Reservoir Modelling and Interpretation with Lamé's Parameters: A Grand Banks Case Study

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ABSTRACT
Lamé parameters (LMR, Lambda, Mu, Rho) assist in the identification of reservoir rock and fluids. Even though general guidelines for rock and fluid classification with Lamé's parameters can be derived, modelling of particular reservoir zones are a must to characterise the reservoir in specific areas. In this paper we focus our attention to the Avalon and Gabriel reservoir in the Grand Banks area offshore Newfoundland. Several wells from the greater area were analysed to model the LMR response of various reservoir qualities and fluid fills. This modelling exercise demonstrated a distinct LMR response separating shale zones from highly porous sand zones. The discrimination of the fluid fill was less successful due to partially non-unique responses of an oil, gas or brine filled reservoir.

Based on the modelling results a marine 3D seismic survey was interpreted. The analysis of the 3D LMR data discriminates shaley from high porosity sand zones and also gives an indication of the possible fluid fills. This reservoir characterisation in combination with the structural interpretation developed a significant exploration prospect.

AVO feasibility workflow

The workflow uses two wells to determine through modelling whether AVO effects are detectable at a seismic scale. The zones of interest are the lower Cretaceous Avalon and Gabriel reservoir. Modelling required density, p-sonic and shear-sonic recordings. When shear logs were not available, they were generated with the help of linear vp-vs relationships derived from other wells in the study area. Fluid substitution using the Gassman equation was performed providing well curves for brine, oil and gas filled sand zones. The wells L-08 and I-78 were used to simulate brine, oil and gas filled responses. I-78 encountered a brine filled Gabriel sand while L-08 hit an Avalon sand filled with gas, oil and brine. Fluid replacement was performed on I-78 to simulate P-wave, S-wave and density for oil or gas responses. The first step used logs to create LMR and Ratio-Difference crossplots. These logs were then forward modelled to produce synthetic gathers used to determine the AVO signature present. These gathers were used for prestack inversion resulting in an estimate of P and S-reflectivity. The reflectivities were inverted for impedances through which Lambda-rho and Mu-rho traces were calculated. These traces reproduce the seismic response of gas, oil and brine filled sands from an LMR perspective.

Interpretation templates

Fig. 1: below shows a template for interpreting Rp Rs crossplots (Goodway)

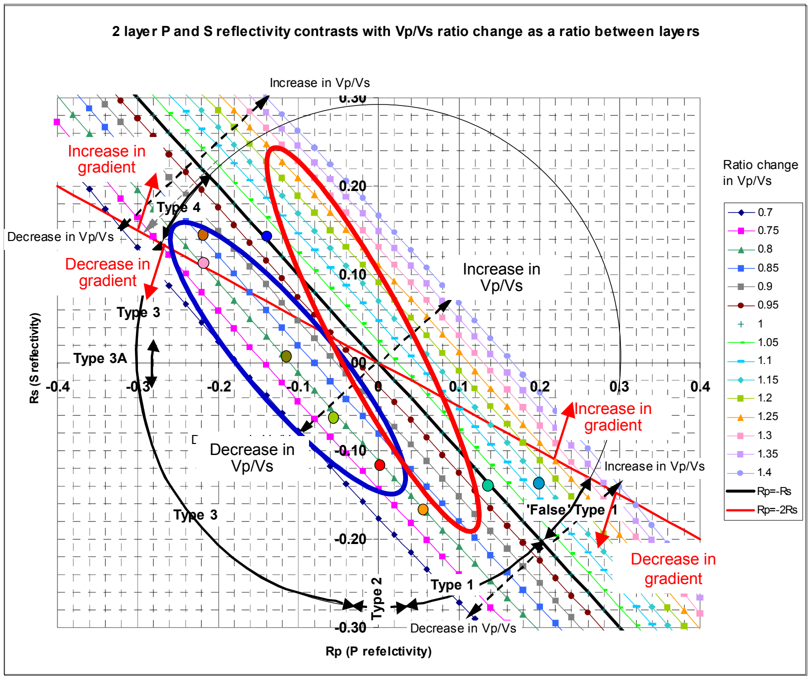

Fig. 1: Rp Rs crossplot template for AVO type identification (Goodway). Note that the y-axis has been flipped (Rs).

