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

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ABSTRACT

The Devonian Redwater reef, northeast of Edmonton, Alberta, is being evaluated for geological storage of CO_2 for the Heartland Area Redwater CO_2 Storage Project (HARP). It is located close to large sources of CO_2 in the Redwater-Fort Saskatchewan-Edmonton region. The main objective of the study was to build a 2D geological model of the Redwater reef, from the reef center to off-reef, and investigate the seismic response of the reef to CO_2 saturation in the Leduc Formation. Fluid substitution and seismic modeling were undertaken to generate PP and PS synthetic seismic data to study the consequences of CO_2 saturation on the seismic response of the various reef facies and formations below the reef, based on seismic attributes and character.

Common shot ray tracing modeling was undertaken to evaluate variations in the seismic response of the Redwater reef along the 2D line across the margin of the reef for CO_2 saturation in the Upper Leduc interval. The input geological model was based on well data and depth-converted seismic data from the interpretation of legacy 2D seismic lines in the area. Seismic reflections display positive structure below the reef in time sections due to the lateral velocity change from on-reef to off-reef, but are corrected in the depth sections.

Terminations and the lateral position of the Upper Leduc and Middle Leduc events are clear 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 seismic modeling predicts a reasonable amplitude difference for the seismic data before and after CO_2 saturation, particularly for reflections from the Upper Leduc, the top of the reef rim, and the Mid Leduc near the reef edge.

INTRODUCTION

This study involved creating a 2D geological model of the Redwater reef, from the reef center to off-reef and assessing the seismic response of the reef to increasing CO_2 saturation in the Devonian Leduc Formation carbonates in the upper part of the reef complex. Seismic modeling was undertaken to generate 2D PP and PS synthetic seismic data to map facies variations within the reef and to characterize the reef members and formations below the reef. An important objective was to undertake time-lapse seismic modeling with increasing CO_2 saturation in the Upper Leduc Formation, based on fluid substitution using a Gassmann (1951) approach.

The study area is located in the Redwater region of Alberta, northeast of Edmonton, and encompasses Townships 56 to 58 and Ranges 20 to 24W4 (Figure 1). The Leduc reef at Redwater is one of the largest Devonian Leduc reefs in the Western Canada sedimentary basin (WCSB) and is the third largest oil reservoir in Canada. 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 (-400 m elevation sub-sea), and has a thickness of 160 to 300 m. The original oil cap was almost 50 m thick. 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).

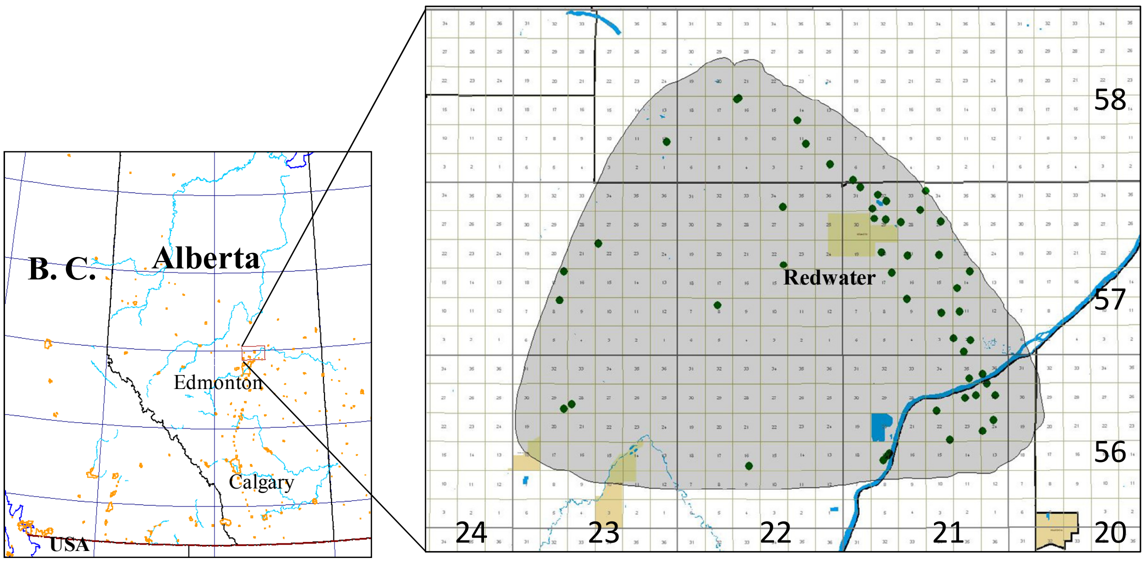

FIG. 1. Alberta map showing the location and outline of the Redwater Reef, and penetrating the Lower Leduc Formation.

GEOLOGICAL BACKGROUND

The study area is located within the Middle to Early Upper Devonian Waterways Basin (Figure 2). It had deposition of deeper water carbonates and calcareous shales of the Beaverhill Lake Group. It has an average thickness of 200 m, and usually shows low porosity and permeability (Klovan, 1974). The Beaverhill Lake Group is conformably overlain by Cooking Lake shelf platform carbonates, which both dip gently southwestward. The average thickness of the Cooking Lake Formation reaches up to 90 m and has a reefal margin bordering a shallow basin to the west. Later, the platform growth gradually became differentiated into a number of isolated shoals that formed a depositional high on which Leduc reef growth subsequently took place (Wendte et al., 1992).

The Redwater Leduc reef is capped by shales of the Ireton Formation, which are 10-50 m thick directly above the reef. The reef developed on the Cooking Lake Formation platform carbonates (Klovan, 1964). The Leduc reef total thickness is up to 290 meters and grew as a bulky isolated carbonate atoll surrounded by shallow water. The depositional facies of the reservoir were foreslope, reef margin and interior lagoon and the reef complex was divided into Lower, Middle and Upper Leduc members. A marine embayment is the key to differentiate between these subdivisions. The embayment incursion is between Lower Leduc and Upper Leduc strata. The marine embayment is present on the eastern side and to a lesser extent on the western side.

