Timelapse seismic modelling of CO_2 fluid substitution in the Redwater Leduc Reef, Alberta

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Summary

Ray tracing and finite difference modeling were undertaken to evaluate the variations in seismic response of the Redwater reef along a 2D line across the reef with 40% CO_2 saturation in upper-Leduc zone. The input geological model was based on well data. Ray tracing and finite difference synthetic seismic sections demonstrate similar seismic attributes for all formations. 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 of the Upper and Middle Leduc events are obvious on the pre-stack time and depth-migrated sections. 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 lagoonal facies within the center of the reef. Time-lapse seismology proved an enormous amplitude difference for the seismic data before and after 40% CO_2 saturation. A high amplitude reflection at the top of upper-Leduc, top of the rim, and base of upper-Leduc near the reef edge was strong evident to monitor the CO_2 saturation seismically.

Introduction

The study area is located in the Redwater region of Alberta, northeast of Edmonton (Figure 1). The Redwater reef is in the Heartland area close to large sources of CO_2 in the Redwater-Fort Saskatchewan-Edmonton region. The Redwater reef complex has a triangular shape with an area of about 600 km^2. It takes place at a depth of about 1000 m (-400 m elevation sub-sea), and has a thickness of 160 to 300 m (Gunter and Bachu, 2007). The main objective of the study was to build a 2D geological model of the Redwater reef, from the reef center to off-reef, with 40% CO_2 saturation in the Leduc target zone. Fluid substitution seismic modelling was then undertaken to generate a 2D synthetic seismic data to trace the consequences of CO_2 saturation on the facies within the reef, the reef members and formations below the reef based on seismic attributes and characters.

Methods

A 2D geological model of the Redwater reef area was constructed for CO_2 fluid substitution. Then, 2D seismic modelling using common shot ray tracing and finite-difference methods were undertaken to produce field survey shot gather seismic data. The model section extends from the lagoonal facies within the central region of the reef to off-reef (Figure 1). The 2D geological model was extracted from the interpretation of the existing 2D surface seismic data associated with geological formations including Mannville, Nisku, Ireton, Leduc, Mid-Leduc, Cooking Lake and Beaverhill Lake.

The 2D geological model developed with CO_2 fluid substitution in the upper-Leduc 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. 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 (Figure 2). Upper-Leduc original fluid (100% water) was replaced by 40% CO_2 saturation (Lawton and Sodagar, 2009) and P-wave velocities and densities were recalculated using Gassmann equation (Gassmann, 1951). Common shot ray tracing and finite-difference modes for primary P-wave events were 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 40 Hz Ricker wavelet.

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) domain, followed by Kirchhoff pre-stack time migration, and pre-stack depth migration. The velocity model used for the migration was created by converting the interval velocities from the input geological model into rms velocities in time.

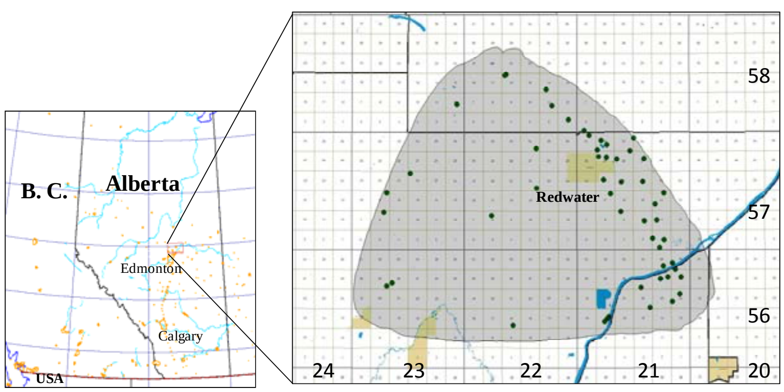

Figure 1: *Alberta map showing the location and outline of the Redwater Reef, and wells penetrating the Lower Leduc Formation.*

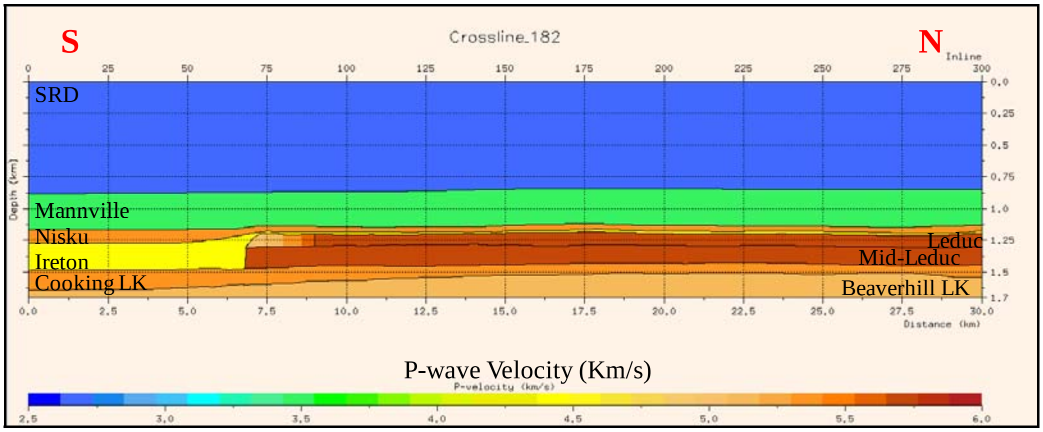

***Figure 2**: 2D geological model with CO_2 fluid substitution across the margin of the Redwater reef, showing P-wave interval velocities of the various formations.*

