AVO analysis of carbonates

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ABSTRACT

We analyze amplitude variations with offset (AVO) in 2D seismic data from the Redwater area of Alberta to investigate whether it is possible to differentiate between limestone and dolomite in the Middle Leduc Formation. We used the P-wave sonic and density logs from two wells, one with dolomite in the Middle Leduc and the other with limestone. Shear wave sonic logs had to be estimated from the P-wave logs. The correlations between the synthetic offset gathers and the seismic data at the projected location of the wells is poor. We are not able to pick a consistent event on the offset gathers for the limestone well. Modification of the dolomite well logs to replace the dolomite with limestone is unsatisfactory because of the lack of shear wave log data for proper modelling.

INTRODUCTION

The Redwater reef in Southern Alberta is under investigation in the Heartland Area Redwater Project (HARP) as a potential target for CO_2 injection. The structure of the reef has been mapped with 2D seismic data (Sodagar and Lawton, this volume). One of the wells at the edge of the reef encountered dolomite near the top of the Middle Leduc Formation, whereas a well in the centre of the reef encountered tight limestone in the same interval. Porous dolomite is an unsuitable lithology for CO_2 injection as it is believed that the CO_2 might seep into the underlying Cooking Lake Formation. We undertook AVO analysis of two 2D seismic lines that had been reprocessed by a contractor specifically to preserve amplitudes for AVO analysis.

AVO analysis utilizes the property that reflection coefficients may change significantly with increasing source-receiver offset, and that observation of such behaviour on pre-stack offset gathers might help us to distinguish between different lithologies or fluid contents. The amount of amplitude change with offset depends on the P-wave and S-wave velocities and the density of the rocks under investigation. These parameters themselves depend on the physical properties of the rocks, the most important being lithology, porosity and fluid content (Tatham, 1982).

AVO analysis of carbonate rocks has not been widely applied. Li et al. (2003) discuss the factors limiting the application of AVO in carbonates and plot the theoretical response of reservoirs with different fluids. Their plots show that the AVO responses of wet porous limestone encased in tight limestone, and for wet porous dolomite encased in tight limestone, are very similar (class III) for porosities above 0.04. They also stress the importance of the correct use of shear-wave velocity information. Xu and Payne (2009) discuss the difficulties in developing carbonate rock physics models. AVO modelling has been used successfully to interpret gas-charged dolomites, and to differentiate tight dolomite from porous dolomite (Li et al., 2007). Eissa et al. (2003) were able to distinguish gas-producing dolomite from tight limestone in Lower Ordovician rocks.

However, our objective is to distinguish dolomite encased in limestone from tight limestone.

METHOD

AVO analysis of the Middle Leduc Formation

We used two well logs and two 1983 vintage seismic lines (A and B) in this study (Figure 1). Well 16-08-57-023W4 is situated near the edge of the reef and encountered dolomite in the Middle Leduc Formation. Well 11-08-57-022W4 is near the centre of the reef, where the Middle Leduc lithology is limestone.
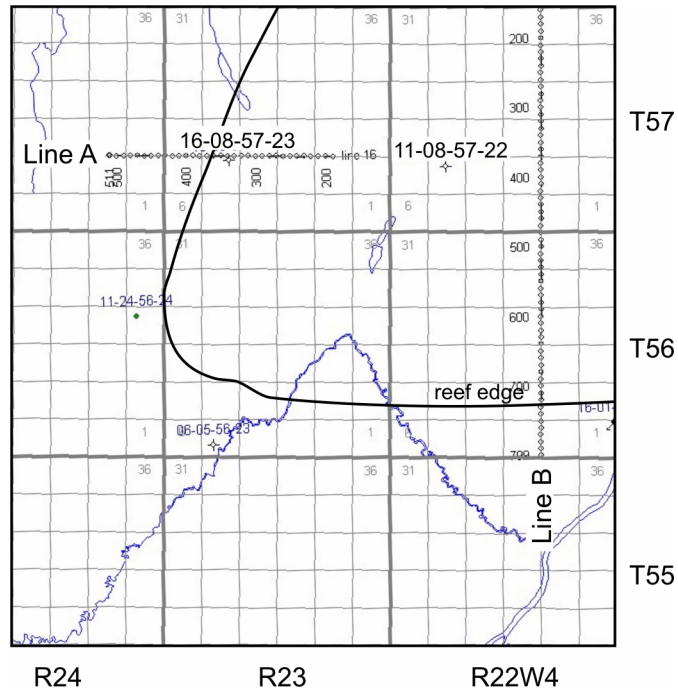

FIG 1. The study area with the locations of the two wells used in this report, the two seismic lines, and the interpreted edge of the Redwater reef.