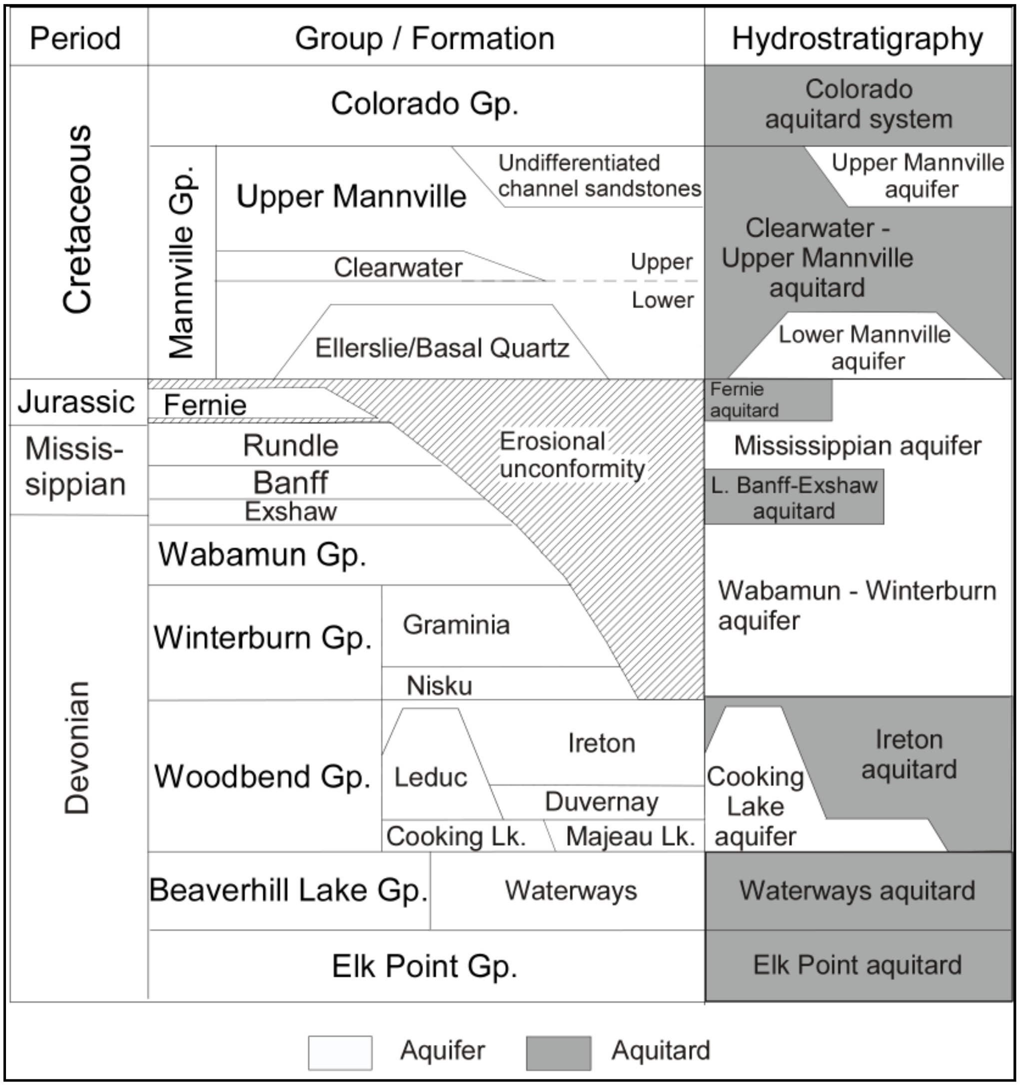

FIG. 2. General stratigraphy and hydrostratigraphy of the Redwater study area (Bachu et al., 2008).

METHODOLOGY

Common Shot Surface Seismic Modeling

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 underlying Cooking Lake Platform and few of these have sonic and density logs. Figure 3 shows the locations of 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, based on available vintage seismic data. PP and PS seismic modeling using a common shot ray tracing method was undertaken to produce shot gathers equivalent to a field survey's. The model section is oriented in a north-south direction and extends from the lagoonal facies within the central region of the reef to off-reef (Figure 3). 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. These time structure maps were converted to depth maps using a gradient velocity at the well locations. Errors in the calculated depth were within 1 m at the well locations for all formations picked for input into the geological model.

The 2D geological models developed are shown in Figures 4 and 5 before and after CO_2 saturation. Interfaces in depth were transformed to event blocks and P-wave velocities and densities were assigned to these blocks using average values from the wells (Sodagar and Lawton, 2010). The P-wave velocities of the model are shown in Figure 4. S-wave velocities were assigned using Vp/Vs = 1.9, calculated from a single existing dipole well on the eastern side of the reef. 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 of 9% in the foreslope facies at the rim of the reef (Figure 4). The original pore fluid of the Leduc Formation (100% brine) was replaced by CO_2 at a saturation level of 40% (Figure 5) since no significant change in seismic response was found for CO_2 saturations between 40% and100% of CO_2 in the Upper Leduc member zone (Lawton and Sodagar, 2009). The velocities and densities were recalculated using the equations of Gassmann (1951).

Seismic Survey Parameters and Data Processing

Multicomponent common shot ray tracing was performed with a shot interval of 40 m and a receiver interval of 10 m from an SRD (Seismic Reference Datum) of 750 m above sea-level. The survey was undertaken with 150 receivers on each side of the source points. The shot gathers were generated by convolving the calculated time reflectivity with a zero-phase 40 Hz Ricker wavelet for PP data and a 20 Hz Ricker for the PS data.

The synthetic seismic shot gathers were processed and migrated to assess imaging of the reef margin and the internal reef facies. For the PP data, a standard processing flow was followed. Processing of the PS data involved converting the trace headers from shot point to ACP (Asymptotic Conversion Point) domain and reversing the polarity of trailing 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.

NORSAR2D software was used to create the 2D interface blocks, perform common shot ray tracing, and generate the converted wave synthetic shot gather seismic data.

ProMax software was used for polarity reversal, geometry sorting, velocity conversion and pre-stack time and depth migration.

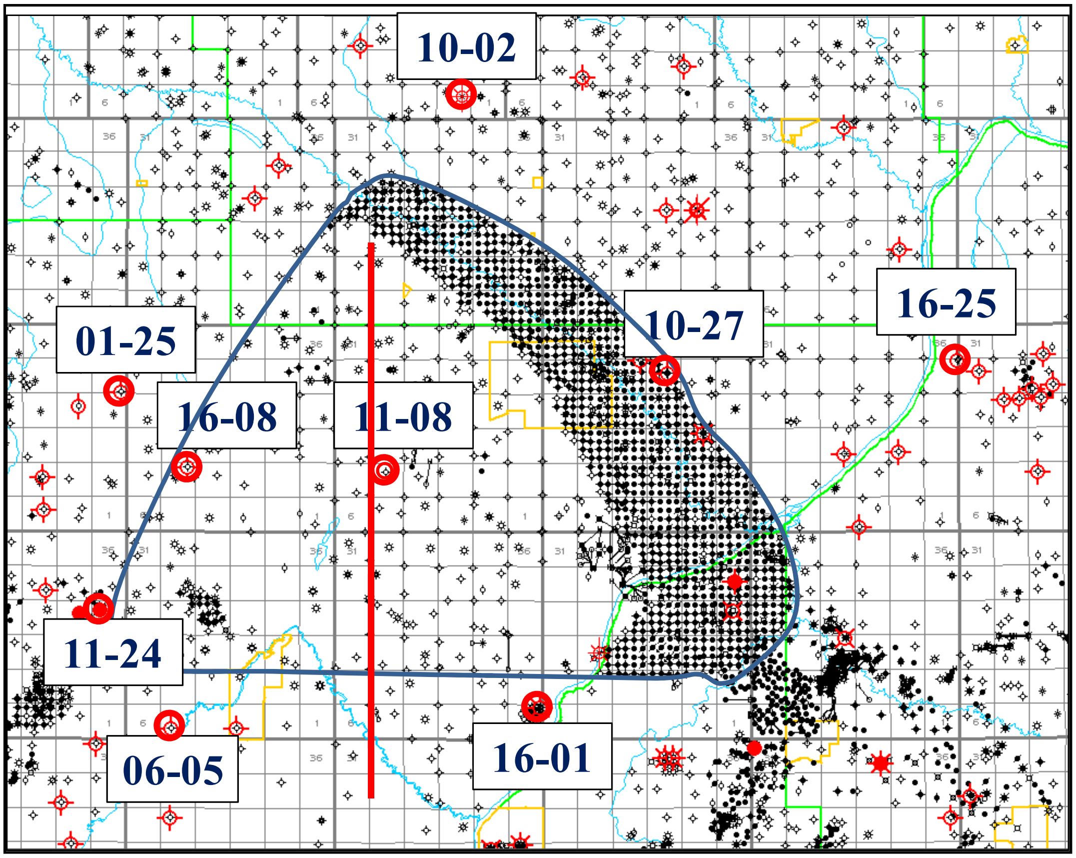

FIG. 3. Redwater reef map showing available wells. Those wells that penetrate the Cooking Lake Formation and have sonic logs are highlighted in red. The red line is the location of the 2D geological model.

