# Seismic interpretation of the Redwater Leduc Reef, Alberta

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## ABSTRACT

Approximately 400 line-km of 2D seismic data were reprocessed and interpreted to characterize the Redwater Reef in order to assess its potential for large-scale storage of $CO_2$. The seismic data, of various vintages, were reprocessed to a common datum in order to provide a uniform character for interpretation of the reef margin and to characterize the internal geometry and facies of the reef.

Interpretation of formation tops in the seismic data was constrained by synthetic seismograms generated from sonic and density logs available from two on-reef and four off-reef wells in the region. The synthetic seismograms tied reasonably well with the surface seismic data for the key formations. Generally, reflections dip gently towards the southwest direction in the 2D seismic datasets and there are no observable faults in the area encompassed by the Redwater Reef.

Devonian age Upper Leduc and Mid-Leduc edges are identified clearly on the 2D seismic lines. Thickening of the reef rim and thinning inside and central of the reef are characteristics of the reef interpreted along individual lines and interpolated through isochron maps. The Cooking Lake and deeper seismic events show time-structure (velocity pull-up) beneath the reef due to higher velocity of the Leduc Formation carbonates compared with the off-reef Ireton shales. A restricted embayment (Duvernay Fm) was mapped from the seismic interpretation into the reef buildup in near the north-west flank and south-west boundaries. Depth-converted seismic event maps compensate for the velocity pull-up beneath the reef except where the shale embayments occurs, since only a single interval velocity for the reef was used in the depth conversion process. Some evidence of dolomitization in the Middle Leduc and Cooking Lake formations was interpreted in seismic lines along western side of the reef. Otherwise, internally to the reef buildup and away from the Duvernay embayments, the seismic character of the Leduc Formation is generally quite featureless.


## INTRODUCTION

The main objective of this study was to use available seismic data to map the external and internal geometry of the Redwater Devonian reef for the potential geological storage of $CO_2$. This phase of the project concentrated on reprocessing the available 2D seismic data and undertaking a detailed interpretation of it to identify the reef margin, and to map facies variations within the reef based on seismic character, constrained by synthetic seismograms generated from available wells with sonic logs.

The study area is located in the Redwater region of Alberta, northeast of Edmonton, and encompasses Townships of 56 to 58 and Ranges of 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). The study is located within the Middle to Early Upper Devonian Waterways Basin (Figure 2).

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 between 160 to 300 m. The original oil cap was almost 50 m thick. The Redwater reef is currently under the last stages of water flooding for oil production, and this depleted oil reservoir is currently used for water disposal (Bachu et al., 2008).

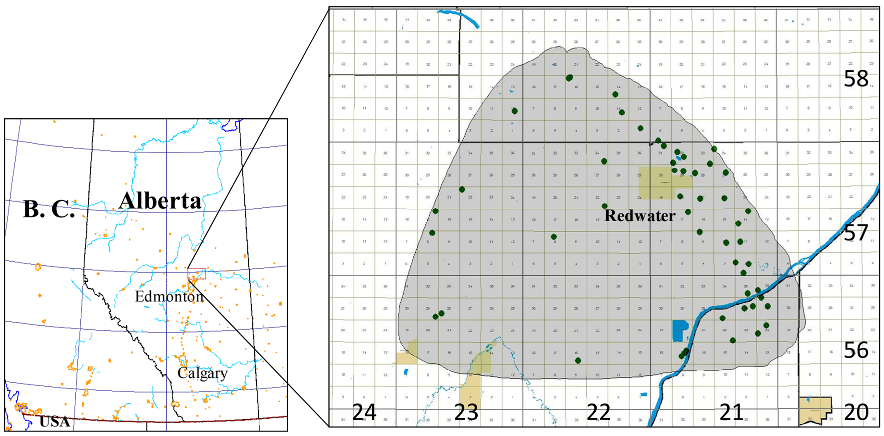


Figure 1: Alberta map showing the location and outline of the Redwater Reef, and wells penetrating the Lower Leduc Formation.

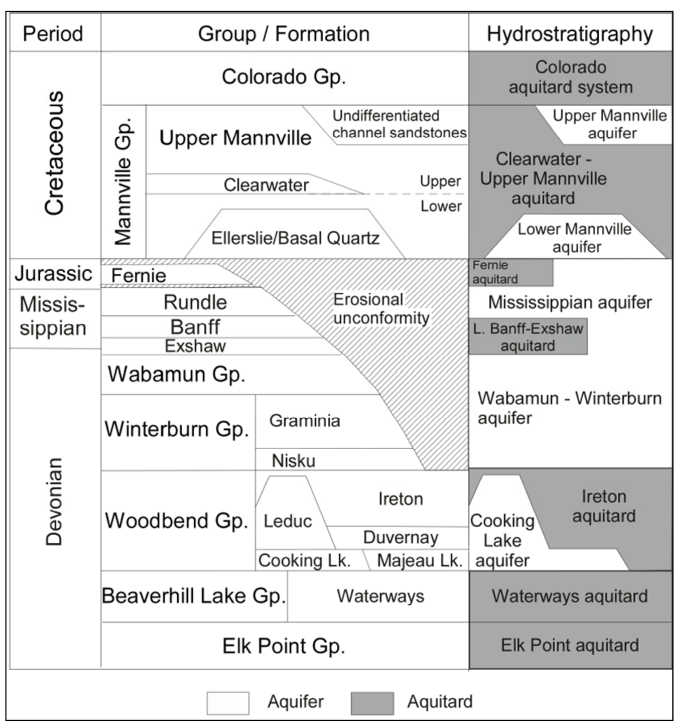


Figure 2: General stratigraphy and hydrostratigrphy presenting the aquifer and aquitard in the study area (Bachu et al; 2008).

## METHODOLOGY

### Surface Seismic and Well Log Datasets

A large number of wells penetrate the Upper Leduc Fm, especially on the eastern margin of the Redwater reef, but only a smaller number of wells penetrate the Cooking Lake Formation and few of these have sonic and density logs. Figure 3 shows three wells inside the reef and six wells off-reef that penetrate the Cooking Lake Formation in the general study area. Of these, two on-reef and four off-reef wells were used to tie the surface seismic data to formation tops using zero-offset and offset-dependent synthetic seismograms.

These well data were also used for fluid substitution modeling, inversion, and rock physics analysis to predict the seismic response of $CO_2$ injection into the Leduc Formation. Approximately 400 line-km of 2-D data were interpreted and the distribution of these seismic lines is shown in Figure 4.

