

Feasibility of 4D Multicomponent Seismic Methods for Monitoring CO₂ Storage in the Redwater Leduc Reef, Alberta

Taher M. Sodagar*

University of Calgary, Calgary, Alberta, Canada

tmysodag@ucalgary.ca

and

Don C. Lawton

University of Calgary, Calgary, Alberta, Canada

Summary

3D multicomponent ray trace modeling was undertaken to evaluate variations in the seismic response of the Redwater reef margin as well as with CO₂ saturation in the Upper Leduc Formation. The 3D 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 synthetic seismic sections and horizon amplitude maps demonstrate similar seismic character and attributes for the reef formations. The formations below the reef display positive structure in time sections due to the lateral velocity change from on-reef to off-reef, but compensated in the depth sections. Terminations of the Upper Leduc and Middle Leduc events are apparent on the both PP and PS sections and amplitude maps. Time-lapse analysis of 3D multicomponent seismic data showed a fairly good amplitude differences occurring at the top and the base of upper-Leduc member, confirming the feasibility of monitoring the CO₂ saturation within the Redwater Reef by repeated 3D multicomponent seismic surveys.

Introduction

The study area is located in the Redwater region of Alberta, northeast of Edmonton (Figure 1). The Redwater reef complex has an approximate triangular shape with an area of about 527 km². It occurs at a depth of about 1000 m, and has a thickness of 160 to 300 m (Gunter and Bachu, 2007). The main objective of the study was to map facies variations within the Redwater Leduc reef, based on seismic character, and to characterize the reef members and formations below the reef by creating a 3D geological model at the southern margin of the Redwater reef. 3D multicomponent seismic modeling was then undertaken to generate a 3D synthetic seismic data (PP and PS data) to study the seismic response of the Redwater reef formations, particularly the Leduc Formation. An essential objective was to undertake time-lapse 3D multicomponent seismic modeling with 40% CO₂ saturation in the Upper Leduc member interval, based on fluid substitution using a Gassmann (1951) approach, to monitor the CO₂ saturation.

Methods

Figure 1 shows the wells on-reef and off-reef that penetrate the Cooking Lake Formation in the general study area. A 3D geological model of the Redwater reef area was constructed from the interpretation of available vintage 2D surface seismic data within the study area as well as available well data. The 3D model is oriented in the southern part of the Redwater reef (Figure 1). The 3D geological model developed with

the formation intervals is shown in Figure 2. The P-wave velocities and densities were assigned to these intervals using average values from the wells. S-wave velocities were assigned using $V_p/V_s = 1.9$, calculated from a single existing dipole well on the eastern side of the reef. The Leduc reef rim region was modeled as a separate block where 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). Leduc formation original pore fluid (100% water) was replaced by 40% CO₂ saturation level in the Upper Leduc member since it was found that there are no significant changes in the seismic velocities between 40% and 100% CO₂ saturation (Lawton and Sodagar, 2009). The P-wave velocities and densities were recalculated using the Gassmann equations (Gassmann, 1951).

Common shot ray tracing for primary PP wave and PS wave events was performed in NORSAR3D software with a shot interval of 100 m and receiver interval of 50 m. The shot and receiver line intervals were 200 m. The survey was undertaken with an orthogonal geometry with parallel receiver lines as well as parallel source lines. The survey dimension is 3x5 km. The synthetic seismic shot gathers were generated by convolving the reflectivity functions at the computed arrival times with a zero-phase 40 Hz Ricker wavelet for PP data and a 20 Hz Ricker wavelet for the PS data. Then, the shot gathers were processed by converting the trace headers from shot point to CDP (Common Depth Point) domain for the PP data and converting the trace headers from common midpoint (CMP) to ACP (Asymptotic Conversion Point) domain and reversing the polarity of trailing traces in the shot gathers for the PS data, followed by 3D Kirchhoff pre-stack time migration (PSTM) in ProMax software, and 3D Kirchhoff pre-stack depth migration (PSDM) in Paradigm GeoDepth software. The PP and PS velocity model used for the migration was created by converting the interval velocities from the input geological model into rms velocities in time.