This crossplot characterizes the AVO signature of an interface between two layers with two parameters, Rp and Rs. Based on the location that a reflection would plot the AVO type can be predicted given knowledge of the basic background Vp Vs relationship. In the crossplot the blue ellipse represents a distinguishable background trend for most reflections. Points that lie outside the background trend are considered anomalous. The red ellipse is drawn as an example of points lying outside the trend. Points in the ellipse correspond to AVO types III and IV. The red line shown corresponds to the Rp=2Rs line, an approximation to the zero gradient line. Lines of constant Vp Vs ratio change have also been plotted as indicated in the legend. The 1:1 line in black is no Vp/Vs change.

Note that anomalous points in the Rp Rs crossplot do not necessarily translate into a hydrocarbon filled zone. There are many lithologic/fluid combinations that can produce AVO anomalies and care should be taken in interpreting the results. That being said, obvious AVO anomalies are a step in the right direction to identifying potential hydrocarbon reservoirs.

The following crossplots (figure 2) from Goodway (2001) can be used as an interpretation template, demonstrating how Lamé parameters yield information about rock type.

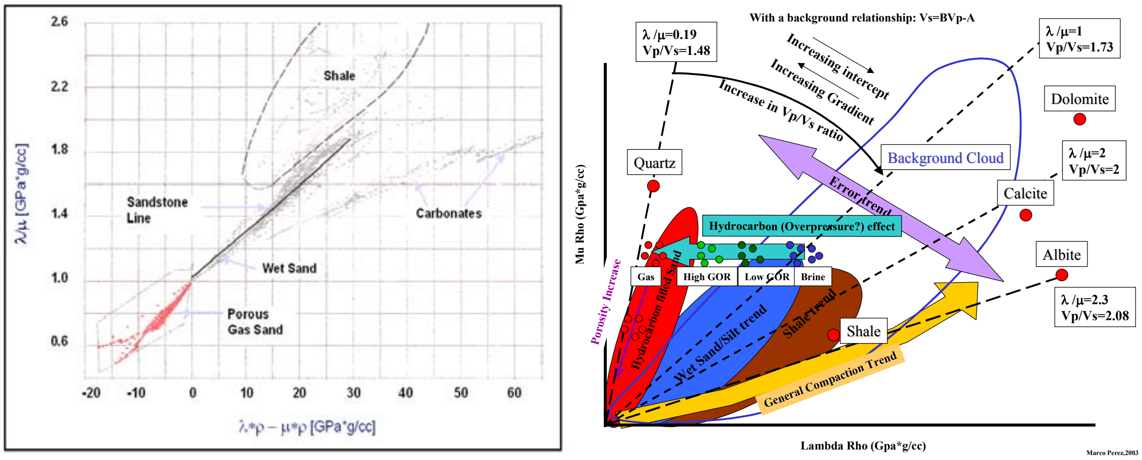

Fig. 2: (a) Ratio Difference crossplot (left) showing fluid and lithology discrimination capability from WCSB well. (b) LMR crossplot (right) with classifications of rocks λ and μ: Lamé parameters, ρ: density (Combination of Goodway, 2001, Downton, 2000).