Results

Figures 3 and 4 demonstrate the seismic shot gathers of ray tracing and finite difference modelling methods respectively with 40% CO_2 saturation in the upper-Leduc member interval. Figures 5 and 6 illustrate the pre-stack time-migrated and depth-migrated seismic sections respectively using the ray tracing method. In these sections, the Mannville event is a strong peak, the Nisku event is a moderate 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 at the time section. 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). This velocity pull-up is corrected to nearly flat in the pre-stack depth-migrated data (Figure 6).

Terminations of the Upper-Leduc and Middle-Leduc events are apparent on the 2D synthetic seismic sections with some enhancements on the depth section at the reef margin, and the Upper Leduc event shows the rim build-up (Figures 5 and 6). A high- amplitude reflection at the base of upper-Leduc member is evident near the reef margin 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.

Figures 7 and 8 present the pre-stack time-migrated and depth-migrated seismic sections respectively with 40% CO_2 saturation in the upper Leduc member zone using finite difference method. All the formations display basically the same seismic attributes as the ray tracing modelling sections. Also, Positive time structure corrected to nearly flat in the pre-stack depth-migrated data.

Taking the difference between two 2D seismic sections is called Time-lapse seismology. Time-lapse method has been applied to examine the effect of 40% CO_2 saturation on seismic reflectivity and attributes (Lawton and Sodagar, 2009). Figure 9 shows the time-lapse seismic section using ray tracing numerical method for pre-stack depth migration seismic data before and after 40% CO_2 saturation. It is noticed that there are high amplitude reflection at the top of upper-Leduc member, top of the rim, and base of upper-Leduc near the reef edge as expected. The time-lapse seismic section was produced using finite difference numerical method for pre-stack depth migration seismic data before and after CO_2 saturation (Figure 10). Figure 11 illustrates the velocity model in colour super-imposed by pre-stack depth migration seismic section with 40% CO_2 saturation in the upper Leduc where it shows the perfect match between the original model (Formation interfaces and velocities) and the depth seismic model.

