Recent advances in application of AVO to carbonate reservoirs: case histories

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Summary
The application of amplitude versus offset (AVO) in the analysis of carbonate reservoirs is on the increase in the Western Canadian Sedimentary Basin (WCSB). This has contributed to a rapidly increasing knowledge of the physical properties of carbonate rocks, and in the active exploration and delineation of carbonate reservoirs. This paper will show that not only porosity but also possibly fluid effects may be determined through AVO based methods in certain types of facies. Seismic information from a carbonate reservoir, even fluid effects can be modelled and extracted from basic AVO gathers using attribute analysis and elastic parameter inversion. Recent advances in these areas are reviewed along with new studies in carbonate rock properties, carbonate AVO characteristics due to fluid effects, and elastic rock properties. This petrophysical understanding forms the basis for AVO calibration and interpretation and is a key issue to be considered.

Introduction
In the past few years, both O & G and service companies have made great efforts in using AVO techniques in carbonate reservoir characterization in the WCSB. A study by Li and Downton (2000) explored the feasibility, potential and sensitivity of carbonate rock properties in responding to porosity and fluid AVO characteristics for commonly encountered reservoir types. The applicability of AVO elastic rock property inversion was also discussed. Li and Downton believed that a lack of carbonate rock property information is one of the obstacles in applying AVO to carbonate reservoir characterization. Recently, this situation has been greatly improved due to a significant acquisition of a number of dipole sonic logs, sampling a variety of carbonate reservoirs and lithologies. These newly acquired logs provide insitu reservoir and non-reservoir measurements (allowing for mud invasion effects), that are beyond that of the laboratory and theoretical rock physics predictions. On the seismic side, experience in both AVO processing and interpretation, and from both amplitude analysis and inverted rock property analysis, has also been growing.

Well-known issues facing the application of AVO in carbonate reservoirs are: 1) physical relationships between rock properties; 2) fluid sensitivity of the carbonate rock property response; 3) data processing; and 4) calibration and interpretation. This study attempts to shed light on all these issues but will focus mainly on calibration and interpretation.

Carbonate Rock Properties

A general description to illustrate carbonate rock properties and their relationship to clastic rocks in the velocity domain using dipole well logs from the WCSB, was given by Li and Downton (2000). To emphasize this comparison, the crossplots in the domain of elastic moduli are shown in Figure 1. In Figure 1a, the mudrock line for clastics is Vs = 0.862Vp - 1172.4. A carbonate 'mudrock' line with the relationship of Vs = 0.4878Vp + 230.0 is fitted to the carbonate lithology cluster. For this typical well, the rocks are wet and consist mainly of limestone.

Fluid effects in carbonates, especially a gas effect, are contentious but of great interest. The common wisdom is that fluids have little or no effect on carbonate rock properties due to carbonate rocks having very high moduli. Put another way, the high velocity of the carbonate rock matrix causes seismic waves to travel primarily through the matrix with less influence from pore fluids. However, the analysis of the data from Rafavich (1984) indicates that gas does influence carbonate rock properties and its effect is significant (Li and Downton, 2000).

Further evidence of this can be seen in an analysis of a large data set of lab measurements on carbonate rocks from the WCSB (Figure 2). The analysis of this data set includes limestones and dolomites representing a wide range of carbonate reservoirs and non-reservoirs and confirms previous conclusions drawn by Li and Downton (2000). Figure 2 shows dolomite rocks in velocity and moduli domains. It can be seen that the behavior of dolomite rocks due to gas saturation is similar to that of
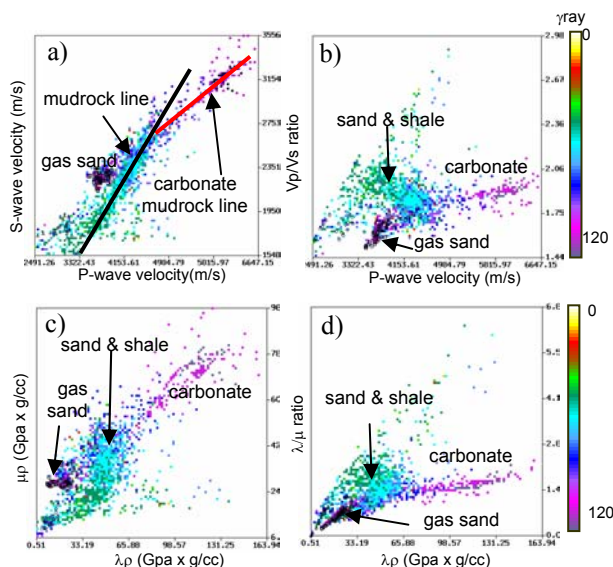