Lamé parameters like λ and μ give the interpreter direct insight into rock physics and avoid indirect interpretation by using velocities or impedances. Goodway (1999, 2001) and Dewar and Downton (2002) established seismic reservoir characterisation using Lamé parameters. The basic principles in distinguishing lithology from a Lamé parameter perspective is the ratio between incompressibility (λ) and rigidity (μ). Consider a rock at depth "feeling" an effective stress. The distribution of this effective stress between the Lame parameters is an indication of the manner in which the grains are organized. In instances in which the material is more incompressible than rigid (λ>μ) an anisotropic distribution of stresses deforms the grain shape resulting in large aspect ratios. These grain shapes are usually found in laminated shales. The case where there is an even distribution of stress (λ=μ) implies that the grains have an aspect ratio of 1 or that the grains themselves are randomly organized. This grain behavior is often found in sand. The ratio of lambda to mu is therefore useful in identifying shale versus sand lithologies. This is seen in figure 2a. Lambda-mu ratios of less than 1 are highlighted as sand zones. From a fluid discrimination perspective, assuming that the rock properties do not change, the only Lamé parameter affected is λ. In sand the pores can be filled by a variety of fluids. This fluid will decrease the incompressibility of the material. Brine will affect incompressibility the least while gas will affect incompressibility the most. Figure 2b shows how filling sand pores with different fluid will decrease the amount of measured incompressibility (yellow to red circles).

Modelling

The AVO feasibility process begins with log crossplotting in $\lambda-\rho$ and $\mu-\rho$ space. The L-08 crossplots of the Avalon reservoir (Figure 3) show the potential to identify sand zones as well as discriminate brine from gas and oil.

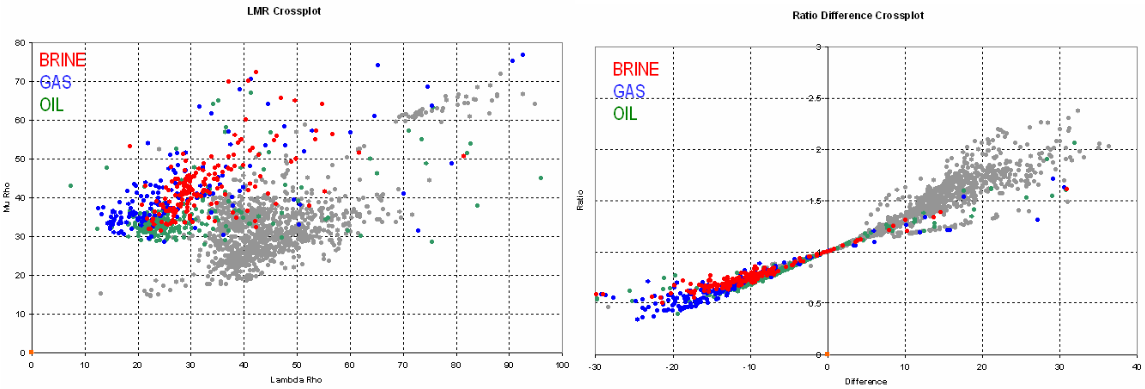

Fig 3. a) LMR crossplot on the right, b) Ratio-Difference crossplot on the left.

Note in figure 3 that the hydrocarbon filled sands occupy lower Lambda-Rho values (left) while a majority of the sand has been identified on the Ratio-Difference crossplot as having ratios less than or equal to 1 (right). There is good potential for fluid detection although the possibility of fliud discrmination is limited. Figure 4 shows the I-78 synthetic responses of brine, oil and gas filled Gabriel sand in LMR and Ratio-Difference crossplot space. Shear logs in this well were synthetically created by using sand and shale Vp Vs relationships determined from other wells in the area. Through fluid replacement, three sets of P-wave, S-wave and density logs were created to simulate brine, oil and gas filled sands.