In Figure 2 we plot the theoretical responses to the top dolomite in well 16-08-57-023W4 (Figures 2a and 2c) and three lower velocity limestone sections in well 11-08-57-022W4 (Figures 2b, 2d, 2e and 2f). Since shear-wave logs are not available, we generated them from the P-wave sonic log using a Vp/Vs ratio of 1.9 for limestone and 1.8 for dolomite (Pickett, 1963). For well 16-08-57-023W4 we manipulated the log digits so that a Vp/Vs ratio of 1.8 was used in the dolomite zone and a Vp/Vs ratio of 1.9 was used outside this zone. The reflectivity/offset responses are very similar to each other and to the plots presented by Li et al. (2003) for porous dolomite and porous limestone encased in limestone. In all responses the reflectivity increases a little with increasing offset, then decreases (becomes more negative) at the farthest offsets. These plots suggest that it will be very difficult to distinguish dolomite from limestone on AVO gathers unless the derived shear-wave log used here is not an accurate representation of the true shear-wave velocity field, and the true shear-wave velocities would change these responses.
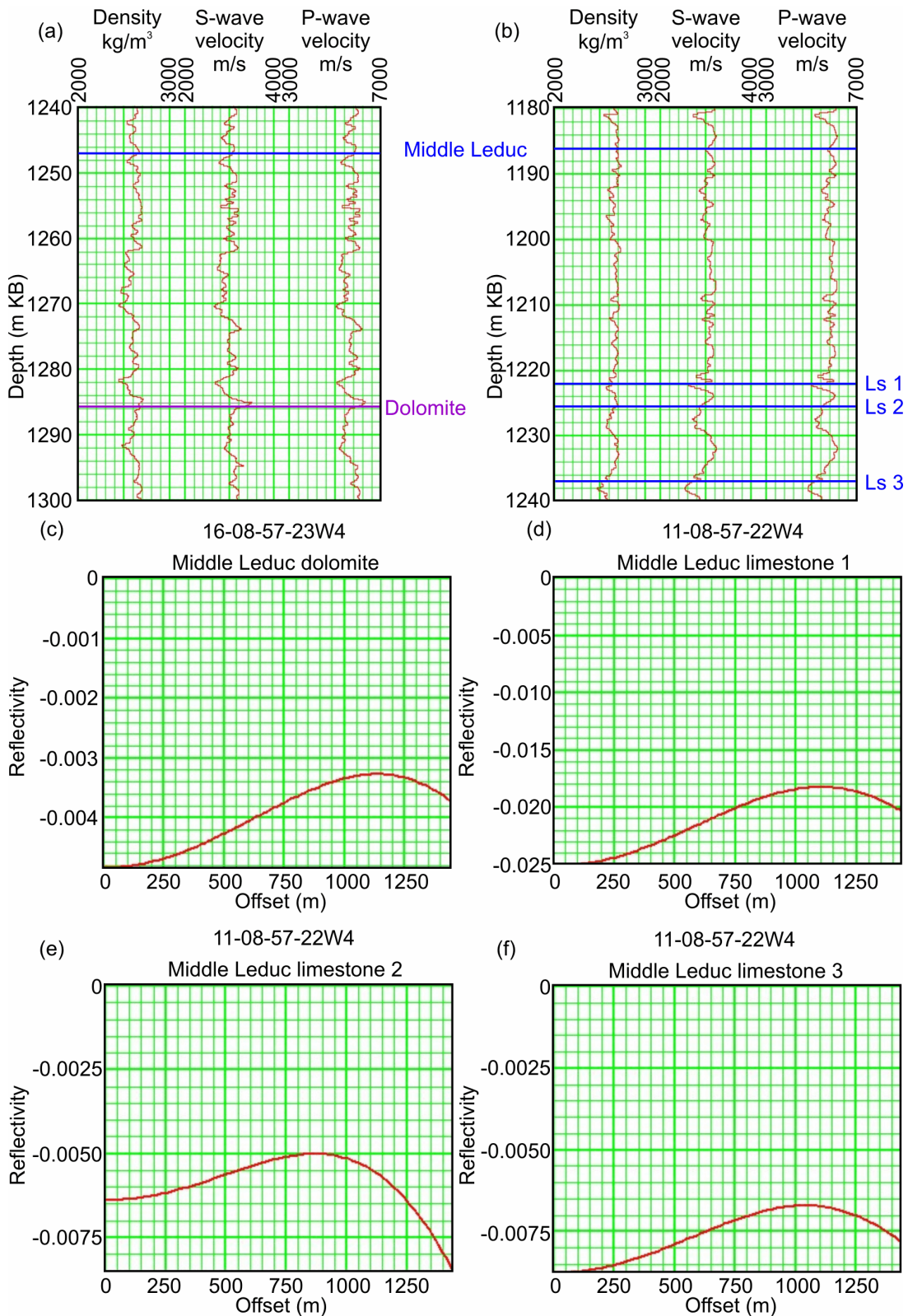
FIG. 2. (a) The logs for well 16-08-57-23W4; (b) the logs for well 11-08-57-22W4; (c) the theoretical response to the top of the dolomite in well 16-08-57-23W4; (d), (e) and (f) the theoretical responses to three lower velocity limestone zones in well 11-08-57-22W4.