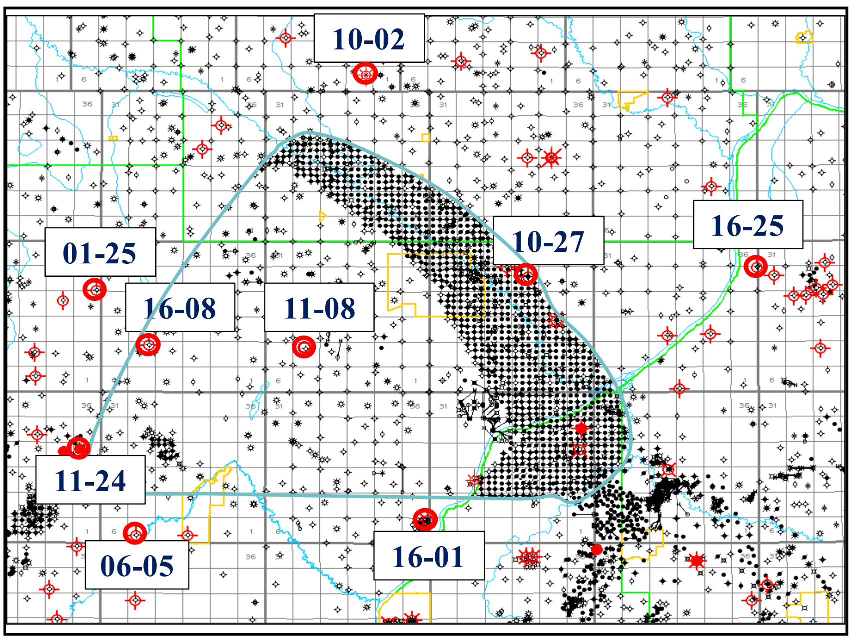


Figure 3: Redwater reef map showing all wells. Those wells that penetrate the Cooking Lake Formation and have sonic logs are highlighted in red.

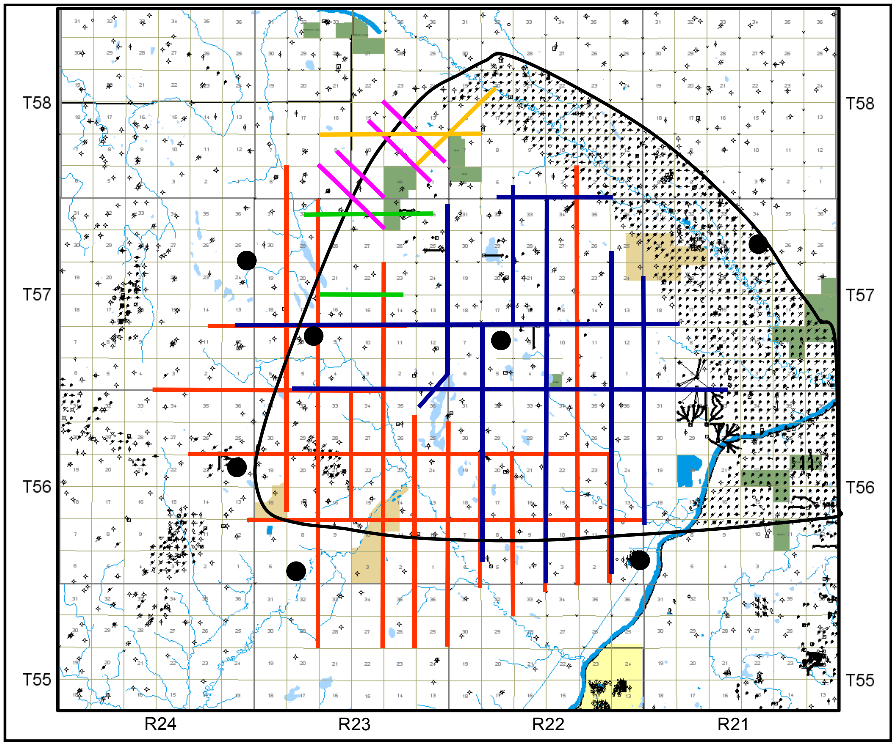


Figure 4: Map showing the outline of the Redwater reef and the distribution of all the 2D seismic data available for the project. The colours depict different vintages of data purchased. The black filled circles show the locations of wells that penetrate the Cooking Lake Formation and which have sonic and density logs.

## Seismic Data Reprocessing

The original seismic data were acquired and processed in the 1980's by various companies. The seismic lines at the south, southwest, and northwest edges of the reef were reprocessed, following a processing flow outlined in Table 1. Lines restricted to the interior of the reef were not reprocessed, but were post-stack migrated at the University of Calgary and bulk-shifted to the same datum as the reprocessed reef-margin data. The objective of the reprocessing was to improve the static solution and enhance imaging of the reef edge as well as the internal reef facies and geometry near the reef margin. The reprocessed data showed significant improvement in resolution and coherency of events over the original sections and yielded more confidence in the delineation of significant features within the reef, particularly embayments in the reef margin and localized area of dolomitization.

Table 1: Processing flow and parameters of the reprocessed 2D seismic data in the Redwater area.

| PROCESSING FLOW | PARAMETERES | | |
|---|---|---|---|
| Demultiplex | 2 ms. sample rate | | |
| Amplitude Recovery | (T) Exp (BT), B= 0.0008 | | |
| Deconvolution Type | Adaptive 5 component suface consistent signaturewith zero phase frequency domain offset compnent | | |
| Deconvolution Gate | 250-1500 ms. at 0 offset, 900- 1600 ms at 1500 m. offset | | |
| Structural Corrections | Datum elevation= 725m., Datum velocity= 2150m./Sec., Processing datum= -100ms. | | |
| Analysis | Preliminary velocities and statics | | |
| Statics and Trace Kills | Surface stack residual | | |
| Velocity Analysis and Final Moveout | Interval= 30 CDPs | | |
| Mean Scaling | Window: 500-1500 ms. | | |
| Time-Varient Scaling | Window: 0-500 ms. | | |
| Mute | Distance (m.)<br>Time (ms.) | 330<br>550 | 1500<br>1150 |
| Statics | Surface consistent residual, Window: 500-1500 | | |
| Trace Gather | Offset Range: 0-1500 m., Maximum fold: 14 | | |
| Statics | CDP cross correlation, Window: 500-1500 ms. | | |
| Stack | Cross correlation weighted | | |
| F-X Noise Reduction | Block size: 150 traces, %model: 60%<br>Prediction filter: 10 traces, PW: 10%<br>300 ms. Window, 100 ms. Overlap | | |
| F-D Migration | 100% theoritical velocities | | |
| Filter | 10/14 - 75/85 Hz. | | |
| Equalization | Mean window: 500-1500 ms. | | |

## Software

ProMax software was used for the post-stack migration, and Kingdom Suite software was used to interpret the 2D seismic data, generate synthetic seismograms, grid interpreted data and create the suite of maps. Data reprocessing was undertaken by Divestco.

## Synthetic Seismograms and correlation to seismic data

The first step in seismic data interpretation was to correlate the formation tops at well locations from synthetic seismogram to the 2D surface seismic data. Therefore, synthetic seismograms were generated for the wells that penetrated the Devonian Cooking Lake Formation, which is deeper than the target Leduc Formation. Only the primary reflection events were modeled, using logs from two wells inside the Redwater reef and from four wells off-reef. Tests with different wavelets showed that a good match between the synthetic seismograms and the 2D surface seismic data was a zero-phase 35 Hz Ricker wavelet (Figure 5). Also, seismic wavelets for some of the synthetic seismograms were extracted from the reprocessed 2D surface seismic data at the well locations.