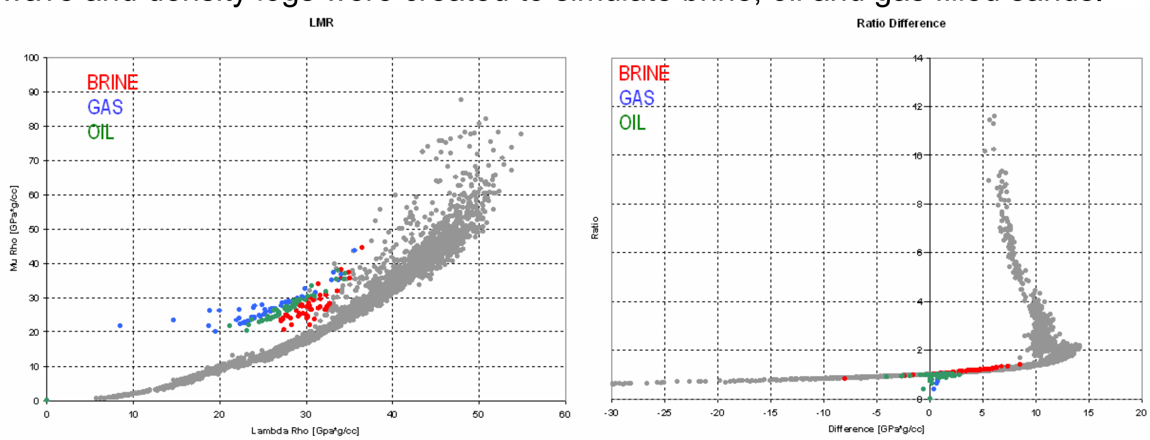

Fig. 4. a) LMR crossplot (left) and b) Ratio-Difference crossplot (right). Note that the LMR crossplot is well constrained in that there are defined relationships between P and S velocities.

Similar responses to the L-08 we are seen these crossplots. Both crossplots in figure 4 display less range as the shear log was synthetically created. Also, the crossplots prove that the ability to discriminate fluids is limited but the sensitivity to lithology is obvious.

Synthetic Gathers

Synthetic gathers were created using a 25Hz Ricker wavelet and an offset range approximately equal to the depth of the zone of interest. For the I-78 well, three synthetic gathers were created with amplitude extractions taken at the top of the Gabriel sand and plotted below each gather. Figure 5 below shows a brine filled synthetic gather.

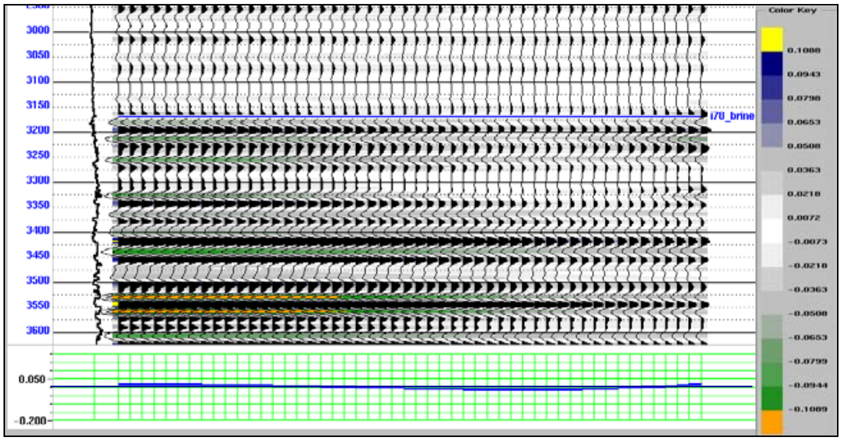

Fig. 5: I-78 brine filled synthetic gather. Amplitude extraction seen in blue.

The AVO response for the top of the sand in this case is a peak at near offsets with a negative gradient, approaching a phase change. This is a type II AVO response. Figure 6 shows the synthetic gathers and AVO responses for oil and gas filled sands.