Figure 3 shows the well logs and synthetic offset seismograms over the zone of interest for the two wells. The synthetic seismograms show the multi-offset response at intervals of 60 m from 0 to 1080 m, to match the offsets of the field seismic data, and the stacked response. The wavelet is a generic 10-15-50-60 Hz Ormsby bandpass. These plots suggest that it will be difficult to differentiate between limestone and dolomite in the Middle Leduc. The theoretical response to the Middle Leduc appears to be a +/- zero-crossing in 16-08-57-23W4 and close to a +/- zero-crossing in 11-08-57-22W4. The top of the dolomite zone in 16-08-57-23W4 correlates to a peak even though the sonic and density logs show decreases. This is probably due to interference from the seismic response to the sonic and density increases observed just below the top dolomite zone. The offset gathers suggest a very subtle decrease in amplitude of this peak with offset.
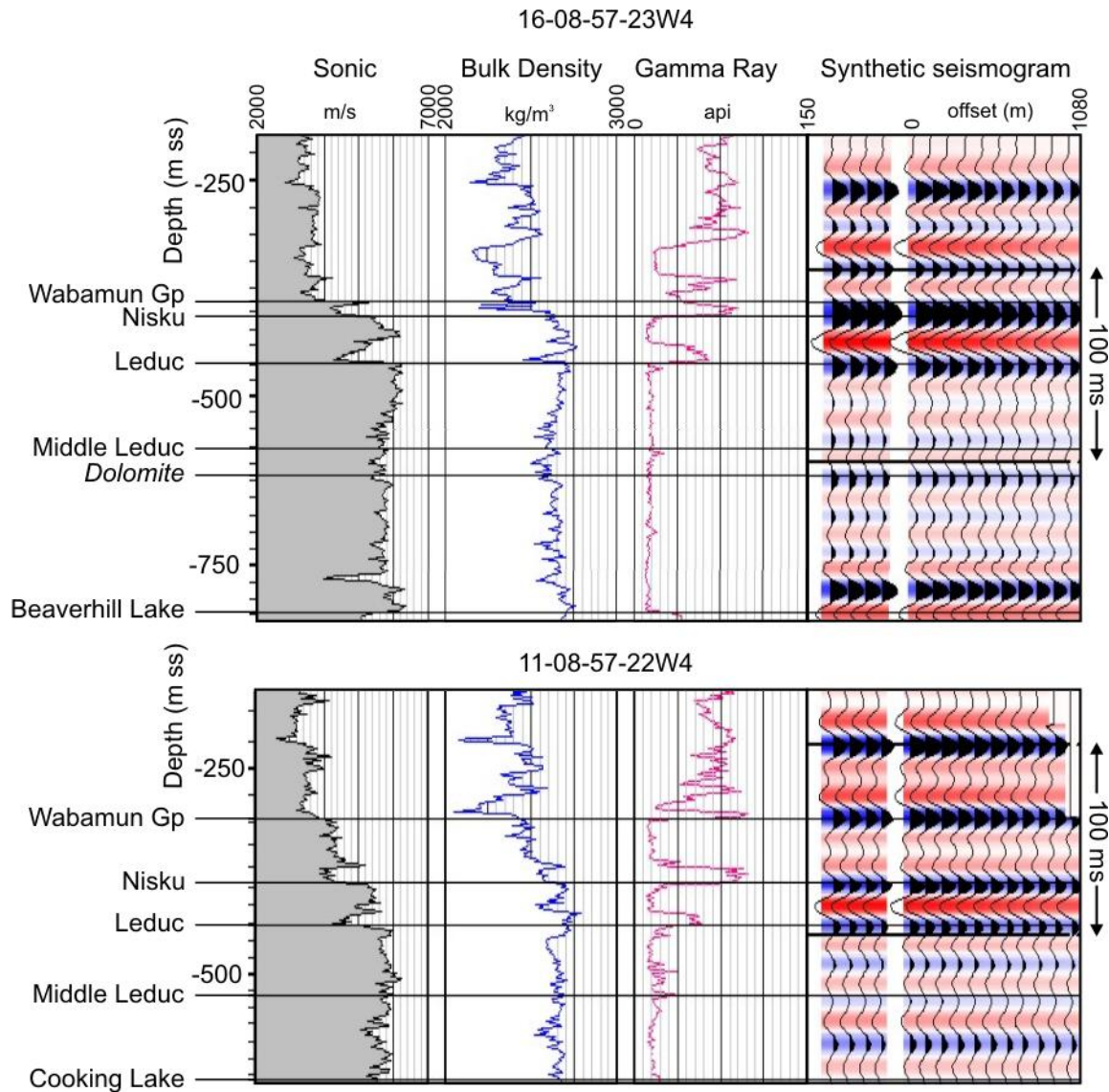
FIG. 3. Sonic, density and gamma ray logs, synthetic seismograms and offset gathers for the two wells used in this study. The dolomite zone in 16-08-57-23W4 appears as a subtle decrease in P-wave velocity and density. A standard Ormsby wavelet was used in the generation of these synthetics.