Results

Figures 3 and 4 illustrate the PP pre-stack time-migrated seismic section before and after 40% CO₂ fluid substitution in the upper Leduc member using 3D ray tracing. 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.) and is removed in the PP pre-stack depth-migrated section. Terminations of the Upper Leduc and Middle Leduc events are clear on the synthetic seismic sections at the reef margin, and the Upper Leduc event shows the rim build-up (Figures 3 and 4). 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 due to the modeled 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. It is observed in the saturated section that there are reductions in reflection amplitude at the top of upper-Leduc member, and an increase in amplitude at the base of upper-Leduc, near the reef edge as predictable due to CO₂ saturation. Taking the difference between two seismic volumes is called time-lapse seismology. Time-lapse method has been applied to examine the effect of 40% CO₂ saturation on seismic reflectivity and attributes. Figure 5 shows the time-lapse seismic section for PP data before and after 40% CO₂ saturation. It is noticed that there are high reflection amplitude at the top of upper-Leduc member, the top of the reef rim, and base of upper-Leduc Formation near the reef edge, as expected.

Figures 6 and 7 illustrate the PS PSTM sections before and after CO₂ saturation. All the formations display mainly the same seismic attributes as the PP seismic sections with lower frequency. Also, high amplitude reflection at the base of upper-Leduc member and terminations of the Upper-Leduc and Middle-Leduc events are apparent on the PS seismic sections. Positive time structure below the reef still exists but corrected in the pre-stack depth-migrated sections. It is noticed in the PS CO₂ saturated section that, there are less reduction in amplitude reflection at the top of upper-Leduc member, and less increase in amplitude

at base of upper-Leduc compared to the PP seismic section with CO₂ saturation. Figure 8 shows the PS difference before and after CO₂ saturation. There are observable differences at the top of upper-Leduc member, the top of the reef rim, and base of upper-Leduc near the reef edge. This difference anomaly on the PS data is weaker than on the PP data and is attributed to a slight increase in S-wave velocity due to reduction in bulk density after brine replacement with CO₂.

Figures 9 and 10 illustrate the PP Leduc horizon amplitude maps with PSTM before and after 40% CO₂ fluid substitution in the upper Leduc member. The amplitude increases from the reef edge (south) toward the reef interior (north) due to the modeled porosity differences. Figure 10 shows that there is an overall reduction in amplitude value as expected due to CO₂ saturation in Upper Leduc carbonate overlain by Ireton shale. The difference map of the Leduc horizon shows a good amplitude differences and therefore it is a significant success to identify and observe the CO₂ saturation seismically. Correspondingly, the PS Leduc horizon amplitude maps before and after CO₂ saturation display mainly the same seismic attributes as the PP amplitude maps but weaker. Difference amplitude maps of Leduc for PS data show reasonable amplitude differences and as a result when combined with PP differences verify the feasibility of monitoring the CO₂ saturation in Upper Leduc Formation by time-lapse multicomponent seismic data.

Conclusions

The time-lapse analysis shows significant amplitude differences for the Upper Leduc and Mid-Leduc members before and after 40% CO₂ saturation on both PP and PS seismic sections and horizon amplitude maps. The 4D multicomponent synthetic seismic data results recommend that it is feasible to monitor the CO₂ saturation within the Redwater Reef by repeated 3D multicomponent seismic survey.

Acknowledgements

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References

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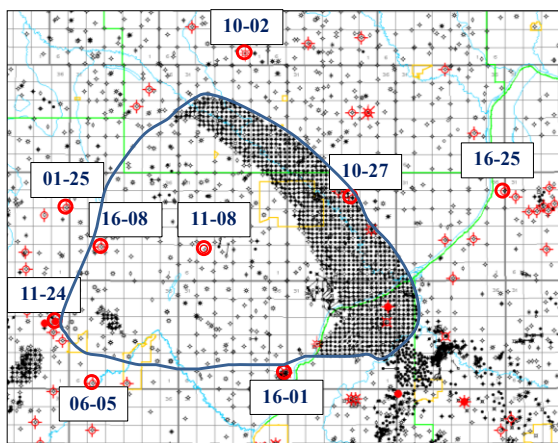


Figure 1: Redwater reef map showing the wells, 2D seismic lines and the 3D seismic survey.