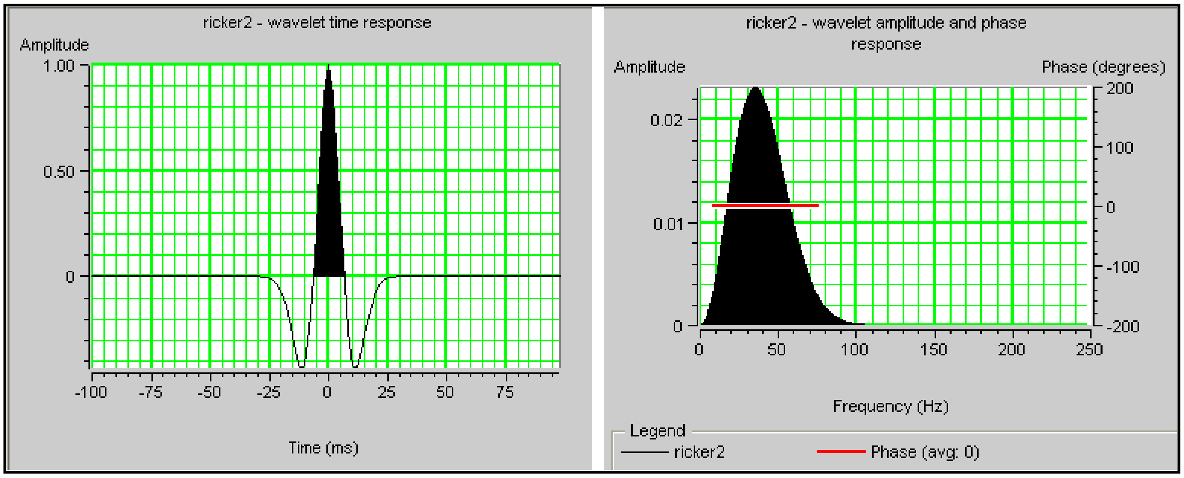


Figure 5: Zero-phase Ricker 35Hz wavelet in time and frequency domain.

## SECTION INTERPRETATION

The two wells within the Redwater reef that were used to generate synthetic seismograms were 11-08-57-22W4 (near the centre of the reef), and 16-08-57-23W4 (near the west margin of the reef). The off-reef wells were 01-25-57-24W4, 11-24-65-24W4, 06-05-56-23W4 and 16-01-56-22W4, all of which are west or south of the reef. Well 10-27-57-21W4 (on the east edge of the reef) has a shale embayment of the Duvernay Formation. However, since there are no seismic data available close to well 10-27-57-21W4, synthetic seismograms were not tied to seismic data, but they did provide the expected seismic character of the embayment to assist in the data interpretation.

Figures 6 and 7 illustrate the synthetic seismograms correlated to the corresponding surface seismic data. They tied reasonably well with the surface seismic data for the main key horizons. In all of the seismograms, the Nisku event is a fairly strong peak, the Ireton shale is a trough and the Cooking Lake Formation correlates to a moderate amplitude peak on-reef but has a higher amplitude in off-reef wells (Figures 6 and 7). This is because the Cooking Lake carbonate, when overlain by Ireton shale, represents a large impedance contrast and generates a high-amplitude reflection.

After correlation with synthetic seismograms, the migrated seismic lines were interpreted, with the following key horizons picked: Mannville, Nisku, Leduc, Mid-Leduc, Cooking Lake, Beaverhill Lake, and Lower Beaverhill Lake Formations. The Second White Speckled shale, Base Fish Scales Zone, Ireton, Elk Point, and the Basement events were picked where possible. All the horizons dip gently to the southwest in the 2D seismic datasets and no observable faults were identified in the region of the study area covered by the 2D lines.

Figure 8 to 10 show samples of the 2D seismic data. The 2D seismic lines clearly define the upper margin of the Redwater Reef (Upper Leduc Fm) and the Mid-Leduc event was used to formally map the lateral extent of the reef buildup. On some lines, the Duvernay embayment was mapped as a moderate amplitude event that is approximately correlative with the mid-Leduc event and extends into the buildup.

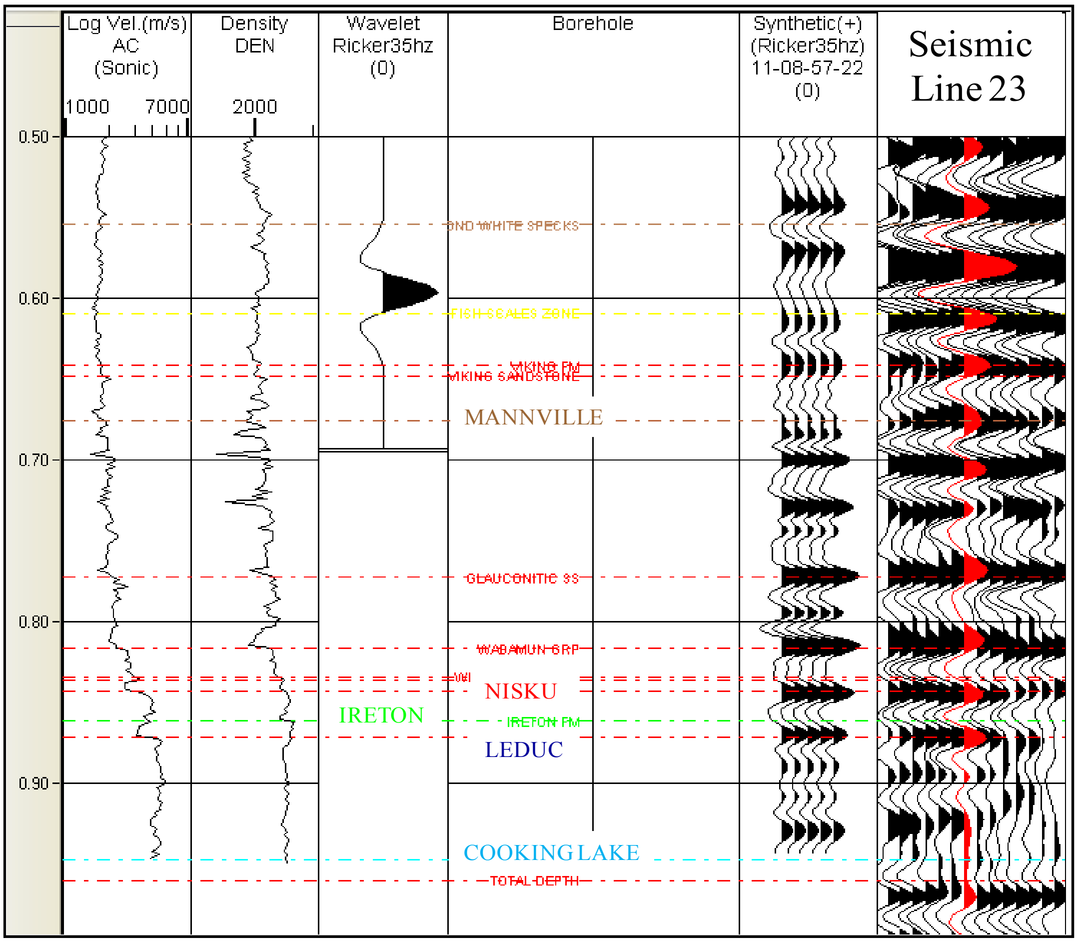


Figure 6: Sonic, density logs and synthetic of the well 11-08-57-22W4 correlated with seismic line 23 with picked key horizons. This is an on-reef well.

