution in the upper-Leduc member is shown in Figure 7. Figures 8, 9, 10 and 11 illustrate the pre-stack time-migrated (PSTM) and depth-migrated (PSDM) seismic sections for P-P and P-S data from ray tracing after CO_2 replacement. In these sections, The Mannville, Nisku, Ireton, Cooking Lake, and Beaverhill Lake Formations display essentially the same seismic attributes as the in-situ seismic sections. Positive time structure below the reef still exists in the pre-stack time-migrated data but corrected to almost flat in the pre-stack depth-migrated data (Figures 10 and 11).

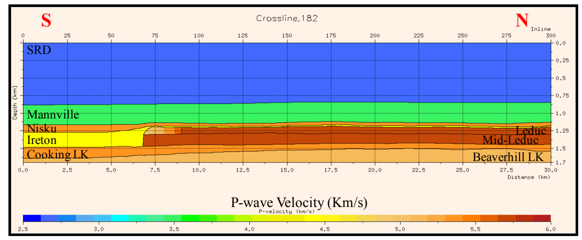

Figure 7: 2D geological model with CO_2 fluid substitution in the Upper Leduc member across the margin of the Redwater reef, showing P-wave interval velocities of the various formations.

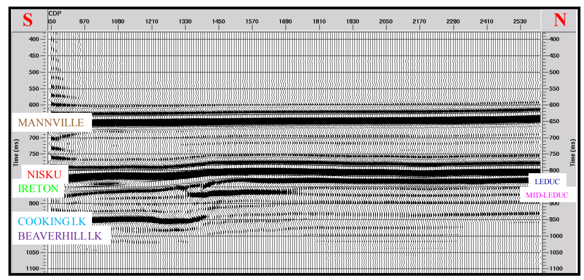

Figure 8: P-P PSTM section of reef seismic data after CO_2 fluid substitution.

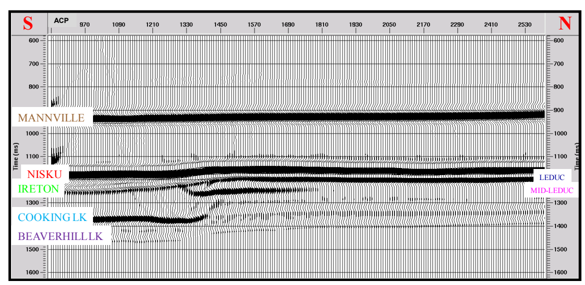

Figure 9: P-S PSTM section of reef seismic data after CO_2 fluid substitution.

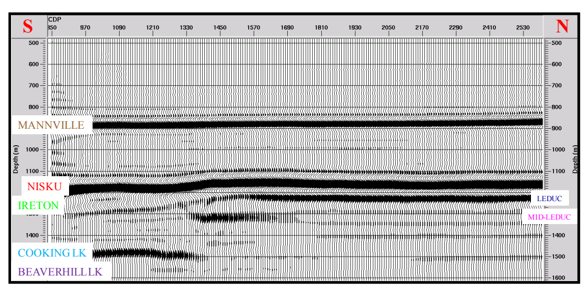

Figure 10: P-P PSDM section of reef seismic data after CO_2 fluid substitution.

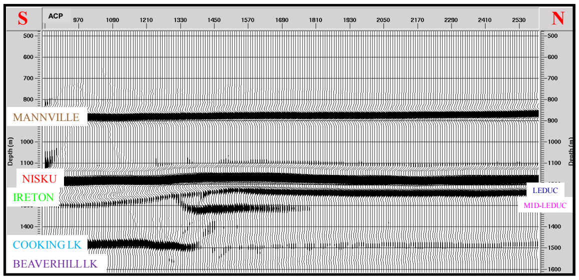

Figure 11: P-S PSDM section of reef seismic data after CO_2 fluid substitution.