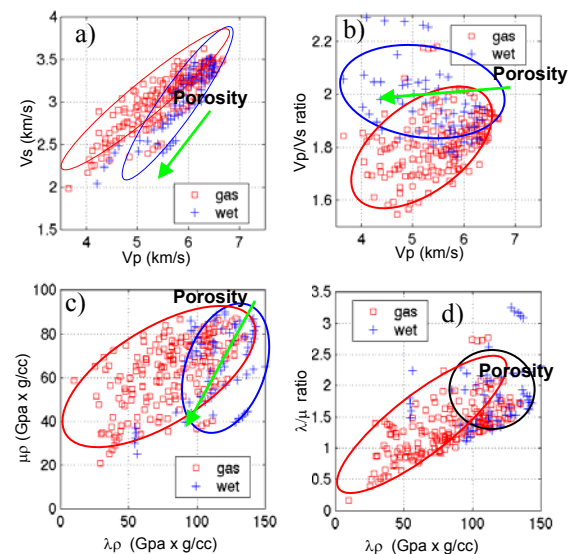*Fig. 1, Velocity, Vp/Vs ratio and moduli of dipole well logs from the West Canadian Sedimentary Basin.*

Fig. 2, Fluid effect in dolomite rocks for a data set from West Canadian Sedimentary Basin.

sands, in that the P-wave velocity, Vp/Vs ratio $\lambda\rho$ and λ/μ ratios all decrease. Note that in Figure 2 the fluid sensitivity is a function of porosity.

The rock property influence of fluids described above implies that the AVO responses to gas and brine saturation should be different. A theoretical calculation to examine this difference is shown in Figure 3. For limestone reservoirs encased by tight limestone, the gradient responses are similar for both gas and wet cases and zero offset amplitude becomes the attribute in differentiating gas from water. However we know that this attribute is ambiguous in determining fluid type in a reservoir as porosity alone could produce the same response. By contrast the gas effect in a dolomite reservoir encased by tight limestone produces a strong class III AVO for a porosity range from 6% to 10% and class III to IV from 12% to 20%. These porosity ranges are of interest in quantitative interpretation (Figure 3d). In these carbonate reservoirs, the class III to IV AVO responses are accompanied by a strong zero offset reflectivity which may further indicate a gas reservoir with good porosity. However as a shale to limestone interface could produce a class II or III AVO response, so care must be taken in standard AVO analysis. In figure 3, both Shuey's two and three term AVO equations are shown demonstrating how much information could be lost for carbonate reservoirs if the two-term equation is used.
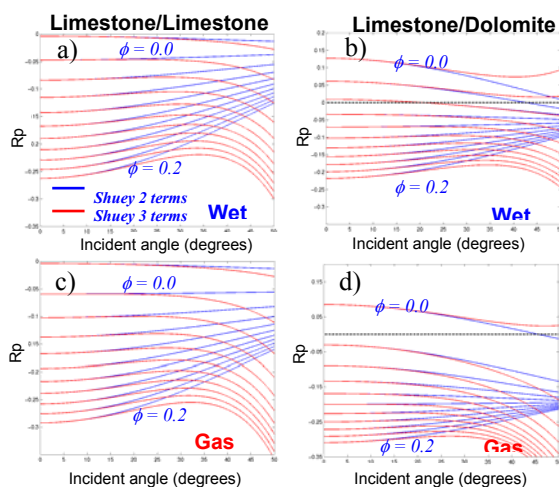

Fig. 3, Theoretically calculated AVO responses for carbonate reservoirs.

The fact that AVO responses in carbonate reservoirs differ from those in clastic reservoirs reminds us that clastics and carbonates should be treated using separate calibration. This calibration affects gather, attribute, and inversion analysis. The limestone and dolomite reservoir types discussed above are most commonly encountered, however there are other types of interfaces and reservoirs associated with carbonates in the WCSB. These are dolomites encased in anhydrite, shale to carbonate interfaces, sands encased by carbonates, and sands overlying carbonates. As the

lithologic complexity increases, so AVO modelling affords a means to determine which type of AVO anomaly represents a specific geological situation. Fractured carbonate reservoirs also exist and other techniques such as azimuthal P-wave AVO and converted shear wave acquisition contribute significant corroborative information.