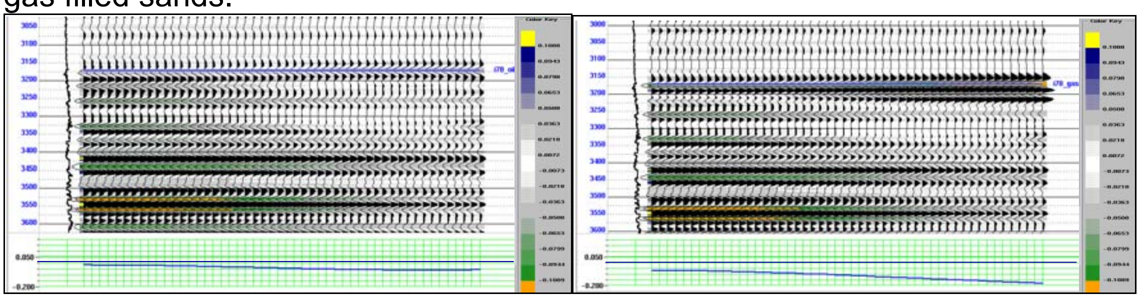

Fig. 6: Oil filled synthetic gather (right) and gas filled synthetic gather (left). The oil gather shows a weak trough at near offsets with a small gradient (Type III). The gas gather shows a strong trough at near offsets with a strong gradient (Type III) .

As the incompressibility of the sand unit decreases with oil and gas, the P-wave velocity decreases. The impedance contrast at the interface between the overlying shale and the hydrocarbon filled sand increases, leading to a discernable difference in the gathers.

In L-08 a gas, oil and a brine zone was penetrated. Figure 7 shows amplitude extractions from the gather at the shale to gas, gas to oil and oil to brine interfaces.

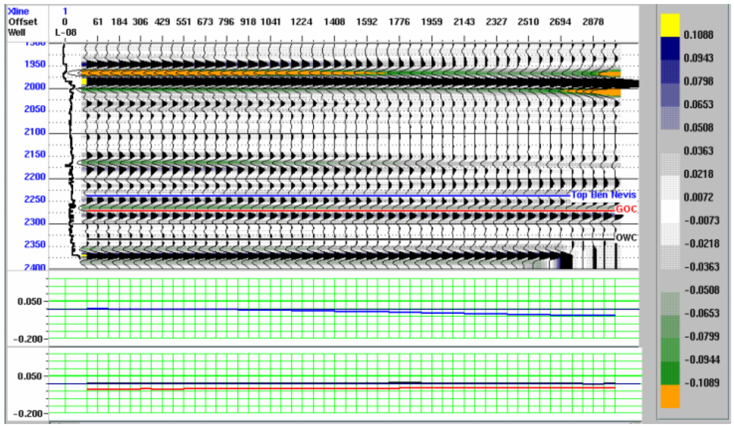

Fig. 7: Synthetic gather created from the L-08 well. The blue pick corresponds to the shale to gas interface, the red pick is the gas to oil interface and the black pick is the oil to water pick.

The top of the sand is characterized by a near offset zero-crossing with a relatively strong negative gradient (borderline Type III). The gas-oil and oil-water contacts are troughs at near offsets with little or no evidence of a gradient (Type IV). The response is most likely tuned as a P-impedance increase is expected in progressing from gas through to oil and on to brine. Note that the only interface which correlates to the I-78 AVO response is the shale to gas interface. The other L-08 interfaces are within the sand and correspond to differences in fluid properties.

Rp Rs Extractions

P and S reflectivities were extracted from the synthetic gathers generated using the Fatti approximation to the Zoeppritz equation. Crossplotting the extracted reflectivities of synthetic L-08 gather show a subtle number of points which lie outside the main background trend (Figure 8). The zones highlighted correspond to the gas-oil contact and the oil-water contact. The subtle nature of the shale to sand impedance contrast does not make the anomaly.

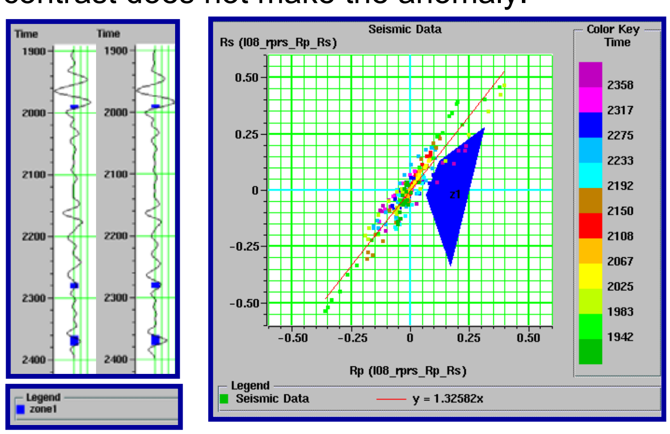

Fig. 8: Rp Rs crossplot of L-08. Points within the blue polygon are highlighted and shown on the Rp Rs traces (left and right respectively).