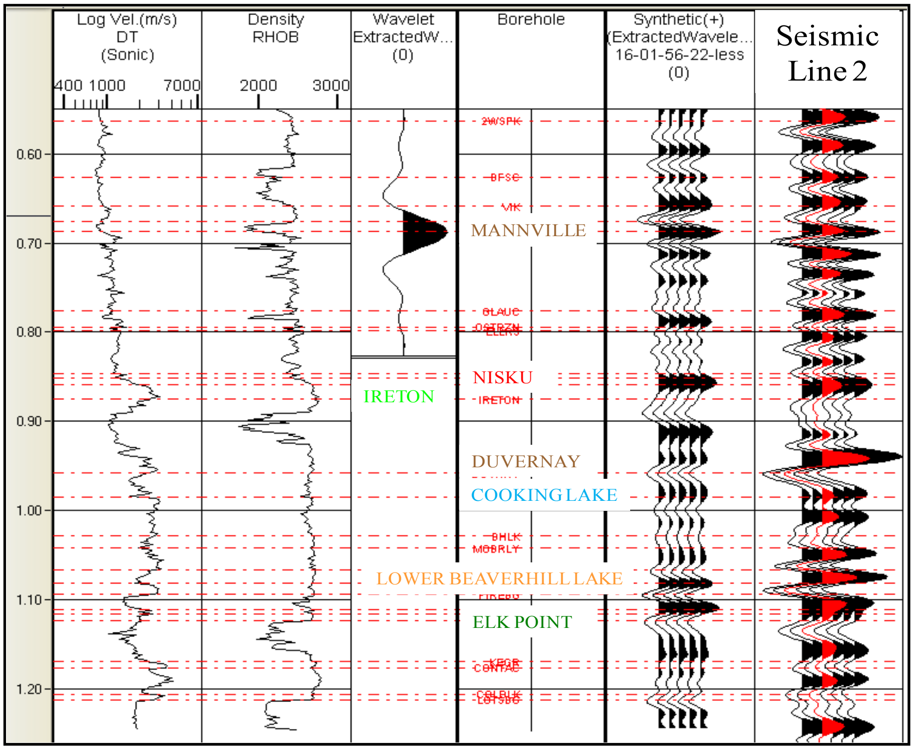


Figure 7: Sonic, density logs and synthetic of the well 16-01-56-22W4 correlated with seismic line 2 with picked key horizons. This is an off-reef well.

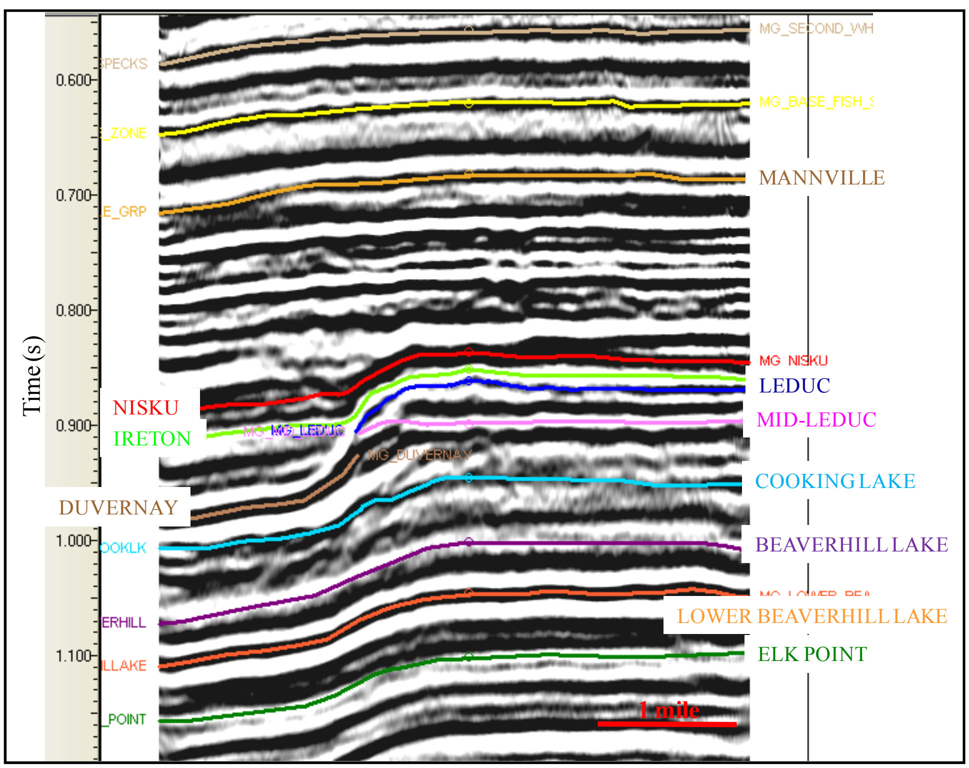


Figure 8: Interpreted north-south seismic section. North is to the right. This line shows the reef edge clearly and the Duvernay event terminating close to the reef margin.

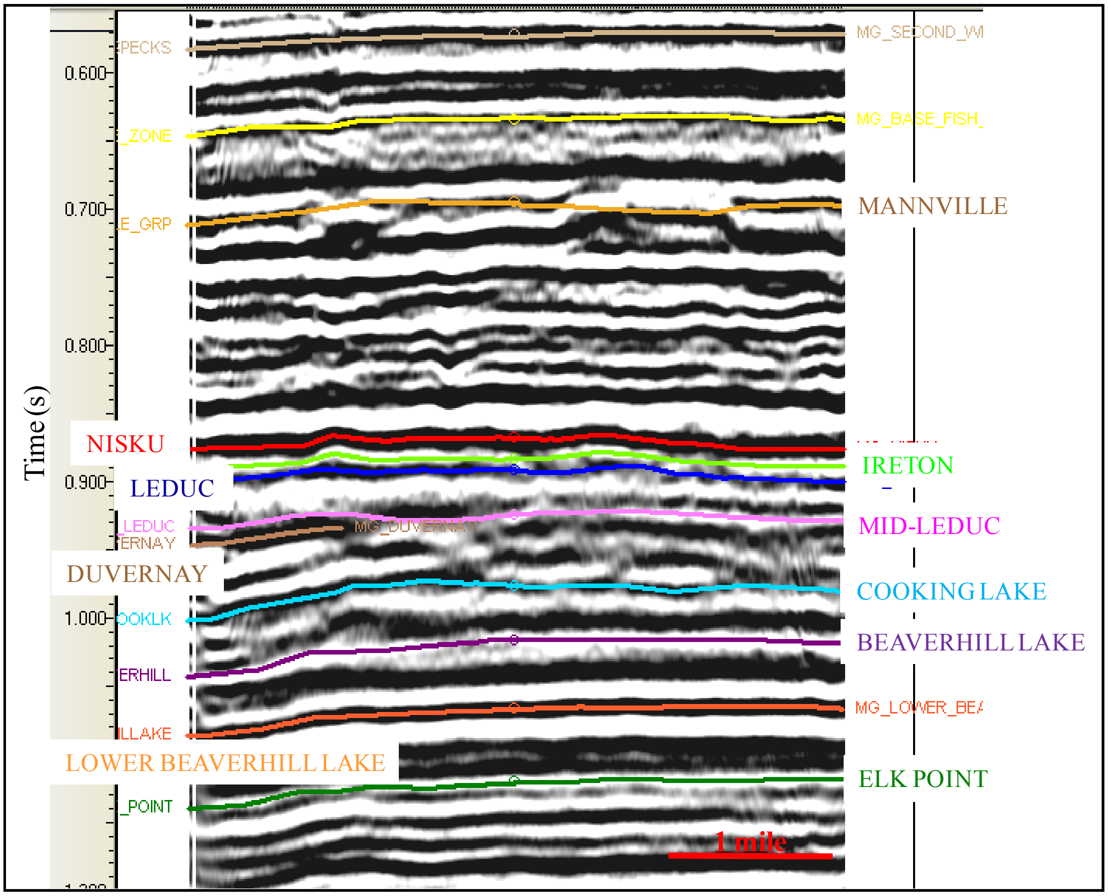


Figure 9: Interpreted north-south seismic section. North is to the right. This line shows Duvernay embayment event encroaching into the reef buildup toward the south.