Two 1983 vintage 2D seismic lines were reprocessed by a commercial contractor to preserve amplitudes, as is necessary for AVO analysis. The CDP-sorted gathers resulting from this processing will henceforth be referred to as the AVO gathers. A nice overview of processing for AVO analysis can be found in Allen and Peddy (1993).

Using the AVO analysis software of Hampson-Russell (part of CGGVeritas) we extracted a statistical wavelet from seismic line A and correlated the resulting synthetic seismogram with the seismic data. Then we extracted a wavelet from line A using the entire well log. The algorithm finds the operator which, when convolved with the reflectivity series from the well, results in a synthetic seismogram that closely approximates the nearest seismic trace. We then re-correlated the synthetic seismogram, created with the new extracted wavelet, with the seismic data. A similar procedure was followed to correlate well 11-08-57-22W4 with seismic line B. The well is projected about 4 km onto line B. Figure 4 shows the correlations for the two wells and the extracted wavelets used in the creation of the synthetic seismograms. The characters of the synthetic seismograms are quite different to those in Figure 3 because of the complex extracted wavelets we used, and that extracted from line B is quite ugly.
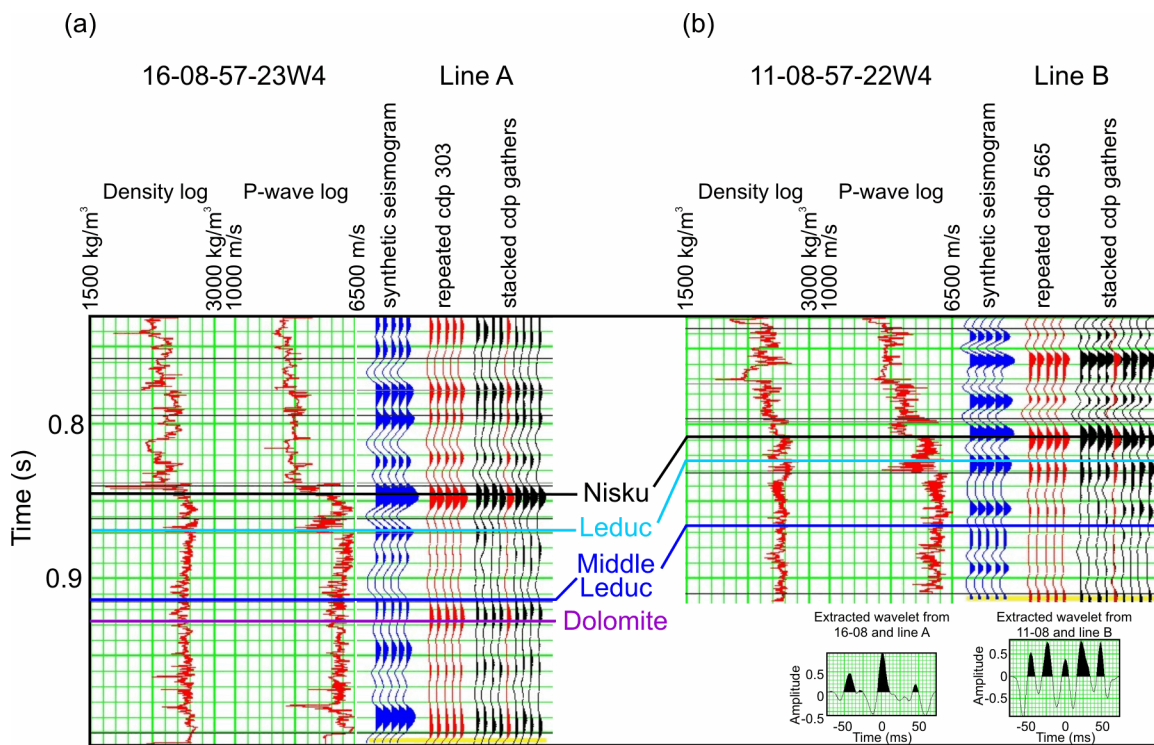

FIG. 4. The well-seismic data correlations for (a) well 16-08-57-23W4 with seismic line A and (b) well 11-08-57-22W4 with seismic line B using wavelets extracted from the seismic data. In each image the blue traces represent the synthetic seismogram repeated five times and the red traces are a repeated sum of a few seismic traces around the well locations.