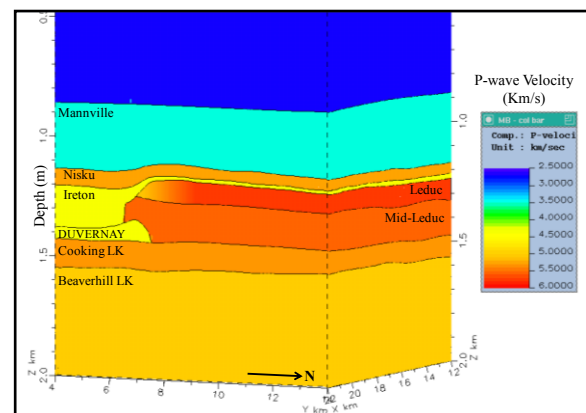


Figure 2: 3D geological model of the Redwater reef, showing P-wave interval velocities of the various formations (brine saturation).

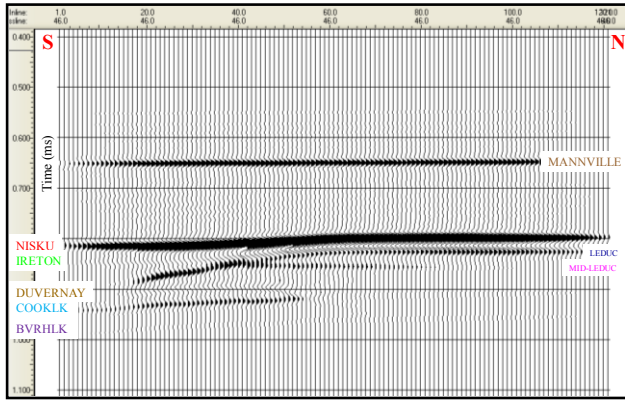


Figure 3: Vertical component (PP) seismic section after PSTM with interfaces identified on the section.

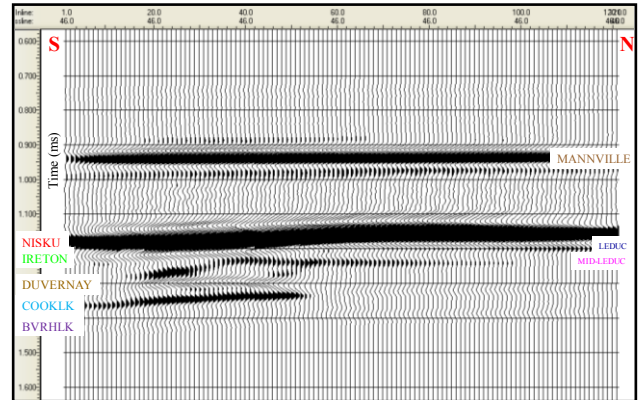


Figure 6: Radial component (PS) seismic section after PSTM with interfaces identified on the section.

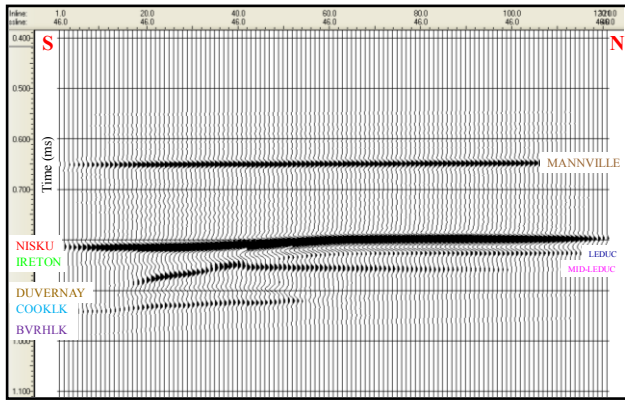


Figure 4: Vertical component (PP) PSTM seismic section after CO₂ fluid substitution in Upper Leduc member.