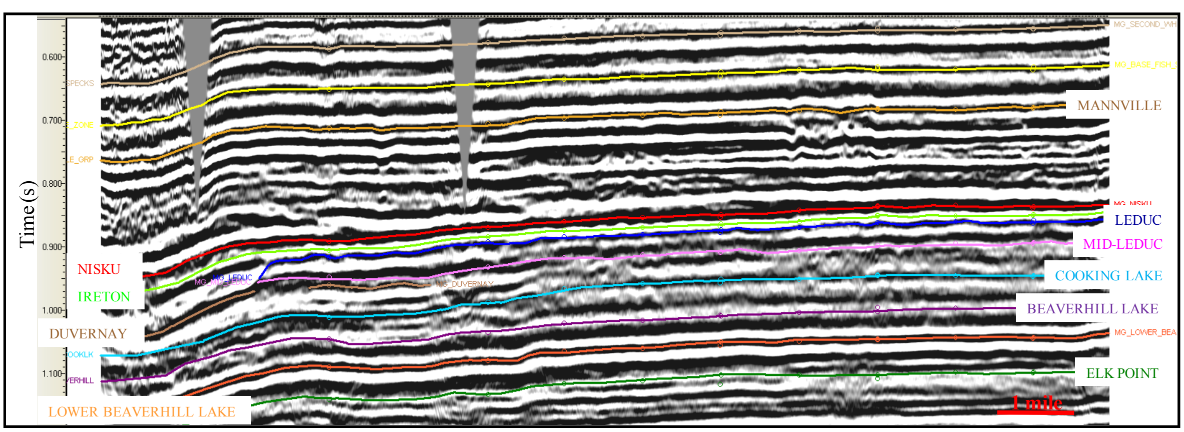


Figure 10: Interpreted west-east seismic section. East is to the right. This line shows Duvernay embayment event encroaching into the reef buildup from the west.

## MAP INTERPRETATION

After the seismic sections had been interpreted, the time picks of all horizons were gridded and contoured, producing time structure maps. Note that for all of the map views, the eastern boundary line marks the edge of data, not the eastern reef margin, whereas the northwestern and southern boundaries do represent the interpreted reef margin at the mid-Leduc level. Examples of time structure maps for the Mannville, Nisku and Upper Leduc formations are shown in Figures 11 and 13 respectively. The Mannville time structure map (Figure 11) shows generally a dip to the southwest and the Nisku time structure map (Figure 12) shows also a dip to the southwest, with some drape evident over the flanks of the reef. The time structure map of the Upper Leduc Formation (Figure 13) illustrates rim buildup in the north-west, south-west, and southern sides of the reef. The Middle Leduc time structure map is used to define the lateral extent of the reef.

Figure 14 show the Duvernay Fm time structure map. It shows the regional off-reef pick and also the embayment inside the reef along the north-west and south-west sides. The Duvernay embayment does not exist at the south side of the reef. Time structure map for the Beaverhill Lake formation is shown in Figure 15. This map demonstrates positive time structure of these reflections below the reef due to a lateral velocity change. The Basement event time structure map is smooth away from the reef edges and no significant basement highs were mapped from the seismic data.

From the geological studies for the HARP Project (Stoakes and Foellmer personal communication, 2008), dolomitization of the Cooking Lake Fm and the Lower Leduc and part of the Middle Leduc formations is observed in cores from wells in the west side of the reef (e.g. well 16-08). Interpretation of the 2D seismic lines in the west side of the reef suggests that dolomitization causes a loss of coherent reflectivity of these units. This character was mapped along other seismic lines along the western and northwestern parts of the reef.

The Nisku depth structure map is similar to the time structure map and shows generally a dip to the southwest, with some drape evident over the flanks of the reef. The depth structure map of the Upper Leduc Formation (Figure 16) illustrates rim buildup in the north-west, south-west, and southern sides of the reef. A single interval velocity function was used for depth conversion of the Nisku, Leduc, Cooking Lake, and Beaverhill Lake events. Interval velocities from all available sonic logs from wells for these intervals were compiled for a simple vertical time-to-depth conversion. Table 2 demonstrates the mean interval velocities that were used in depth conversions for the targeted formations.

Isochron maps (defined as differenced time structure maps) between the Upper Leduc and Cooking Lake formations and also between the Upper Leduc and Beaverhill Lake formations (Figure 17) also demonstrate the thickening of the rim of the reef and thinning in the central region of the reef which is corroborated by well data elsewhere around the reef rim. Isopach maps (defined as differenced depth structure maps) between the Upper Leduc and Cooking Lake formations and also between the Upper Leduc and Beaverhill Lake formations (Figure 18) also demonstrate the thickening of the rim of the reef and thinning in the central region of the reef which is corroborated by well data elsewhere around the reef rim.

Depth structure maps for the Cooking Lake and Beaverhill Lake formations illustrate generally a dip to the southwest and compensate for the velocity pull-up due to a lateral velocity change. They also demonstrate negative depth structure of these reflections below the reef embayment because of the simplification of using a single interval velocity technique for depth conversion for the Upper, Mid and Lower Leduc Formations (averaged from the logs). Therefore, the average velocity is less below the reef embayment due to the presence of shales instead of carbonates. Since no wells are penetrated the embayment at the southwest edge of the reef, no velocity control is present.

Table 2: Interval velocities computed from sonic logs for targeted intervals.

| Formation Interval | Interval Velocity (m/s) |
|---|---|
| **Surface to Nisku** | 2450 |
| **Nisku to Leduc/Cooking Lake** | 4400 |
| **Leduc to Cooking Lake** | 5760 |
| **Cooking Lake to Beaverhill Lake** | 5513 |