We created supergathers for AVO analysis by summing traces in CDP gathers into 120 m bins from 120 m to 1440 m. A running average of 5 CDPs contributed to each CDP gather. Synthetic offset gathers for line A were created using the Zoeppritz (1919) equations and the wavelet extracted from line A (shown in Figure 4). Offsets from 120 to 1440 m were modelled at 120 m intervals to match the seismic data offsets. However, the farthest offsets had to be removed because of anomalously high amplitudes. Figure 5a shows the modelled and actual offset gathers at the location of well 16-08-57-23W4. The quality of the seismic data and the correlation between the seismic offset gather and the modelled gather are not very good. The top of the dolomitic zone is close to a trough on the modelled gathers, so we picked this trough on the synthetic gather and the closest trough on five of the nearest seismic gathers to CDP 303. The purple lines in Figure 5a show these picks on the synthetic gather and the CDP 303 gather. The pick on the seismic data varies from the zero-offset arrival time of the dolomite top because the data quality is poor. We also picked the preceding peak close to the top of the Middle Leduc. The picked peak amplitudes are displayed in Figure 5b and the trough amplitudes in Figure 5c. They had to be scaled for comparison between the synthetic and the seismic data. The amplitude trends do not match for the peak picks. The well response is a decrease in amplitude followed by a slight increase whereas the seismic response shows generally increasing amplitude. For the dolomite trough picks the well and seismic data both show an increase in absolute amplitude.

We created similar supergathers for line B and synthetic offset gathers for well 11-08-57-22W4. These are displayed in Figure 6. The Middle Leduc event is not a consistent peak or trough across the gathers and the character correlation between the synthetic gathers and the seismic gathers is poor, so we were not able to pick amplitudes.