For I-78, three different reflectivity pairs of brine, oil and gas filled sand provide a clear difference in reflectivity making the hydrocarbon filled Gabriel clearly identifiable. The brine and oil filled Rp Rs crossplots do not show a large difference in reflectivity between sand and shale and as a result little or no points lie outside the background trend. The oil filled sands produce slight gradient/reflectivity changes.

The gas filled sand produces a large reflectivity contrast identifiable as the top (blue) and bottom (yellow) of the zone of interest (Figure 9). Following the template given in figure 1, these events correspond to type III AVO anomalies. This agrees with the amplitude extraction of the synthetic gather.

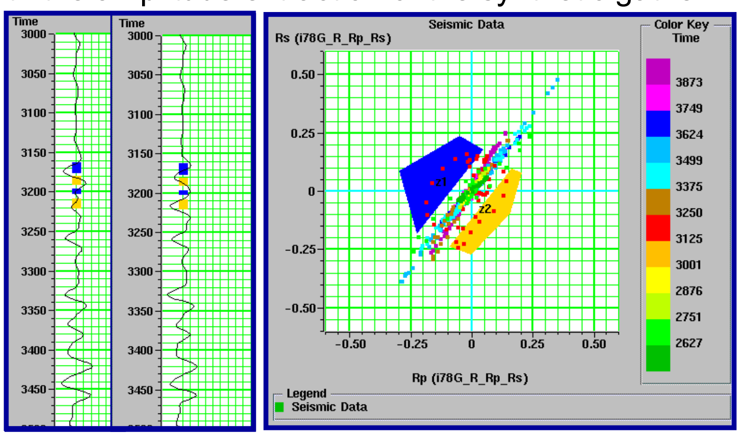

Fig. 9: I-78 Rp Rs crossplot of the gas filled sand. The yellow and blue polygons correspond to the top and bottom of the anomalous zone.

Ip Is Inversions

Inverting Rp Rs values extracted from the synthetic gather yields P and S-impedances. Manipulating these provides λ–ρ and μ–ρ traces: $\lambda\rho = Ip^2 - 2Is^2 \quad \mu\rho = Is^2$. Crossplotting these provide lithological and fluid information. Figure 10 shows that the L-08 well after inversion has a distinct number of points with a λ–μ ratio less than 1 (an indication of sand) as well as populating relatively low λ–ρ values (an indication of hydrocarbon). Drawing polygons around these points correctly identifies the sand zone of interest.

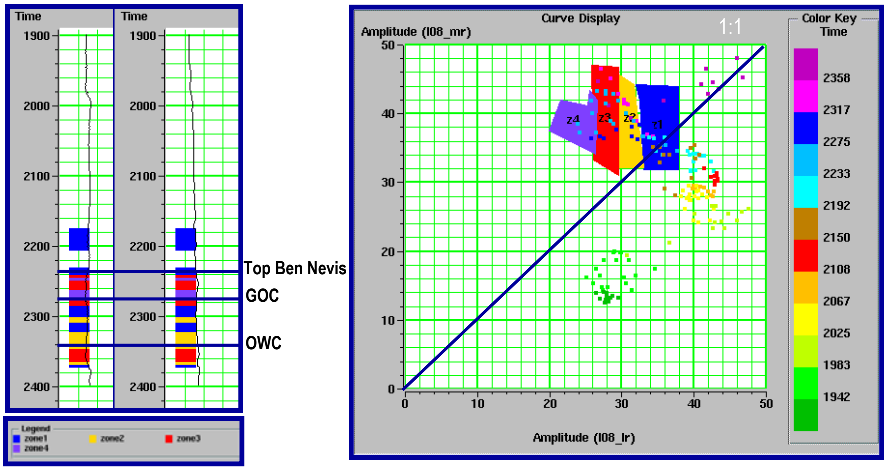

Fig. 10: L-08 LMR crossplot with purple, red, yellow and blue polygons (low lambda-rho values to high lambda-rho values).