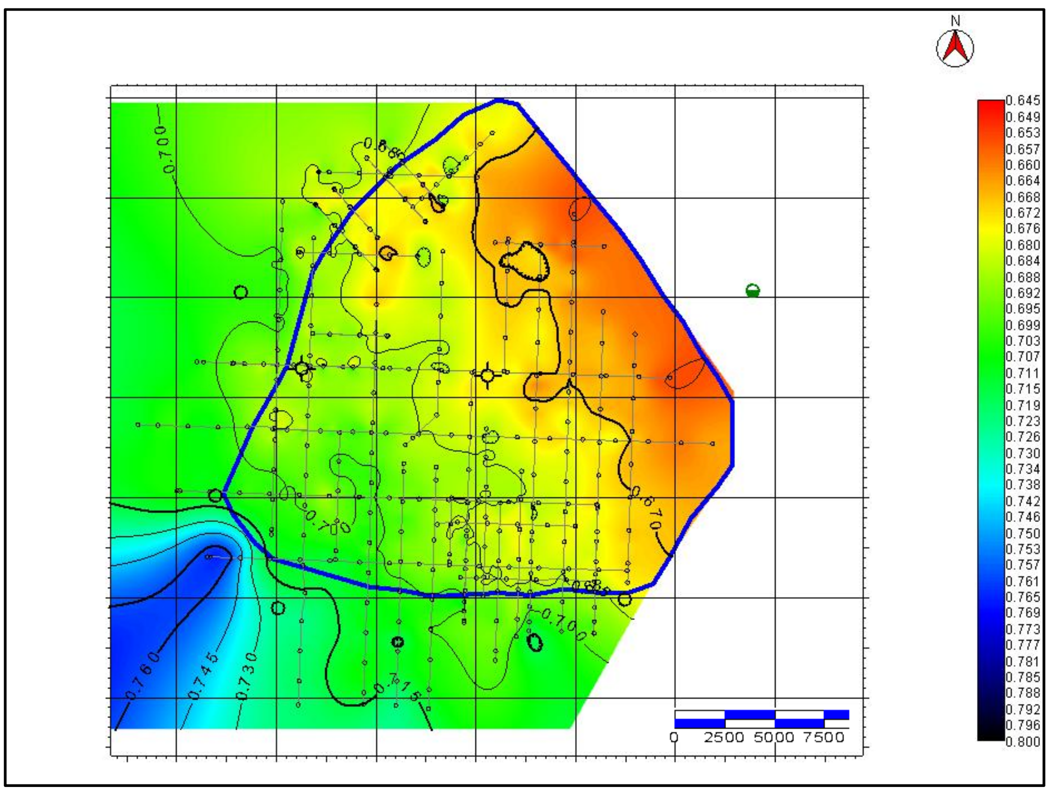


Figure 11: Time structure map of the Mannville Formation with the Devonian Leduc reef edge outlined. Color bar legend represents the two-way time in ms. The eastern boundary marks the edge of data.

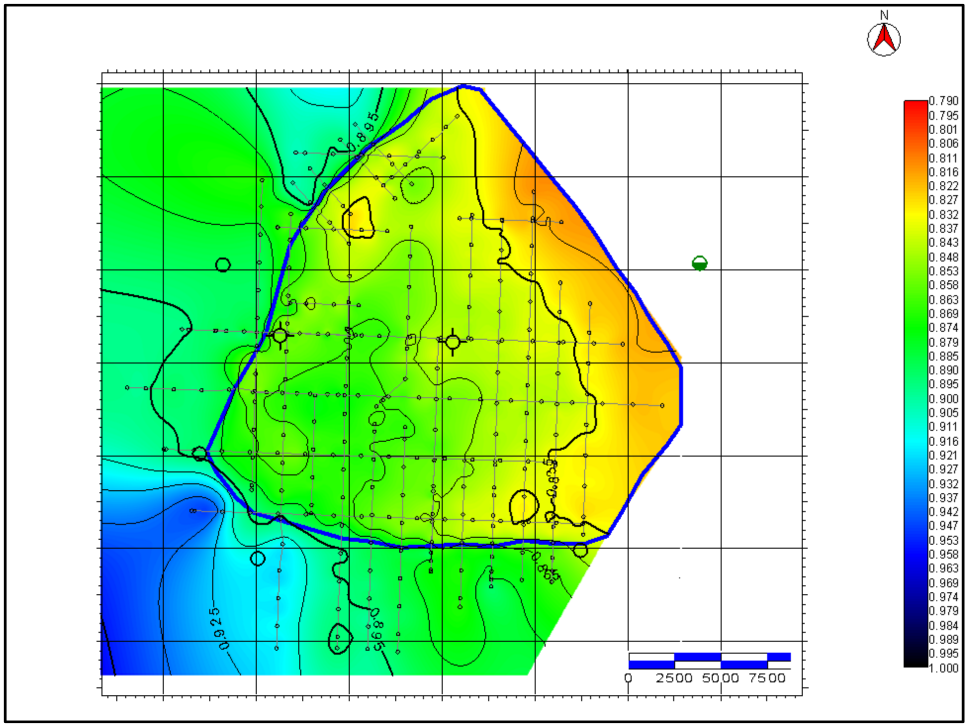

Figure 12: Time structure map of the Nisku Formation with the Devonian Leduc reef edge outlined. Color bar legend represents the two-way time in ms. The eastern boundary marks the edge of data.

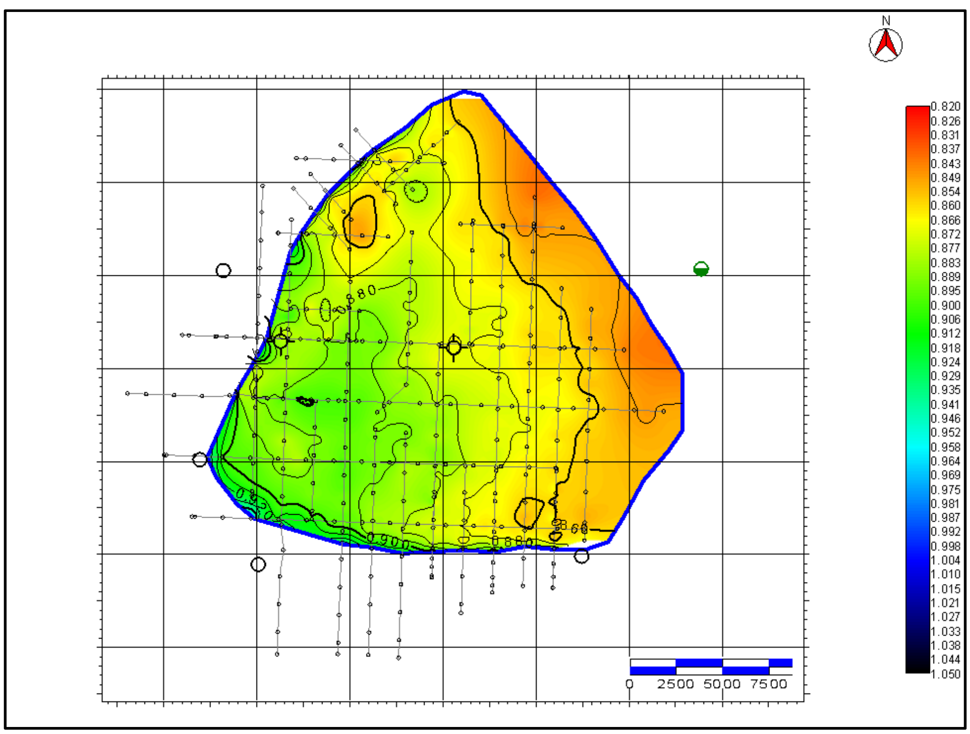

Figure 13: Time structure map of the Upper Leduc Formation with the Leduc reef edge outlined. Color bar legend represents the two-way time in ms. The eastern boundary marks the edge of data.