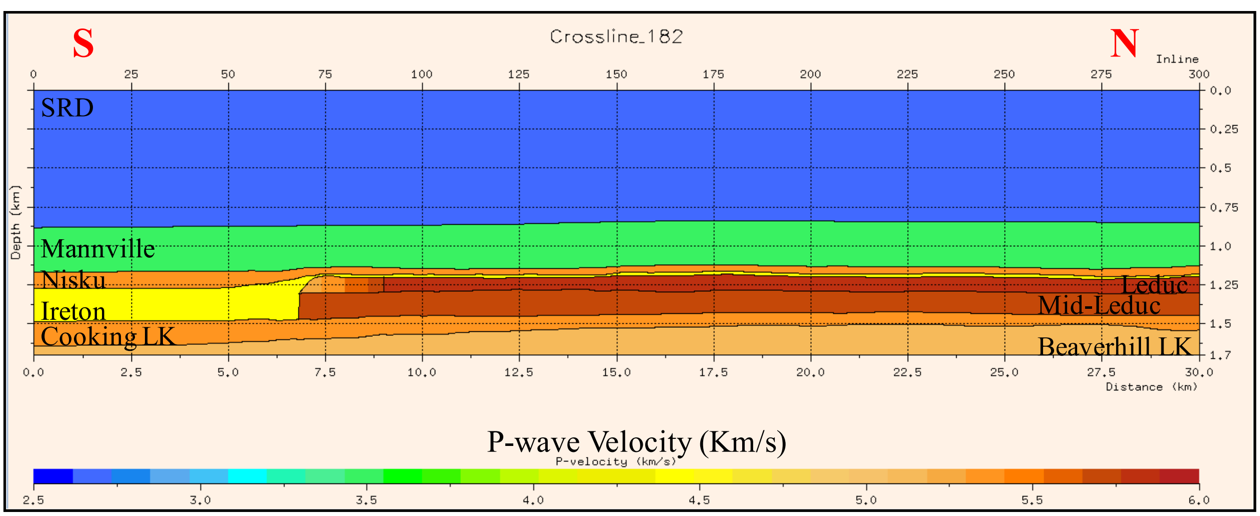

FIG. 4. Baseline 2D geological model across the southern margin of the Redwater reef, showing P-wave interval velocities of the various formations.

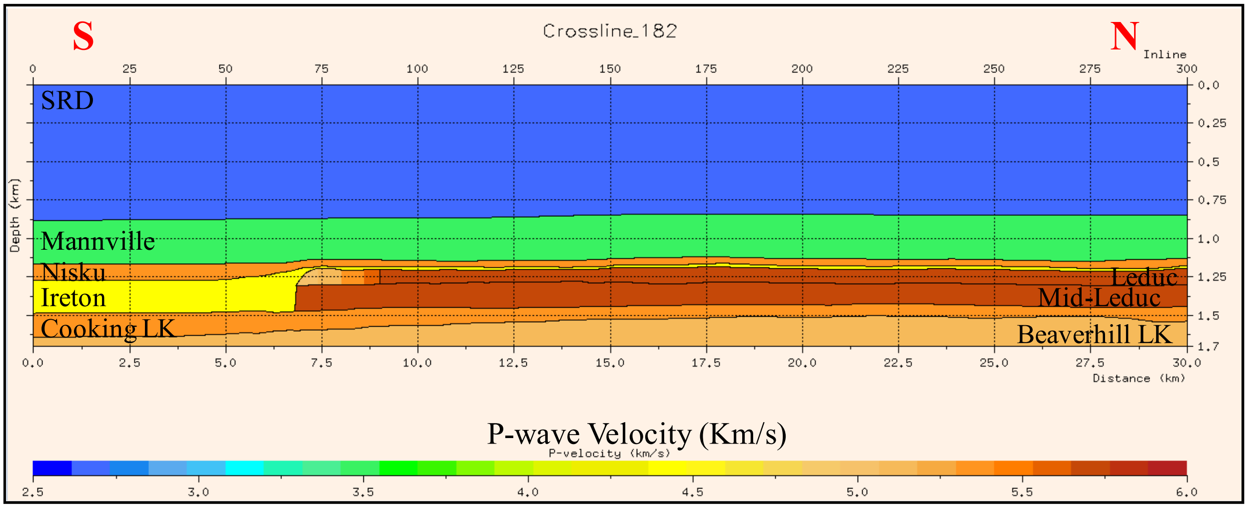

FIG. 5. Monitor 2D geological model after CO_2 fluid substitution in the Upper Leduc member across the margin of the Redwater reef, showing P-wave interval velocities of the various formations.

RESULTS

Baseline model

Figures 6 and 7 show examples of the vertical and radial component shot gathers, and Figures 8 to 11 illustrate the pre-stack time-migrated (PSTM) and pre-stack depth-migrated (PSDM) seismic sections for both PP and PS datasets. Generally, the Mannville event is a high-amplitude peak, the Nisku event is also a moderate to high amplitude peak, the Ireton shale event is a trough, and the Cooking Lake Formation correlates to a moderate amplitude trough on-reef but has a 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 a rather 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 in the time sections for both PP and PS data (Figures 8 and 9 respectively). 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 (Figure 4). This velocity pull-up is corrected to being nearly flat in the pre-stack depth-migrated data (Figures 10 and 11).

Terminations of the Upper Leduc and Middle Leduc events are clear on the 2D synthetic seismic sections at the reef margin, and the Upper Leduc event shows the rim build-up with some enhancement in PSDM sections (Figures 8, through 11). 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 (Figures 8 to 11). 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. All the horizons dip gently to the south on the 2D synthetic seismic section.

It is noteworthy that the seismic attributes and character on the PS seismic data are comparable to the PP seismic data in this part of the reef, and thus may be supportive as a potential porosity indicator. Figure 12 shows the comparison between the PP and the PS section (scaled approximately to PP time). In the PSDM section, PP and PS sections are displayed at the same depth scale and match very well with only a small error of 0-10 m due to smoothing the velocity required for migration.