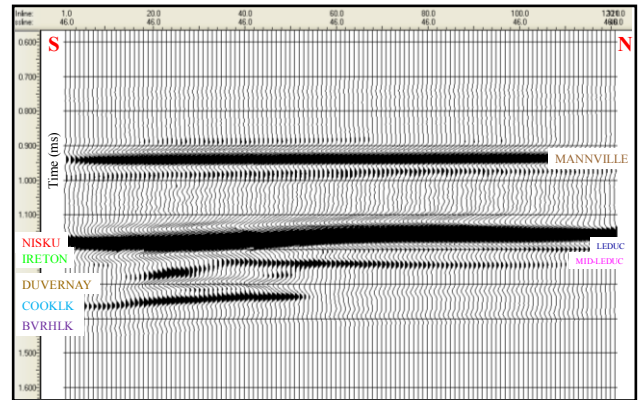


Figure 7: Radial component (PS) PSTM seismic section after CO₂ fluid substitution in Upper Leduc member.

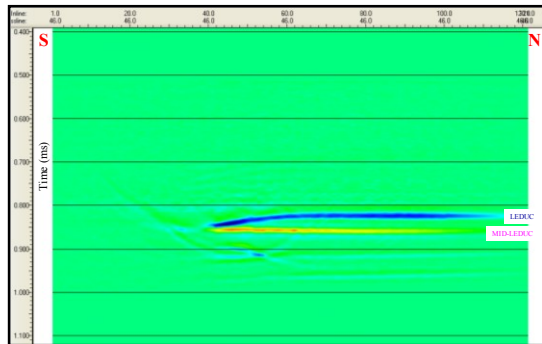


Figure 5: PP difference before and after CO₂ fluid substitution.

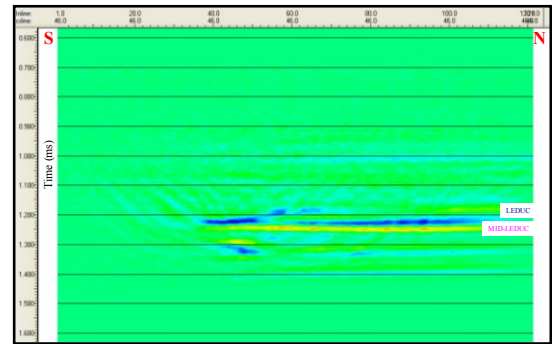


Figure 8: PS difference before and after CO₂ fluid substitution.

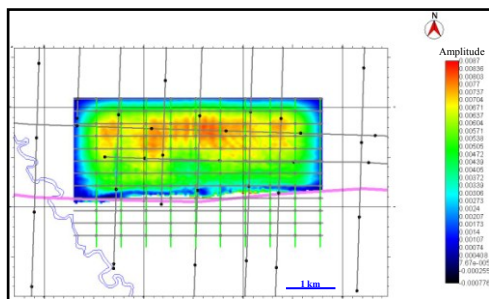


Figure 9: Amplitude map of Leduc horizon of (PP) PSTM seismic data.

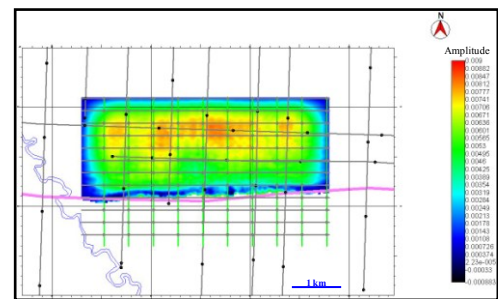


Figure 10: Amplitude map of Leduc horizon of (PP) PSTM seismic data after CO₂ fluid substitution.