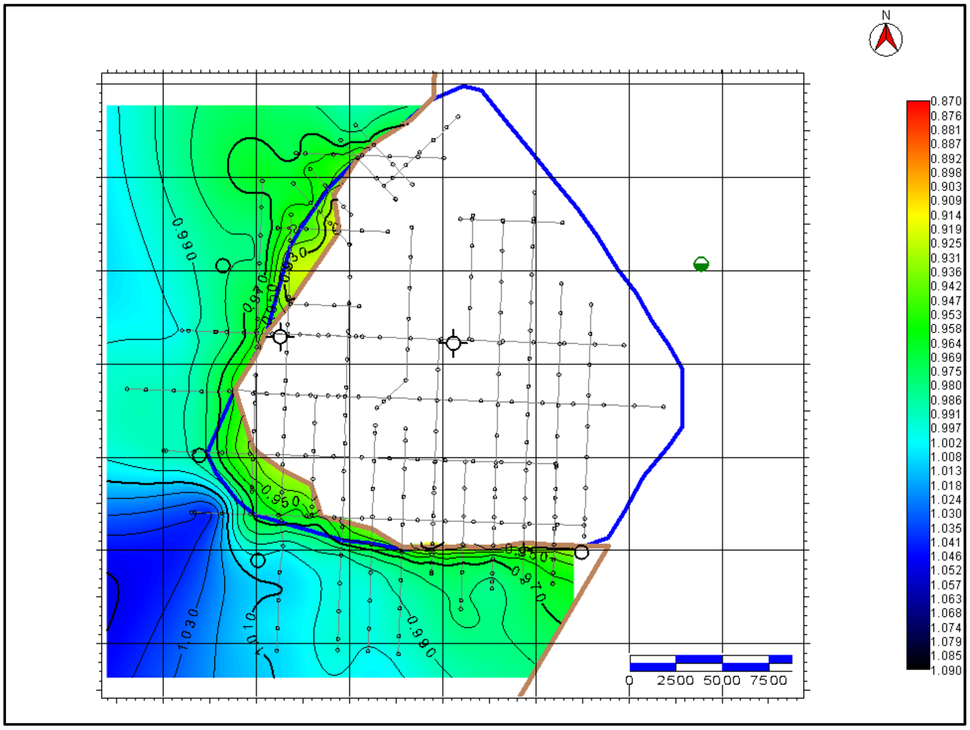


Figure 14: Time structure map of Duvernay Fm with the embayment (Brown) and Leduc (Blue) edges outlined. Color bar legend represents the two-way time in ms. The eastern boundary marks the edge of data.

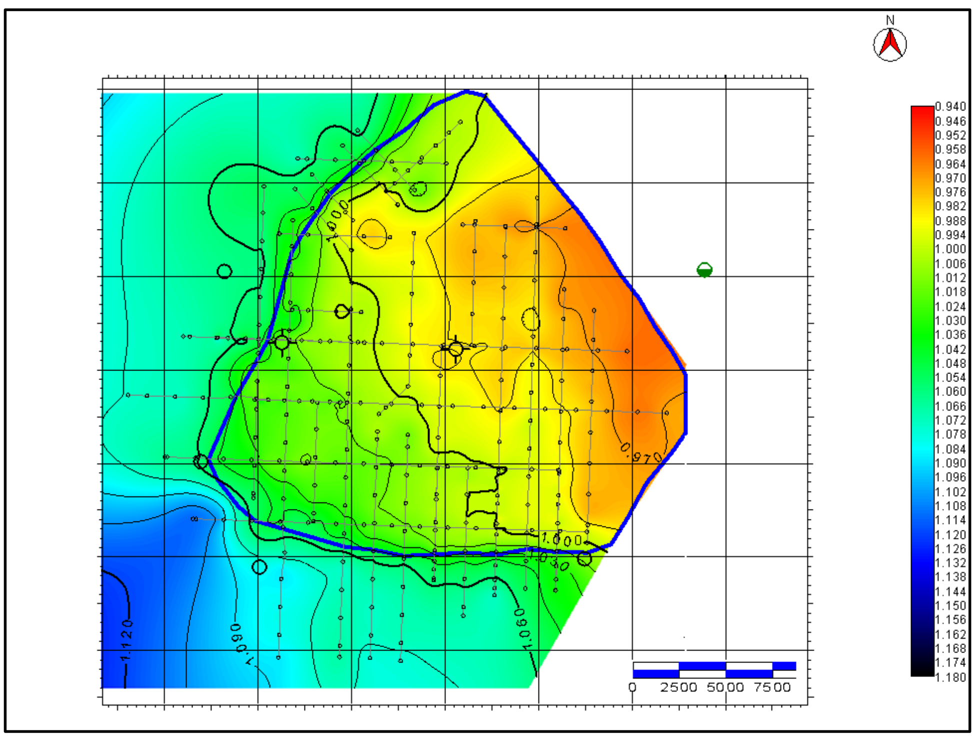


Figure 15: Time structure map of top of Beaverhill Lake Formation with the reef edge outlined. Color bar legend represents the two-way time in ms. The eastern boundary marks the edge of data.

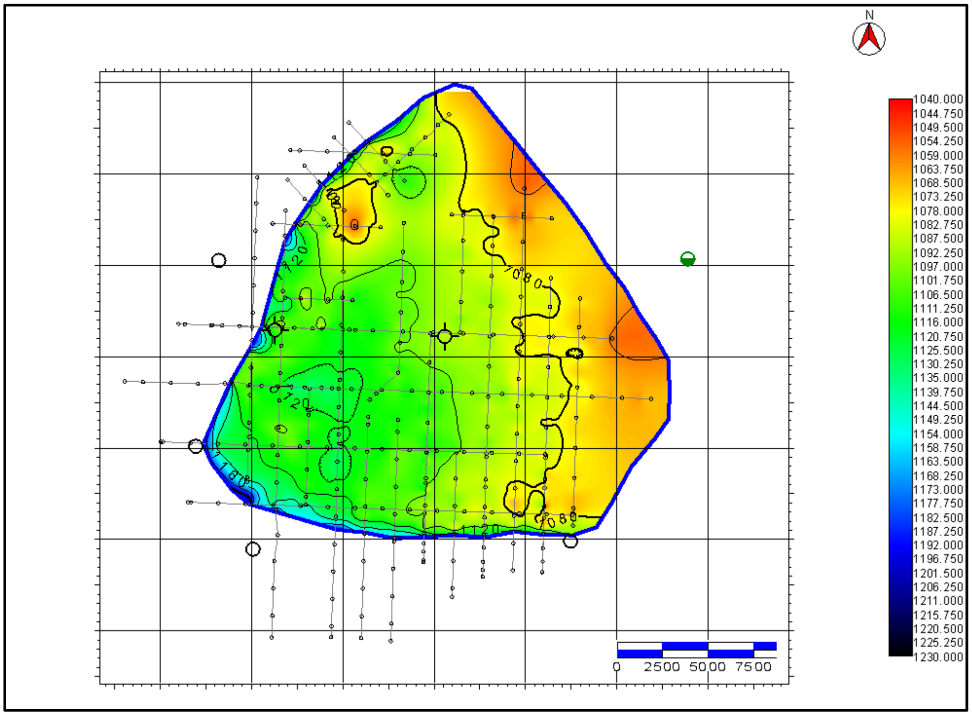


Figure 16: Depth structure map of the Upper Leduc Formation with the Leduc reef edge outlined. Color bar legend represents the depth in meters. The eastern boundary marks the edge of data.