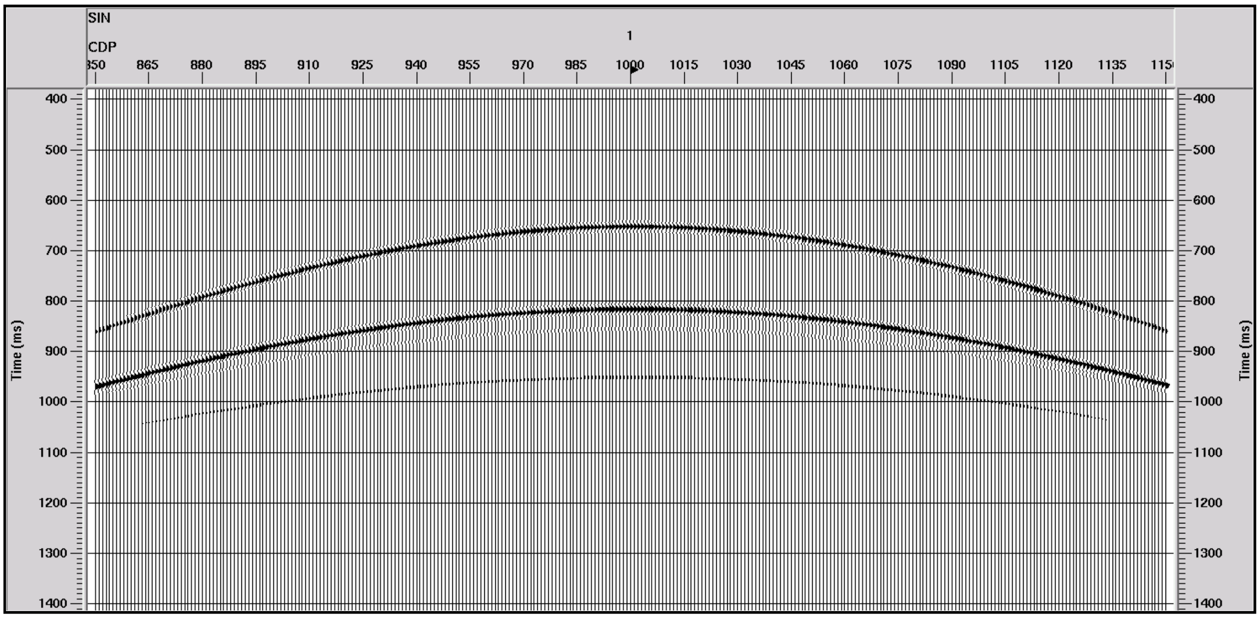

FIG. 6. Example vertical component (PP) shot gather from the Redwater Reef model.

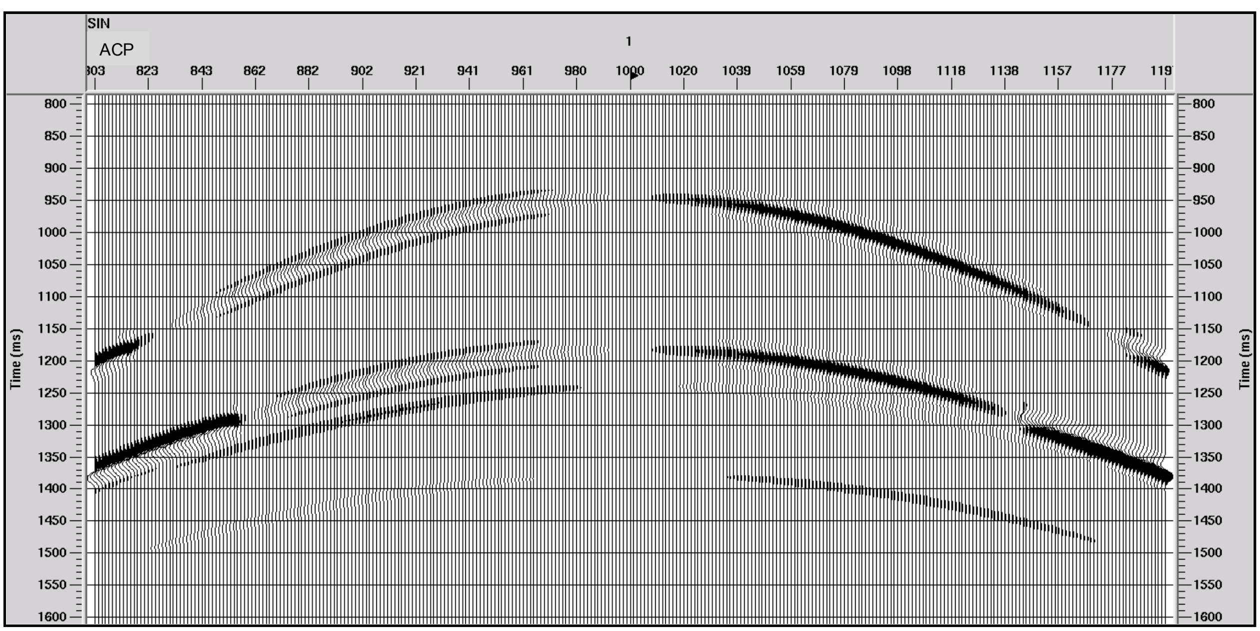

FIG. 7. Example radial component (PS) shot gather from the Redwater Reef model.

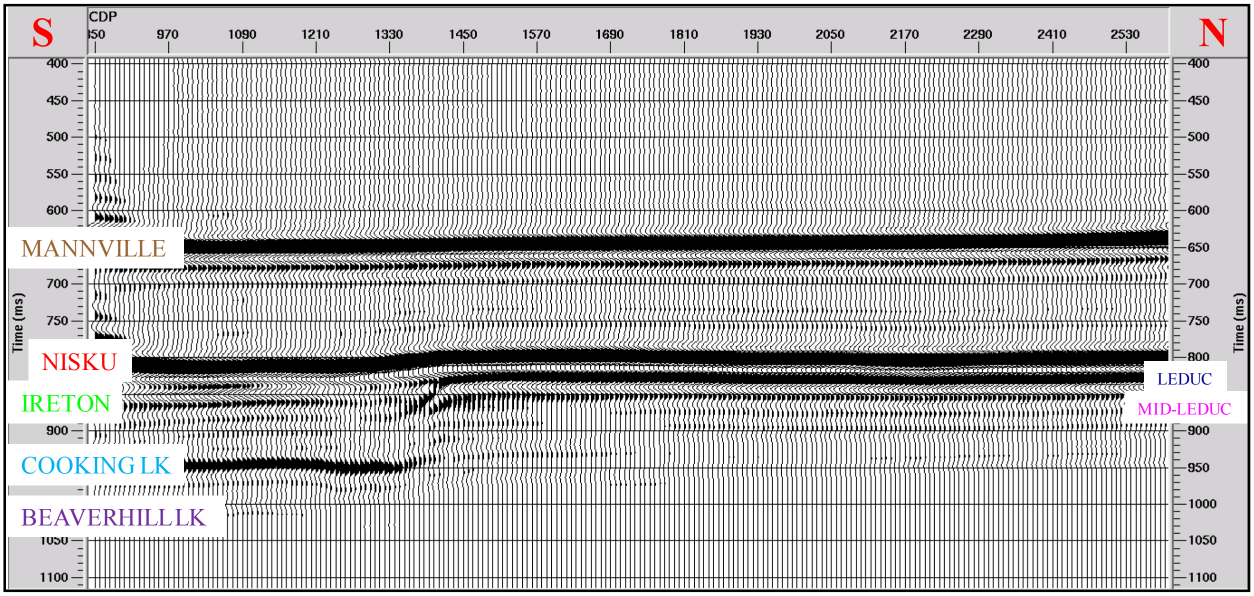

FIG. 8. Vertical component (PP) seismic section from the Redwater Reef model after pre-stack time migration.