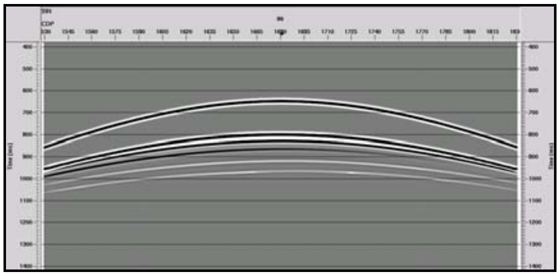

***Figure 3**: Ray-traced numerical seismic shot gather from the Redwater Reef model.*

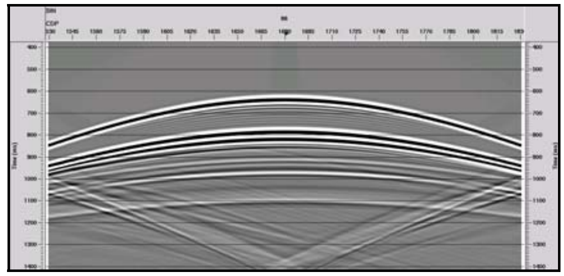

***Figure 4**: Finite difference numerical seismic shot gather from the Redwater Reef model.*

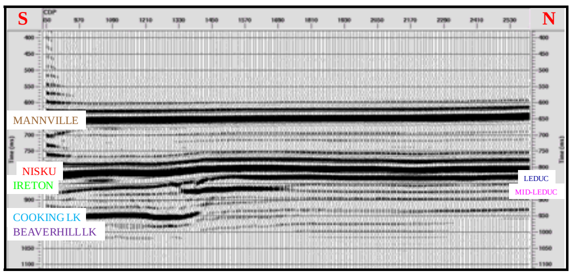

***Figure 5**: PSTM of reef seismic data after CO_2 fluid substitution using ray-tracing model.*

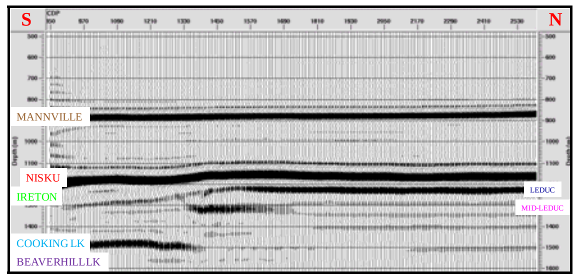

***Figure 6**: PSDM of reef seismic data after CO_2 fluid substitution (ray-tracing model).*

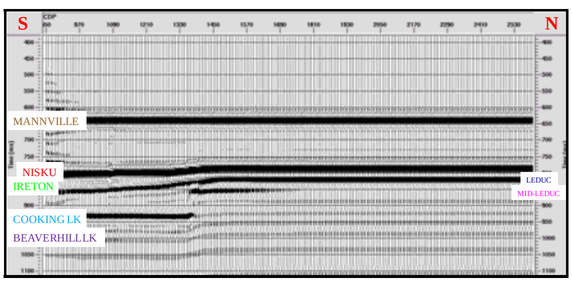

***Figure 7**: PSTM of reef seismic data after CO_2 fluid substitution using finite difference model.*

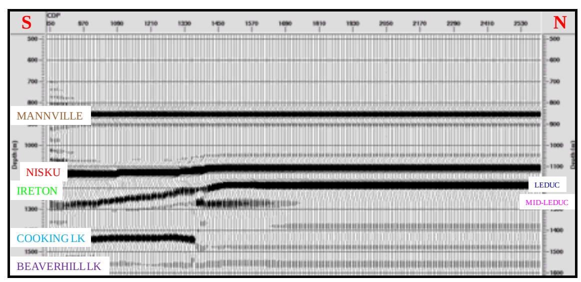

***Figure 8**: PSDM of reef seismic data after CO_2 fluid substitution (finite difference model).*

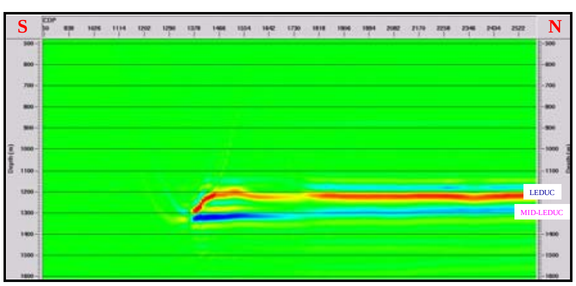

***Figure 9**: Time-lapse difference in PSDM seismic section before and after CO2 substitution (ray tracing model).*

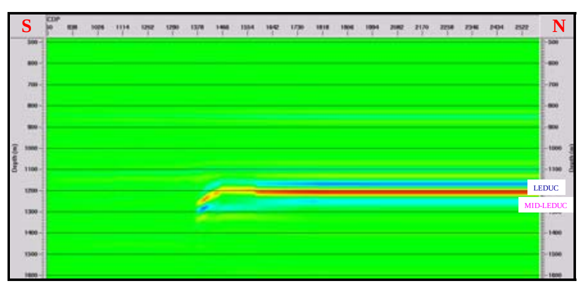

***Figure 10**: Time-lapse difference in PSDM seismic section before and after CO2 substitution (finite difference model).*

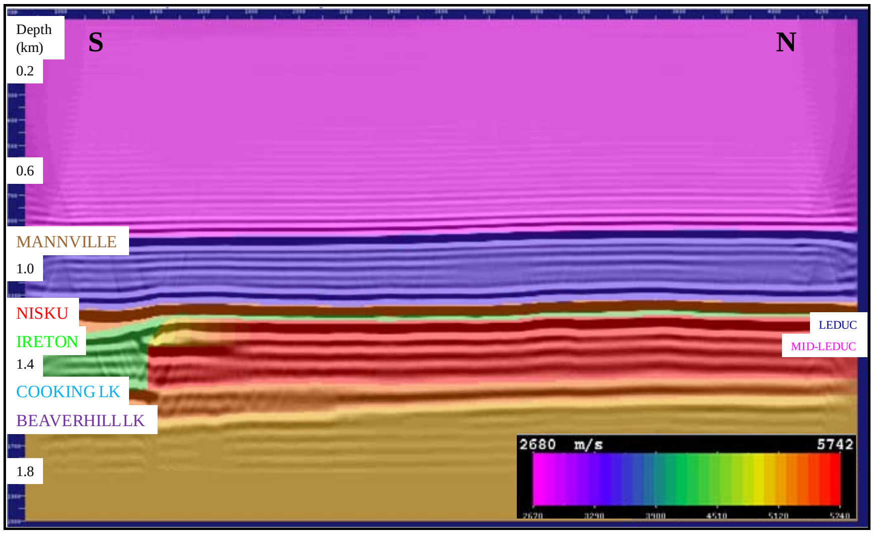

Figure 11*: colored velocity model super-imposed by pre-stack depth migration seismic section.*

Conclusions

The 2D ray tracing and finite difference synthetic seismograms 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 a lateral velocity change. This structure is apparent on time section 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 pre-stack time and depth-migrated seismic sections. 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 shows a great amplitude difference for the seismic data before and after 40% CO_2 saturation. A high amplitude reflection at the top of upper-Leduc, top of the rim, and base of upper-Leduc near the reef edge is evident to detect the CO_2 saturation seismically. There is a perfect match between the original model and the depth seismic model which gives more confident in the experimental results.

Acknowledgments

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