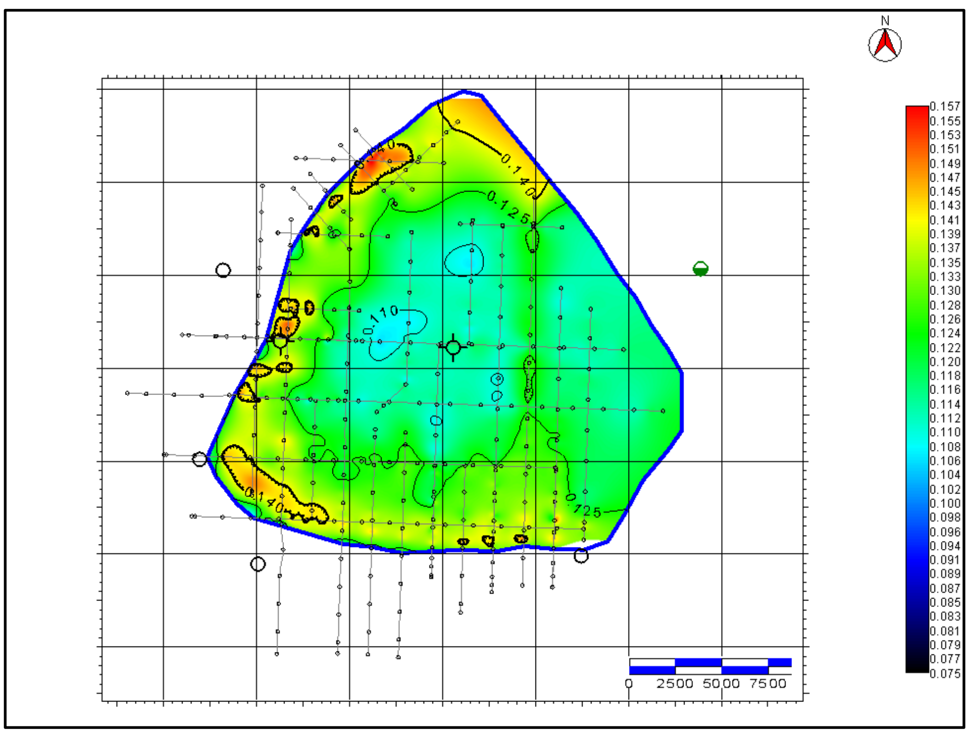


Figure 17: Isochron map between Leduc and Beaverhill Lake Fms with the reef edge outlined. Color bar legend represents two-way time thickness in ms. The eastern boundary is the edge of data.

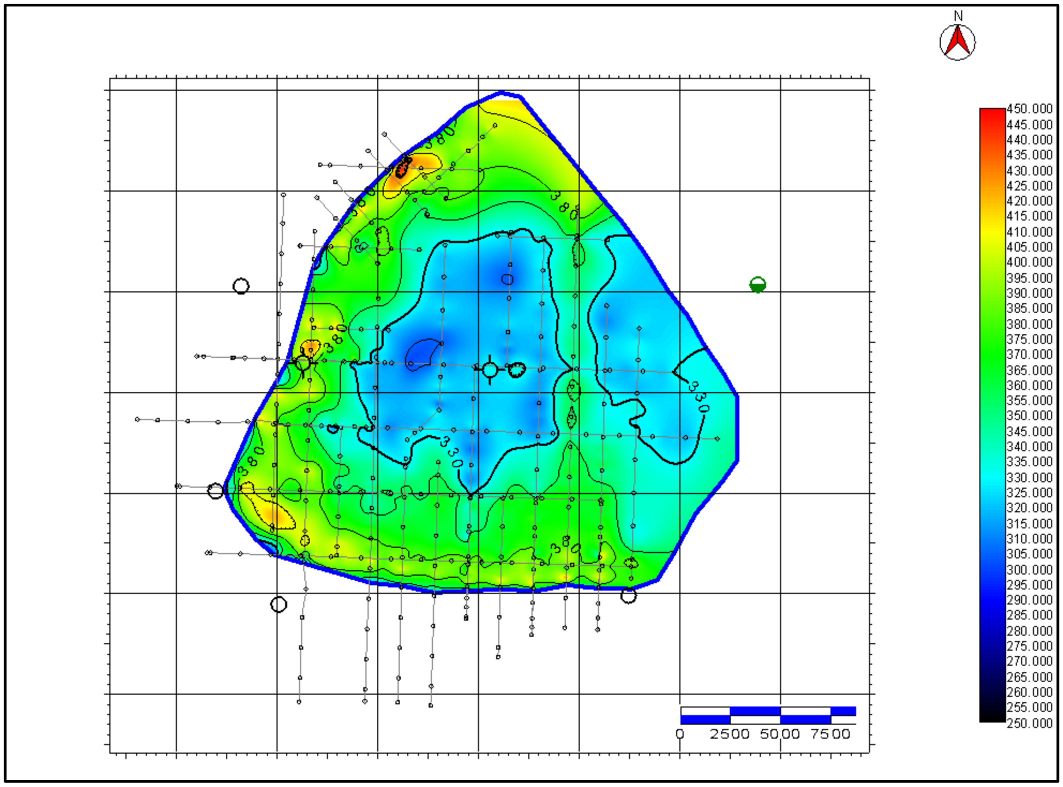


Figure 18: Isopach map between Leduc and Beaverhill Lake Fms with the reef edge outlined. Color bar legend represents the thickness in meters. The eastern boundary marks the edge of data.

## DISCUSSION AND CONCLUSIONS

Interpretation of 400 line km of vintage 2D seismic data was completed for this study. Prior to interpretation, the data were reprocessed through to post-stack time migrated to improve the lateral position of reflectors and to correctly image the reef edges. Overall, the data quality is good. Six wells were used to generate zero-offset synthetic seismograms to tie the seismic data to formation tops. Two wells are inside the reef and four wells are off-reef. The ties between the synthetic seismograms and the migrated seismic data were good.

During the interpretation, the key horizons picked were the Mannville, Nisku, Leduc, Mid-Leduc, Cooking Lake, Beaverhill Lake, Lower Beaverhill Lake formations. An interpreted Basement event was also picked. Generally, all the horizons picked dip towards the south-west and no observable faults in the study area were indentified. Time structure of formations younger than the Leduc Formation exhibits compactional drape over the reef, and this decreases upwards. Reflections from below the reef exhibit significant positive time structure and appear as highs in time structure maps. This structure is apparent only and is due to high velocities of on-reef strata (Leduc Fm.) being juxtaposed beside lower velocity off-reef strata (Ireton Fm.). Depth maps generally compensated for the velocity pull up. However, they demonstrate negative depth structure below the reef embayment because of using the single interval velocity technique for depth conversion, due to lack of wells penetrating the embayment where seismic data are available. The average velocity is lower within the reef embayment due to the presence of shales instead of carbonates.

Terminations of the Upper Leduc and Middle Leduc events are clear on the 2D seismic lines and the latter pick was used to define the reef margin. Isochron and Isopach maps between the Upper Leduc and deeper formations delineate thickening of the reef around the rim on the western and southern sides, and thinning in the central part of the reef. This was corroborated with well data.

A Duvernay embayment was mapped encroaching into the reef along the northern part of the north-western reef flank, and also around the southwestern corner of the reef. The embayment was evidenced by a high-amplitude reflection within the reef. Elsewhere, the internal reflectivity of the reef is generally low and uncharacteristic. A loss of coherence in reflectivity along some seismic lines near the western edge of the reef was interpreted to be an indicator of dolomitization in the Middle Leduc and Cooking Lake formations.

## ACKNOWLEDGMENTS

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