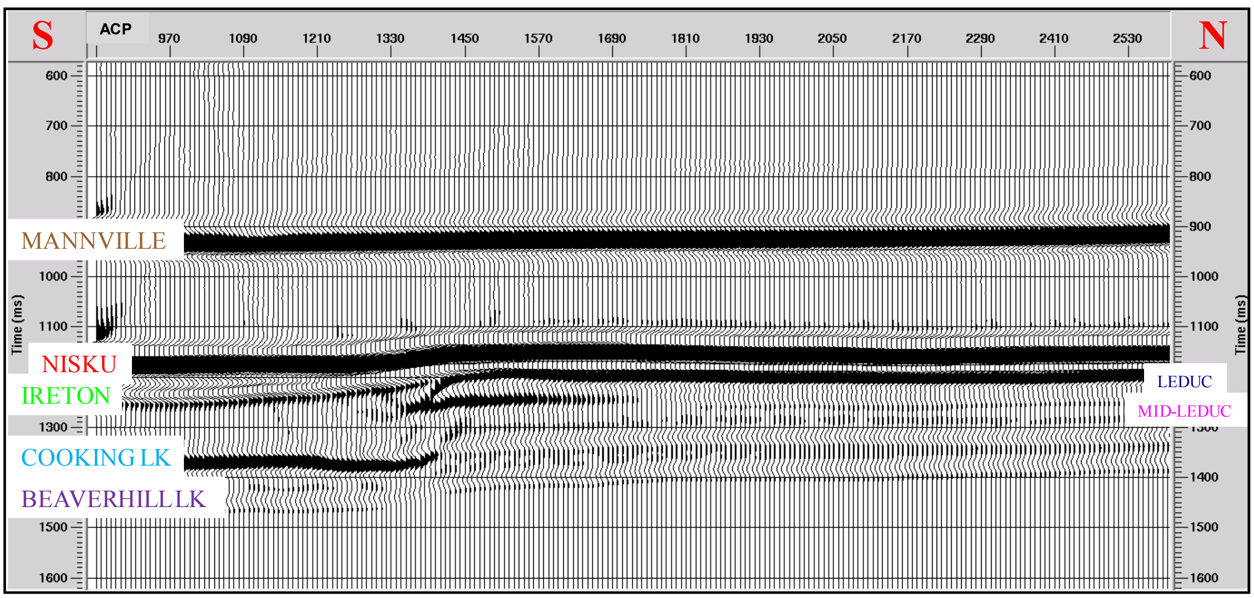

FIG. 9. Radial component (PS) seismic section from the Redwater Reef model after pre-stack time migration.

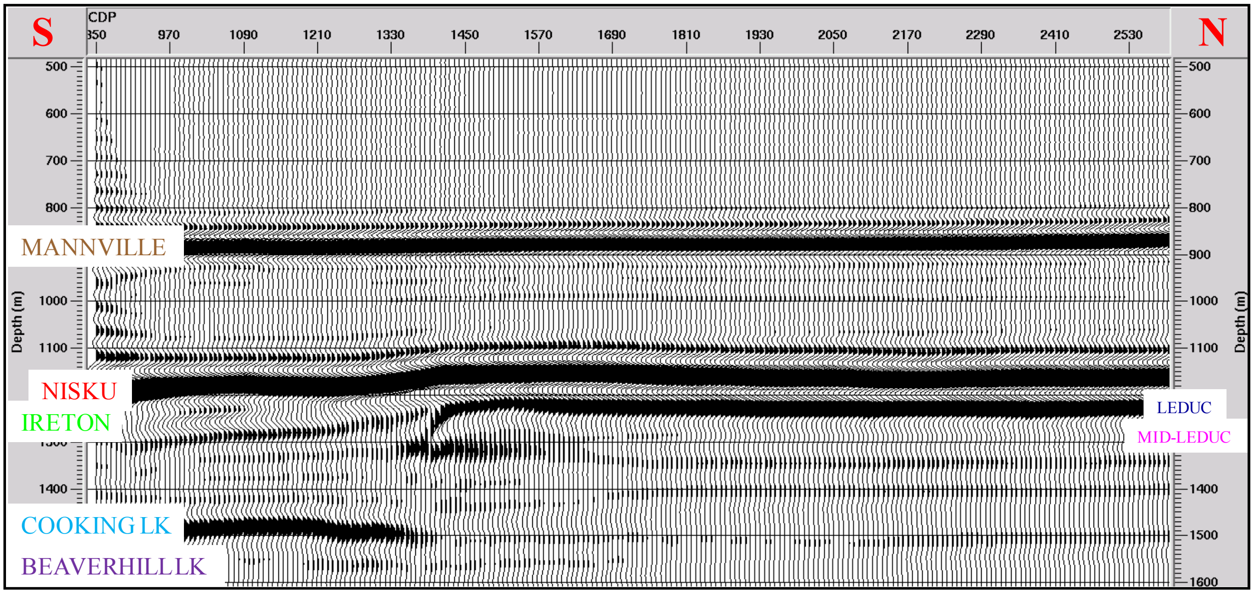

FIG 10. Vertical component (PP) pre-stack depth migrated section from the Redwater Reef model.