The gas filled sand zone is populated by points in the purple and red LMR crossplot polygons. These are the lowest $\lambda-\rho$ values. The oil filled sand zone has points corresponding to the yellow and blue polygons with lambda-rho values greater than those of the gas filled sand. There is ambiguity between the brine and oil filled sand zones making precise zone identification difficult. Reasons for this could be resolution and the inversion processes used.

Figure 11 shows the I-78 Gabriel reservoir inversion results in form of the LMR crossplot. This figure illustrates the best example for identifying hydrocarbon filled sand using the LMR crossplot.

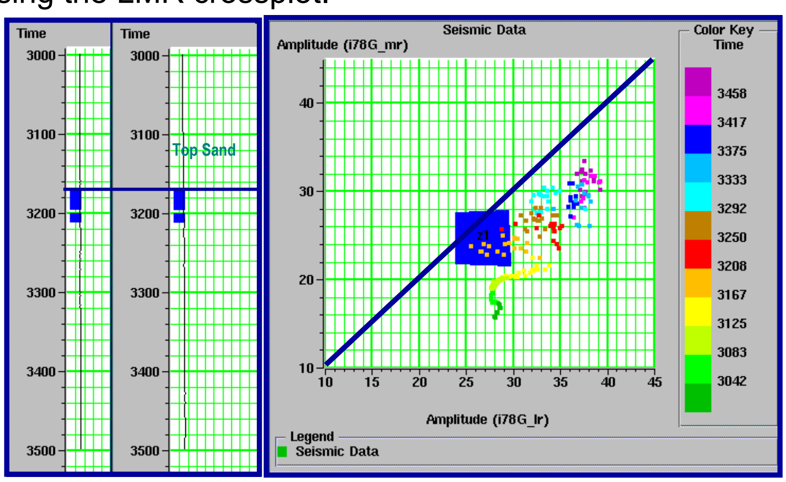

Fig. 11. I-78 LMR crossplot of gas filled sand. The blue polygon correctly identifies the gas filled sand.

In conclusion we can summarize:

- The crossplot of log data of L-08 and I-78 allow for lithologic separation and fluid detection but no fluid discrimination.
- The synthetic gathers display distinct responses for different fluid fills.

- Rp-Rs inversions of the gathers allow for an identification of the sand anomaly at I-78 but not at L-08.
- LMR crossplots identify both sand (L-08 and I-78) anomalies computed from the RpRs and help to identify fluids.

Application on 3D Seismic

The 3D seismic survey is located approximately 400km off the East coast of Newfoundland. The water depth is about 1000m. In 2001, EnCana Corporation acquired a high quality 3D seismic survey and interesting structures of sufficient size were interpreted.

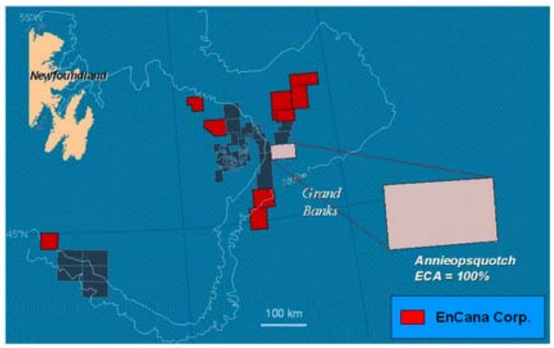

Fig. 12. EnCana's landposition in Newfoundland

In the prospect area several potential reservoir zones are present. In particular the Avalon and Gabriel reservoir can be identified with significant structural-stratigraphic closure. Here we will focus our interest on the Gabriel zone. After the interpretation of the prestack time migration confirmed structural closure and the amplitude mapping of the possible reservoir zones showed high amplitudes correlating with structural highs, a careful inversion for Lamé parameters was conducted. The objective is to characterise the Gabriel reservoir rock with Lamé parameters; to identify seismic indicators for hydrocarbons and find the "sweet spots" for drilling.