AVO analysis of seismic line B around the projected location of well 11-08-57-22W4 is not possible because of the poor quality of the seismic data. Thus we attempted to modify well 16-08-57-23W4 by removing the low velocities and densities corresponding to the dolomite in the Middle Leduc and replacing them with values compatible with limestone. Unfortunately, since we do not have shear wave data, we could only modify the shear log using a Vp/Vs of 1.9 for limestone. The resulting logs and offset gathers are presented in Figure 7a. The synthetic gather for the no dolomite case is very similar to that of the dolomite apart from some small amplitude differences. In Figures 7b and 7c we plot the same picks as in Figure 5 with the addition of the picks for the case of no dolomite. The offset response of dolomite and no dolomite is very much the same for the trough that represents the top of the dolomite zone (Figure 7c) and only slightly different for the peak above this trough (Figure 7b). Thus it would be very hard to distinguish between the dolomite and the no dolomite case on offset gathers. It is possible that correct shear-wave information might change the synthetic offset responses.
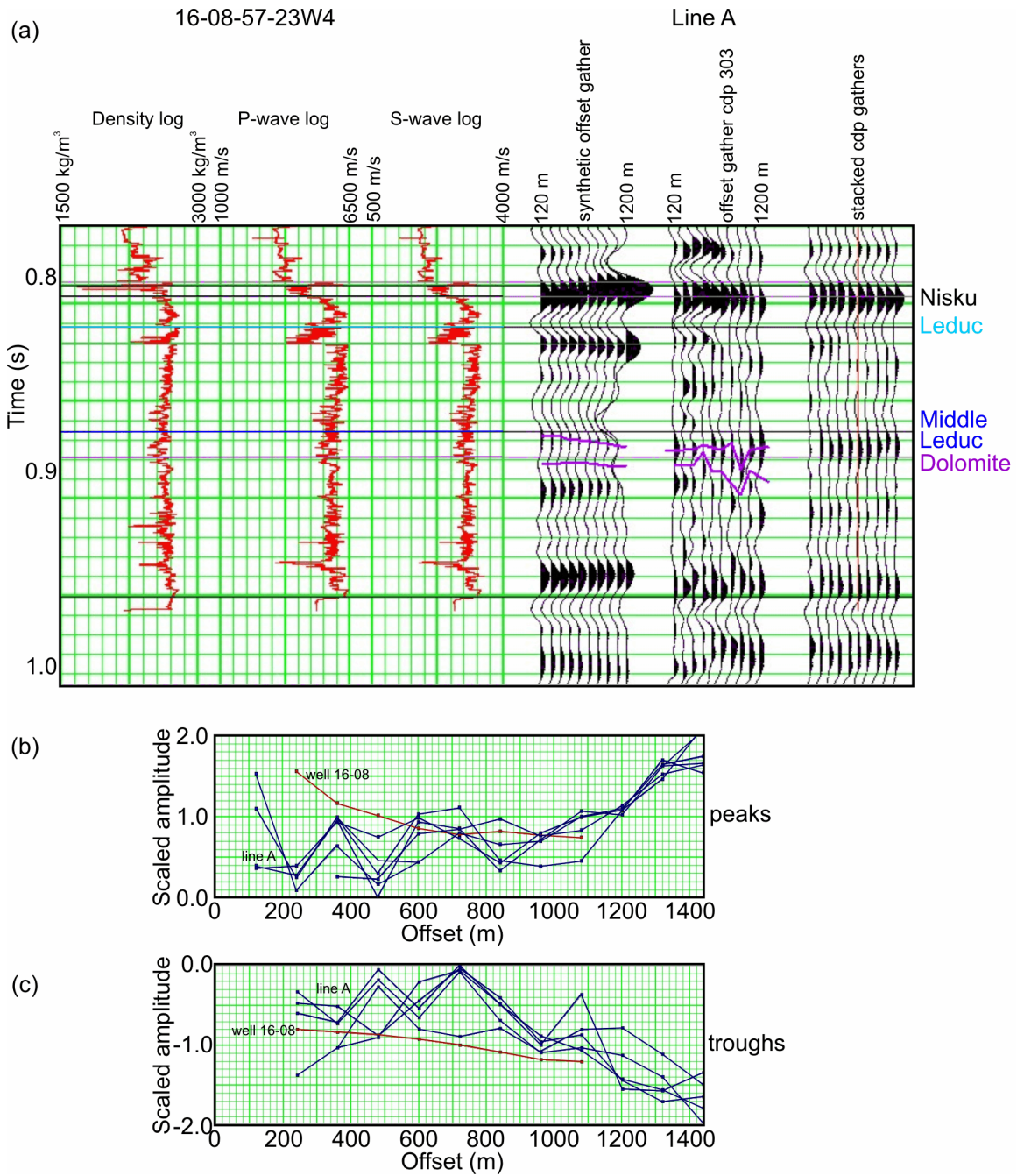
FIG 5. (a) The density, P-wave and S-wave logs used in the creation of the synthetic offset gather for well 16-08-57-23W4. The seismic offset gather and part of the stacked seismic section are centred on the location of the well at CDP 303. The purple picks are those of the peak close to the top of the Middle Leduc and the trough close to the dolomite zone. (b) The scaled peak picks for the synthetic gather and five CDP gathers around CDP 303. (c) The scaled trough picks for the synthetic gather and five CDP gathers around CDP 303.
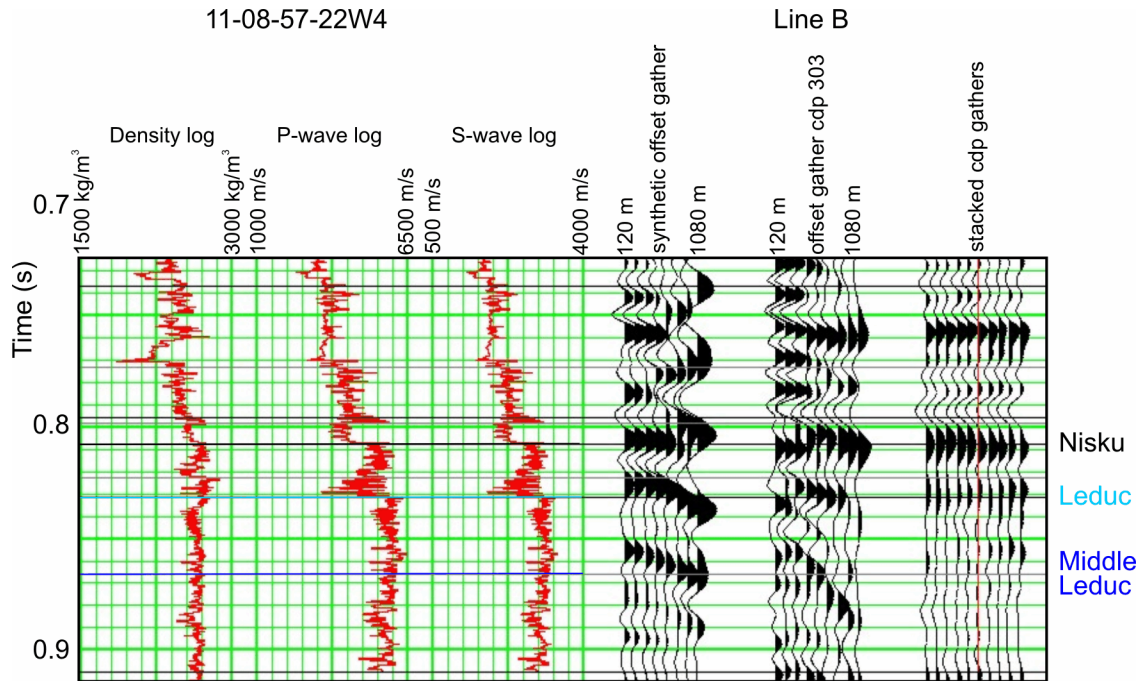
FIG. 6. The logs and synthetic offset gather for well 11-08-57-22W4 and seismic traces from line B. There is not a consistent event on the offset gathers we can pick for the Middle Leduc.

AVO analysis of the Leduc Formation

The porous limestone of the Leduc Formation is encountered immediately below a thin, hard cap rock at the top of the Leduc Formation in the Redwater reef. Porous limestone was not encountered at the top of the Leduc Formation in the two wells we have analysed here but was encountered in other wells in range 21 to the east. We analysed three of the wells which encountered porous dolomite, 07-10-57-21W4, 10-27-57-21W4 and 16-08-57-21W4. Density logs were only available for 10-27-57-21W4 so we used Gardner's equation (Gardner et al., 1974) to generate density logs from the sonic logs for the other two wells. S-wave logs were generated using a Vp/Vs of 1.9.