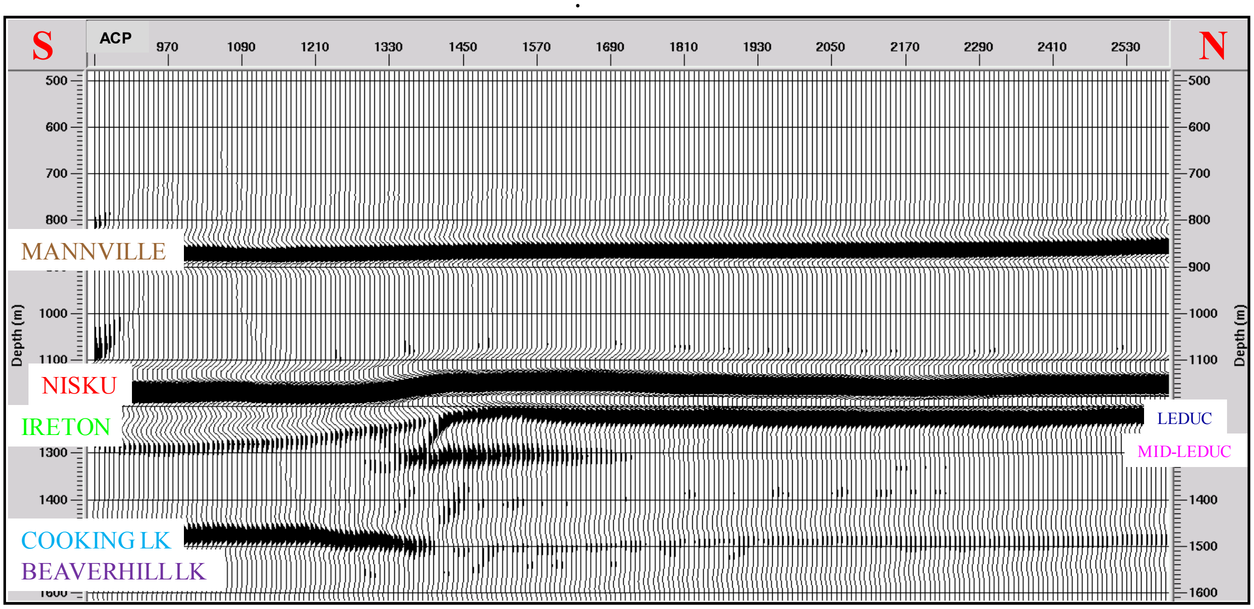

FIG. 11. Radial component (PS) pre-stack depth migrated section from the Redwater Reef model.

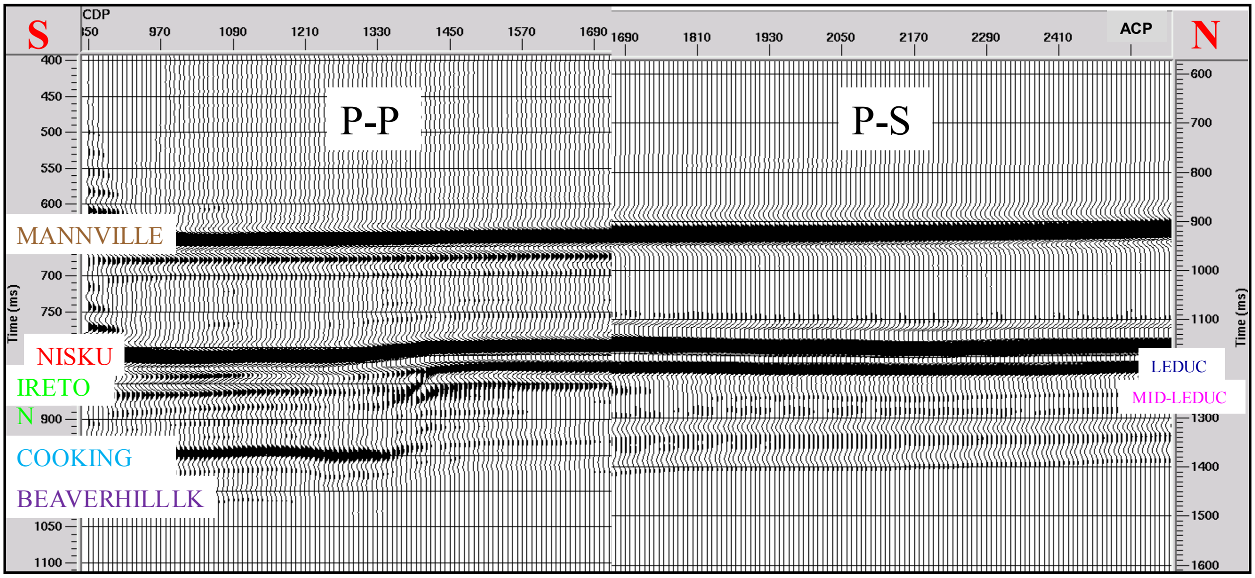

FIG. 12. Comparison and matching of the events between PP wave and PS PSTM seismic section from the Redwater Reef model.

Models after CO_2 fluid replacement

The 2D geological model developed with CO_2 fluid substitution in the Upper-Leduc member is shown in Figure 4. Figures 13 to 16 show the pre-stack time-migrated (PSTM) and depth-migrated (PSDM) seismic sections respectively for both PP and PS data generated from ray tracing. 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 are corrected in the pre-stack depth-migrated section (Figures 15 and 16 respectively).

Terminations of the Upper-Leduc and Middle-Leduc events are apparent on the 2D synthetic seismic sections with a modest improvement on the depth section at the reef margin, and the Upper Leduc event shows the rim build-up with lower amplitude compared to baseline sections (Figures 8 through 11) because of the brine replacement with CO_2 (Figures 13 through 16). A stronger and higher amplitude reflection at the base of the upper-Leduc member is evident near the reef margin compared to the baseline 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 the lagoonal facies within the central region of the reef.

The comparison between PP and PS PSTM and PSDM seismic sections with 40% CO_2 saturation in the upper Leduc show a fairly good tie for the seismic events. Time-lapse analysis was applied to examine the effect of CO_2 saturation on both the PP and PS seismic reflectivity and attributes. Figures 17 and 18 show the PP and PS difference seismic sections after pre-stack depth migration, before and after brine replacement with CO_2 saturation. It is noticeable that there are good reflection differences at the top of the upper-Leduc member, around the reef rim, and at the top of the mid-Leduc member near the reef edge, as expected. This difference anomaly on the PS data is attributed to a slight increase in S-wave velocity due to reduction in bulk density after brine replacement with CO_2.

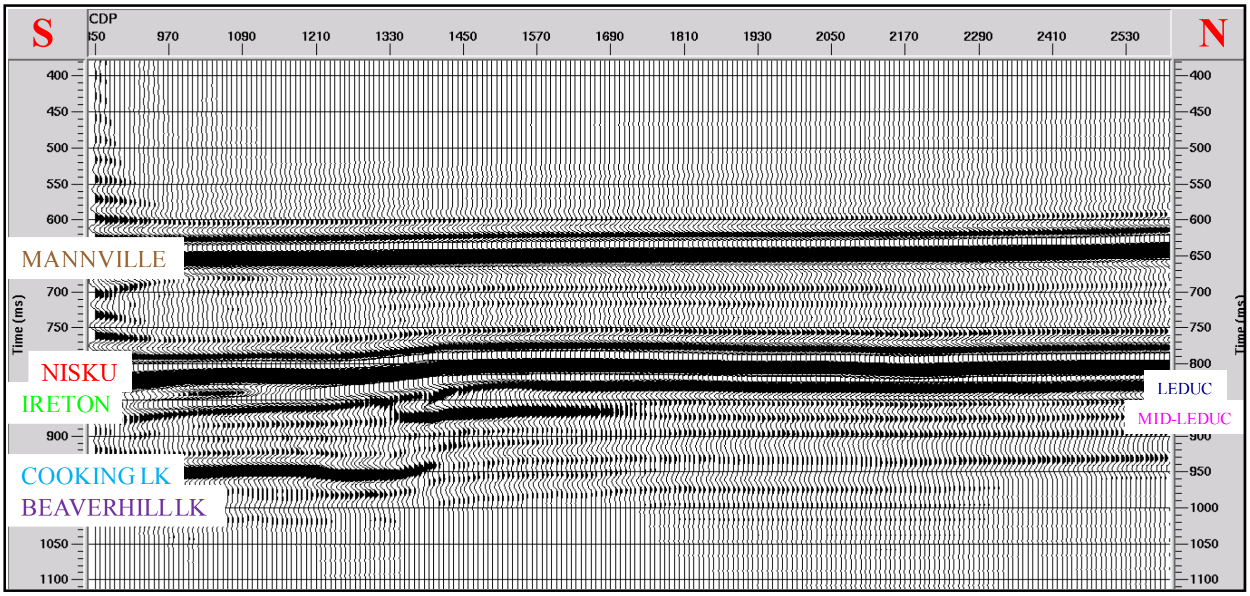

FIG. 13. Vertical component (PP) PSTM of reef seismic data after CO_2 fluid replacement.