In the potential Gabriel reservoir zone λ and μ were extracted from the surface seismic and a crossplot of the difference λ-μ over the ratio λ/μ was created (figure 13).

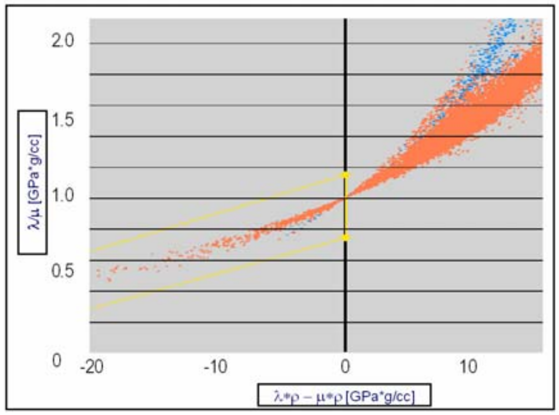

Fig. 13: Lamé parameter crossplot for Gabriel Reservoir

This distribution of all samples within the reservoir zone has the same shape as the model in figures 2a, 3b and 4b and made sand identification possible, which is in the lower left quarter, i.e., difference less than 0 and ratio less than 1. At this point the discrimination of the fluid content is not possible, because the accuracy of the inversion was limited due to scaling problems. Highlighting the reservoir rock in the crossplot and plotting the highlighted samples back into the seismic section illuminates an anomaly, which indicates the good reservoir zones (figure 14a). The map display of the anomaly is shown in figure 14b superimposed on the time structure. Since the anomaly terminates at a certain time level this constant time line could be a fluid contact.

The result of these investigations provides templates that increase the possibility of finding reservoir sand and mitigates the risk involved in finding hydrocarbons. An optimal well location can then be based on the interpreted time structure as well as the reservoir distribution and possible fluid contact.

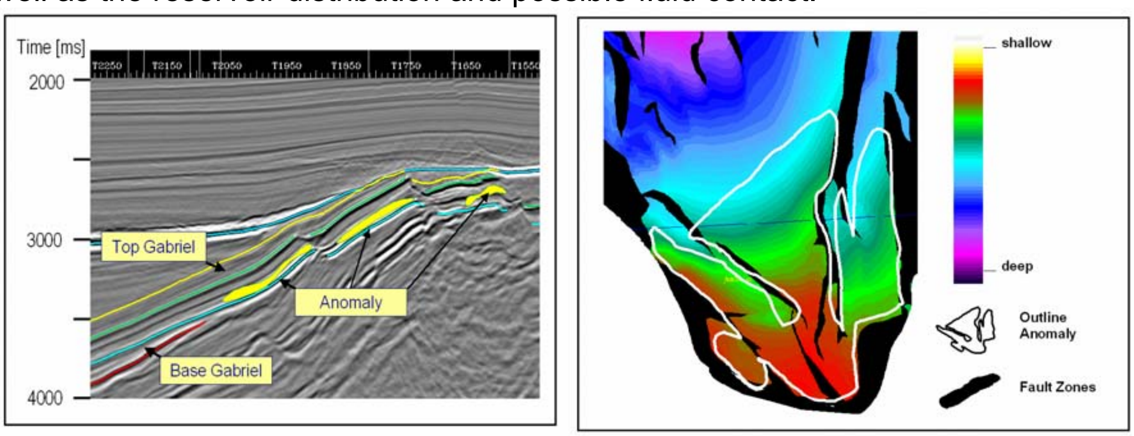

Fig 14. a) Reservoir zone highlighted (left) on Gabriel zone b) Outline of the anomaly superimposed on a time structure map (right)

References

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