Terminations of the Upper-Leduc and Middle-Leduc events are apparent on the 2D synthetic seismic sections with a modest improvement on the depth sections at the reef margin, and the Upper Leduc event shows the rim build-up with lower amplitude compared to in-situ sections because of the CO_2 replacement (Figures 8 through 11). A stronger and higher amplitude reflection at the base of upper-Leduc member is evident near the reef margin compared to in-situ sections due to CO_2 saturation, and but this event becomes weaker toward the interior facies. This is because of the porosity differences and consequently velocity and density differences between the foreslope facies in the reef rim and lagoonal facies within the central region of the reef. The P-P and P-S PSDM sections are at same depth scale and match very well with a tiny error of 0-10 m due to smoothed velocity required for migration purpose (Figures 10 and 11).

Time-lapse method has been applied to examine the effect of CO_2 saturation on P-P and P-S converted wave seismic reflectivity and attributes (Lawton and Sodagar, 2009). Figures 12 and 13 show the time-lapse sections for PSDM seismic data before and after CO_2 saturation for P-P and P-S respectively. It is noticed that there are fairly strong contrast reflection at the top of upper-Leduc member, top of the rim, and base of upper-Leduc near the reef edge for P-P section and weak contrast for P-S section as expected because S-wave is affected only by gas density contrast.

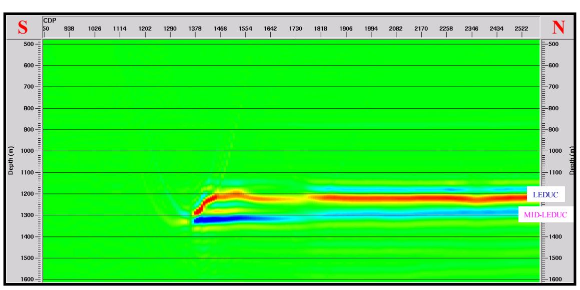

Figure 12: P-P Time-lapse difference in PSDM seismic section before and after CO_2 substitution.

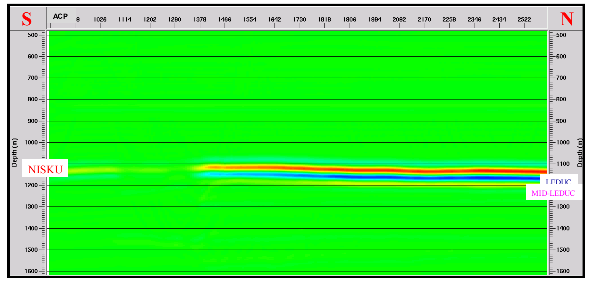

Figure 13: P-S time-lapse difference in PSDM seismic section before and after CO_2 substitution.

Conclusions

The 2D ray tracing synthetic seismograms for P-P and P-S waves exhibit similar seismic attributes for the Mannville, Nisku, Ireton, Cooking Lake, and Beaverhill Lake Formations for in-situ geological model as well as with CO_2 saturations. The Cooking Lake and Beaverhill Lake formations demonstrate positive structure below the reef in time sections for both P-P and P-S due to a lateral velocity change. This structure is evident on time sections and both formations are corrected to nearly flat in the depth model.

Terminations and the lateral position of the Upper Leduc and Middle Leduc events are obvious on the 2D PSTM and PSDM synthetic seismic sections for in-situ geological model as well as with CO_2 saturation. The reef rim is observed at the reef margin. High amplitudes at the base of upper-Leduc member are evident at the reef edge due to porosity differences between the foreslope facies in the reef rim and tidal flat lagoonal facies within the central region of the reef.

Time-lapse seismology demonstrates a fairly good contrast reflection at the top of upper-Leduc, top of the rim, and base of upper-Leduc near the reef edge that is evident to detect and monitor the CO_2 saturation seismically. The comparison between PSDM P-P and P-S shows an excellent tie of the seismic events with a higher frequency in P-P section.

Acknowledgments

Data for this project was acquired through funding provided by the Alberta Energy Research Institute and ARC Resources. Software for the modelling and processing of the data was provided to the University of Calgary by NORSAR Innovation AS and Landmark Graphics Corporation. Special thanks to Helen Isaac for her tremendous software support.