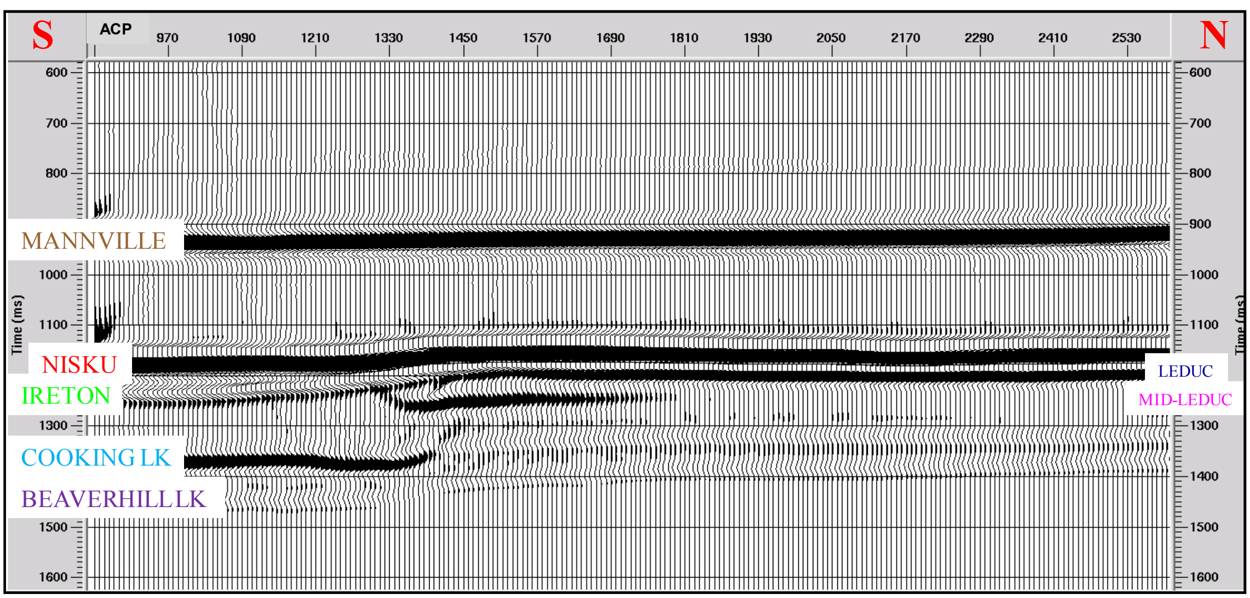

FIG. 14. Radial component (PS) PSTM of reef seismic data after CO_2 fluid replacement.

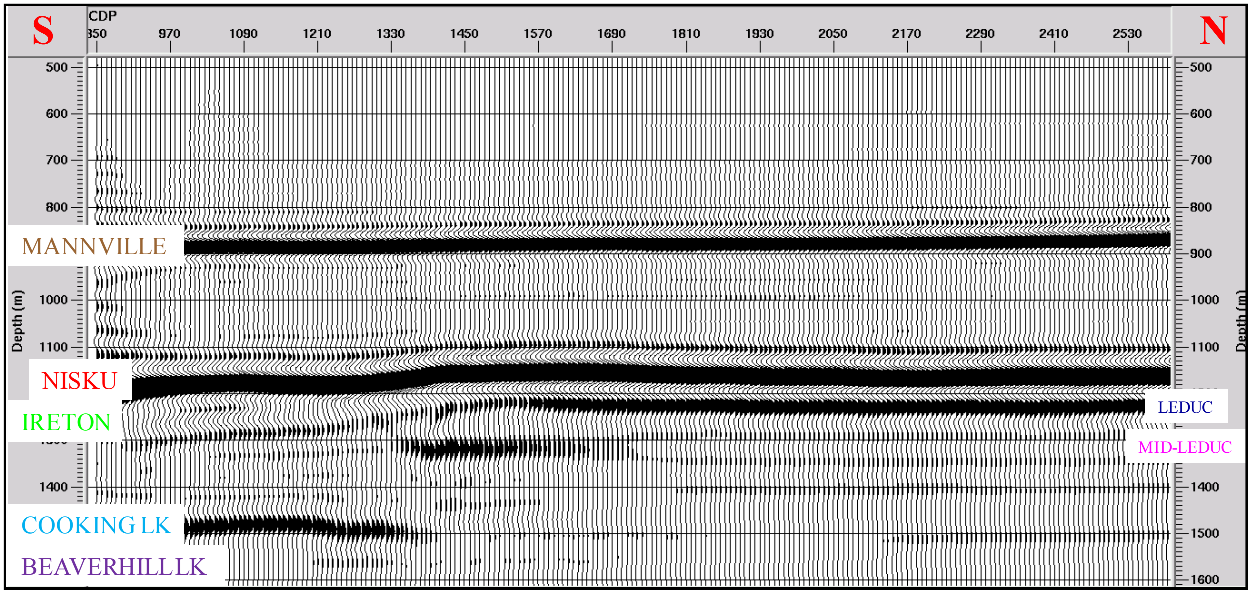

FIG. 15. Vertical component (PP) PSDM of reef seismic data after CO_2 fluid replacement.