We generated synthetic offset gathers using a Ricker wavelet and picked the amplitudes of the top Leduc peak. Figure 8a shows the P-wave logs and gathers. The offsets had to be restricted because of the large interfering amplitudes of events near the critical angle. The plot in Figure 8b shows the unscaled reflectivity of the Leduc peak for all five wells. The three wells that encountered porosity show higher amplitudes than do the wells with tight limestone. The offset response is similar in all cases and suggests that with this range of offsets it would be hard to distinguish between porous and tight limestone at the top of the Leduc Formation on different seismic lines. However, it might be possible to map lateral changes in porosity by measuring the amplitude responses in offset gathers obtained from good quality seismic data.

CONCLUSION

We were not able to use AVO analysis to distinguish between dolomite and tight limestone in the Redwater reef. Our analysis was hampered by the poor quality of the seismic data and the lack of shear sonic logs for use in the generation of synthetic offset gathers. Better modelling could be done with a shear sonic log rather than having to estimate one using a constant Vp/Vs ratio. Better quality seismic data would help, too.

Modelling of the AVO response to the top of the Leduc Formation shows a higher amplitude response to porous limestone than tight limestone, and thus it might be possible to map lateral changes along a seismic line.

Future work includes Lambda-Mu-Rho analysis (Goodway et al., 1997; Goodway, 2001) of the porous and tight limestone responses. Converted-wave AVO analysis will also be undertaken to determine whether converted-wave data might assist in differentiating between dolomite and limestone or between porous and tight limestone.

ACKNOWLEDGEMENTS

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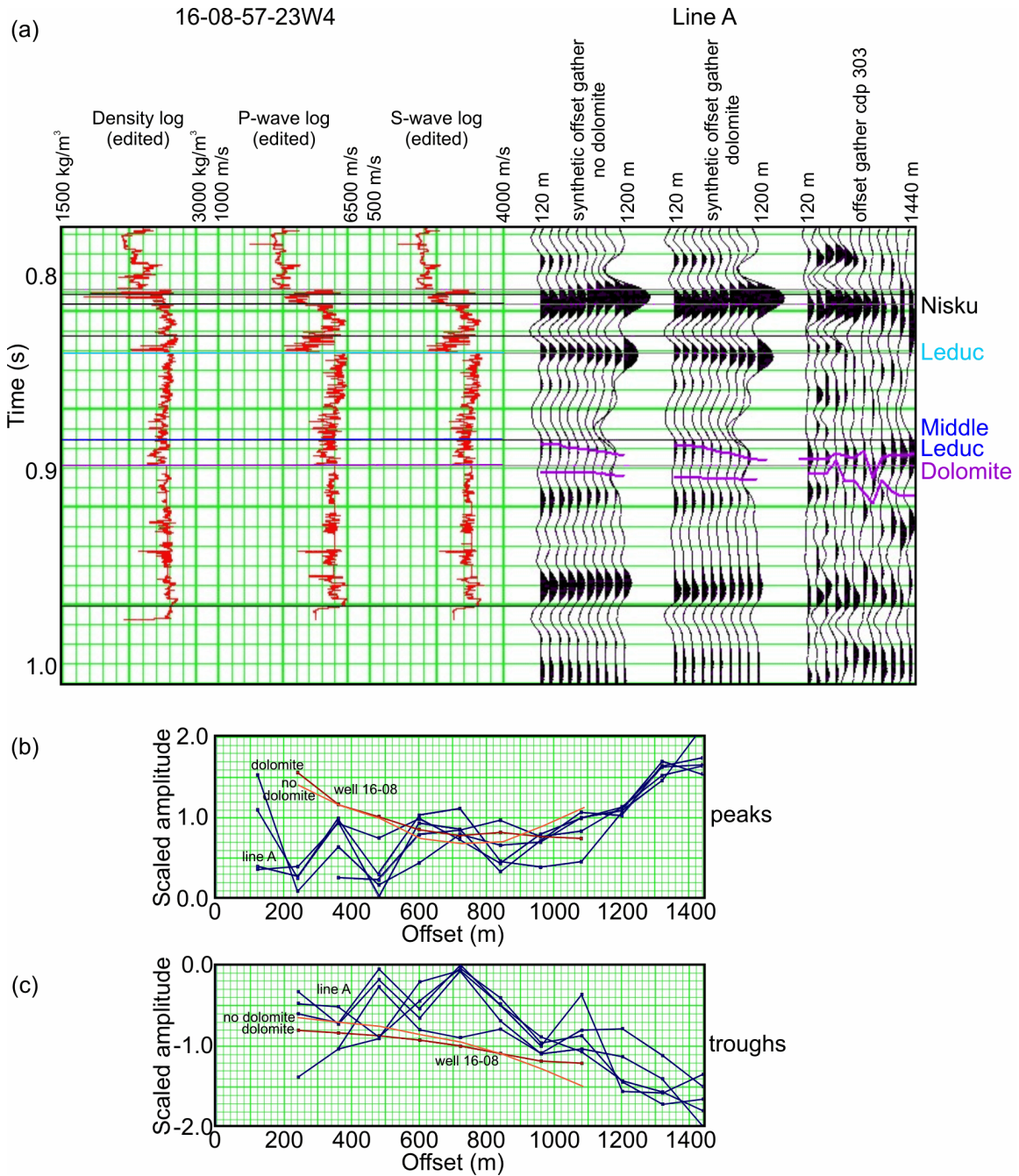
FIG 7. (a) The sonic and density logs for 16-08-57-23W4, edited to remove the dolomite zones in the middle Leduc, the synthetic offset gathers for both the dolomite and no dolomite cases, and the seismic offset gather from line A. (b) The scaled peak picks for the synthetic gathers and five CDP gathers around CDP 303 on line A. (c) The scaled trough picks for the synthetic gathers and five CDP gathers around CDP 303 on line A.

(a)

(b)
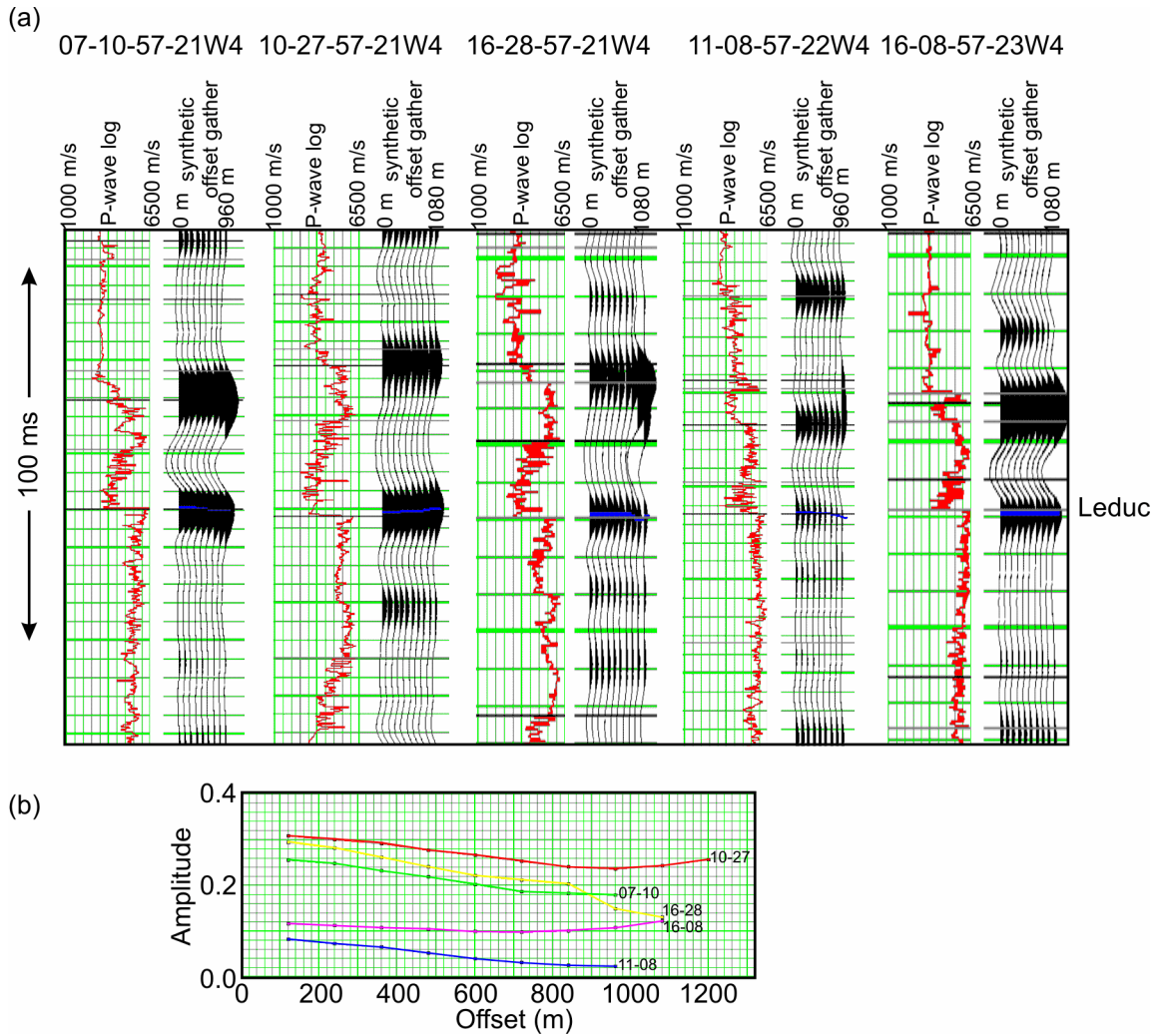
Figure 8: (a) Synthetic offset gathers for five wells and (b) the response to the top of the Leduc Formation. Wells 07-10-57-21W4, 10-27-57-21W4 and 16-28-57-21W4 encountered porous limestone at the top of the Leduc while 11-08-57-22W4 and 16-08-57-23W4 encountered tight limestone.