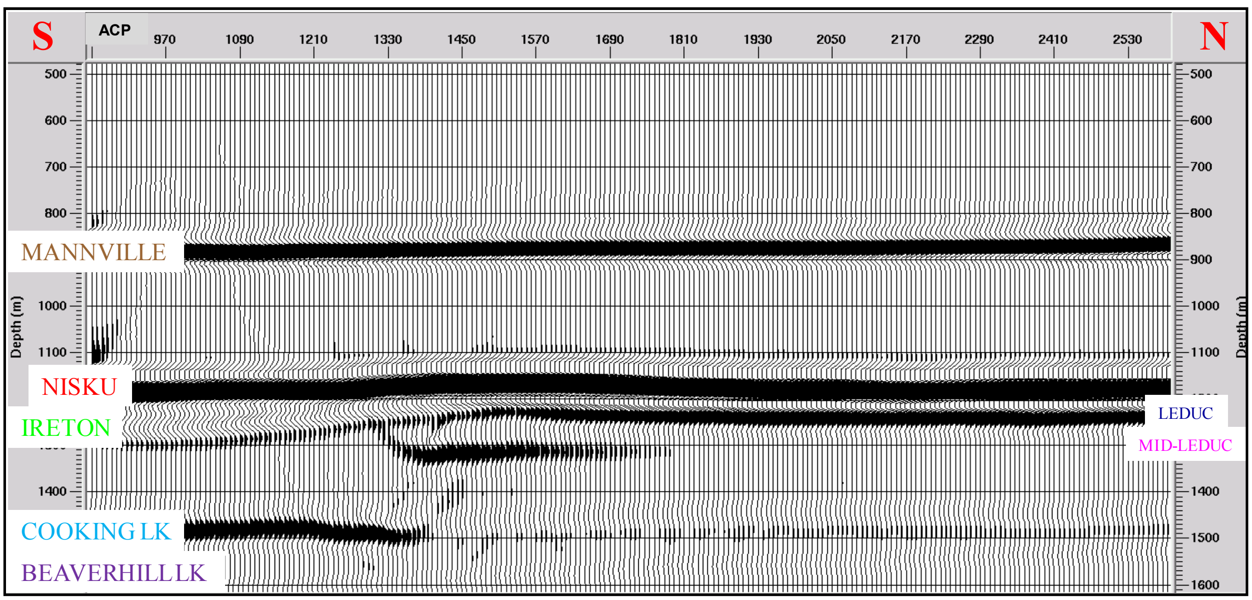

FIG 16. Radial component (PS) PSDM of reef seismic data after CO_2 fluid replacement.

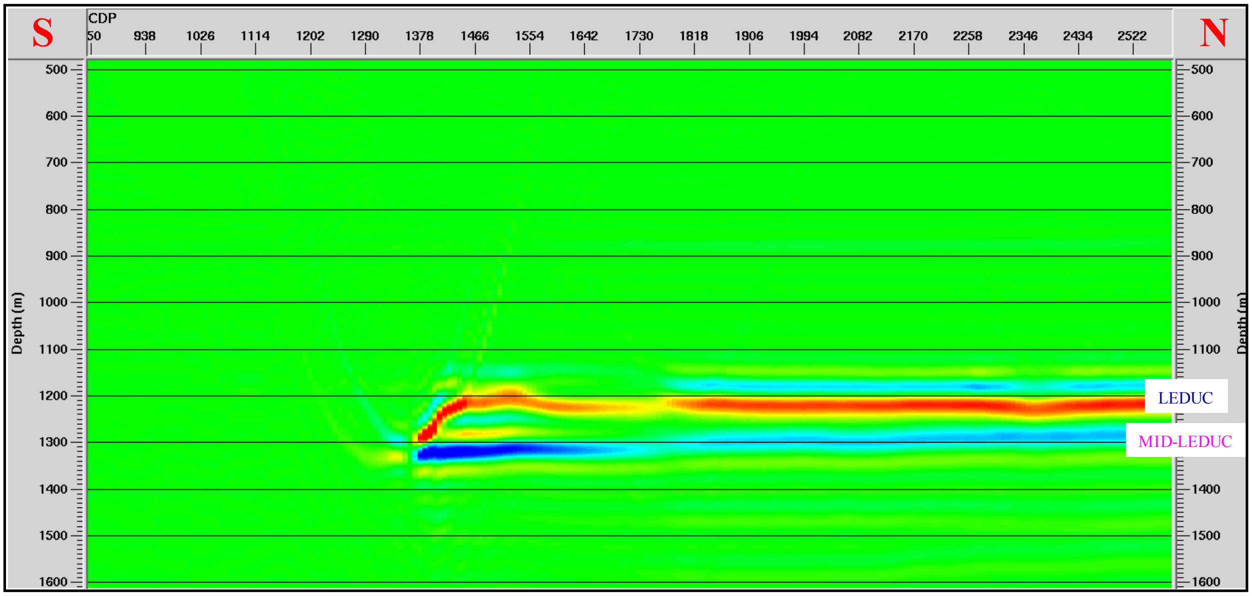

FIG. 17. PP difference after PSDM before and after CO_2 replacement.

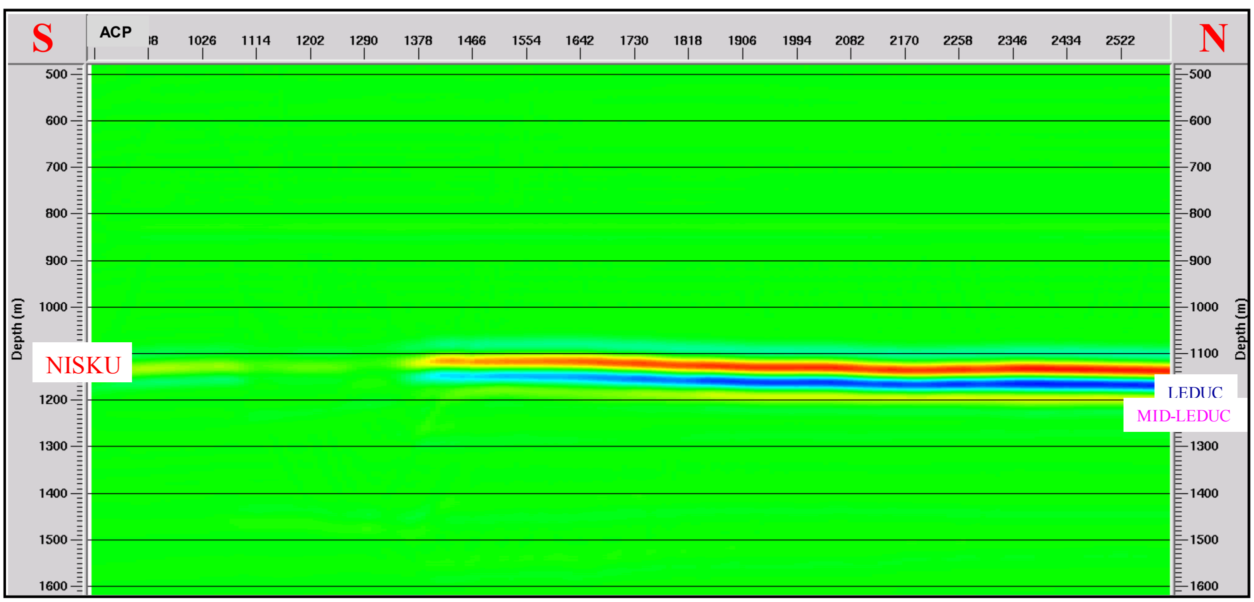

FIG. 18. PS difference after PSDM before and after CO_2 replacement.

CONCLUSIONS

The 2D ray traced synthetic PP and PS seismic sections demonstrate similar seismic attributes for the Mannville, Nisku, Ireton, Cooking Lake, and Beaverhill Lake formations for the baseline geological model as well as after replacement of brine with 40% CO_2 saturation in the Upper Leduc member. 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 a time section, and both formations are nearly flat after prestack depth migration.

Terminations and the lateral position of the Upper Leduc and Middle Leduc events are clear on the 2D pre-stack time and depth-migrated synthetic seismic sections for the baseline geological model as well as the monitor geological model after fluid substitution in the Upper Leduc Formation. The reef rim is observed near the reef margin. Higher reflection amplitudes at the mid-Leduc member are evident at the reef edge and reef rim 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 analysis demonstrates amplitude differences for the seismic data before and after CO_2 fluid substitution. Reflection differences at the top of Upper-Leduc, the reef rim, and Mid-Leduc events near the reef edge are evident.

ACKNOWLEDGMENTS

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