Case studies
Selected well logs with a good representation of a gas saturated dolomite reservoir at the depth about 3700 m and a water-saturated dolomite reservoir at a depth of 3000 m were analyzed. In Figure 4, the well log data are crossplotted and the gas, wet, and tight limestone data points are highlighted in red, green and black squares, respectively. A set of empirical relationships for sand, shale, and carbonates are overlain on these crossplots. These crossplots compare clastic to carbonate lithologies, as well as showing the consistency between log and lab measurements. The measured gas sand points can be obtained from the data in Figure 1. The following observations can be made from these crossplots,: a) the gas effect is apparent and its magnitude is magnified in the Vp/Vs ratio, λ/μ ratio, and $\lambda\rho$ domains; and b) wet dolomite or wet limestone or a mix of both must be used as the background reference in order to quantitatively determine the degree of the gas effect.
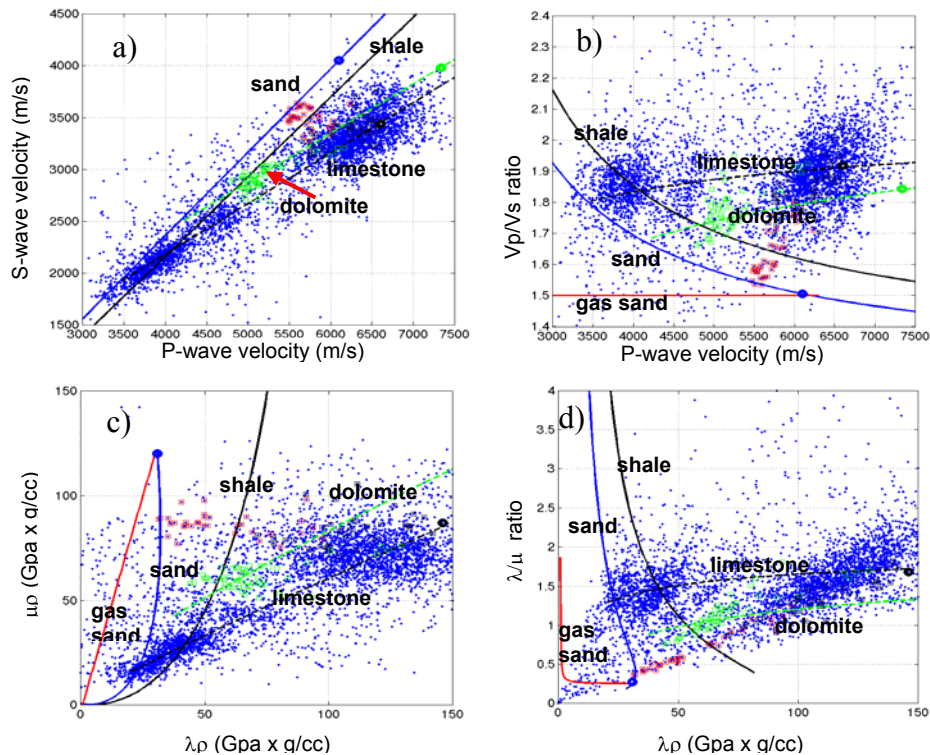

Fig. 4, Gas and water saturated reservoirs in velocity and modulus domains. Blue dots are the entire well log points.

To determine fluid saturation effects, Biot-Gassmann brine substitution was performed and an AVO model was generated (Figure 5). In Figure 5, the gas case produces a class II or III AVO anomaly with amplitude brightening at far offsets. For the brine case, the AVO changes to a class II response with a very weak zero offset amplitude. This is consistent with the theoretical predictions (Figure 3).
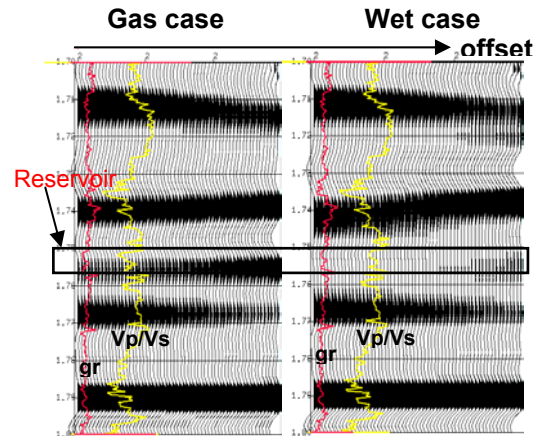

Fig.5, AVO responses of gas charged and water saturated dolomite reservoir.

An AVO inversion example for a gas charged dolomite reservoir at a depth of about 3000 m is given in Figure 6. This reservoir has around 14% porosity and its inverted rock properties are displayed in crossplot space as black points. The inversion work followed a procedure developed by Goodway et al (1997). First, P- and S-reflectivities were extracted from CDP gathers and then these reflectivities were inverted into P- and S-impedances. The moduli attributes $\lambda\rho$, $\mu\rho$, and λ/μ ratio were calculated using $\mu\rho = Is^2$ and $\lambda\rho = Ip^2 - 2Is^2$. The overlays of empirical lithology relationships used here are the same as in Figure 4. An apparent gas response can be seen with the reference background of water-saturated dolomite. Note that if the dolomite reservoir rock
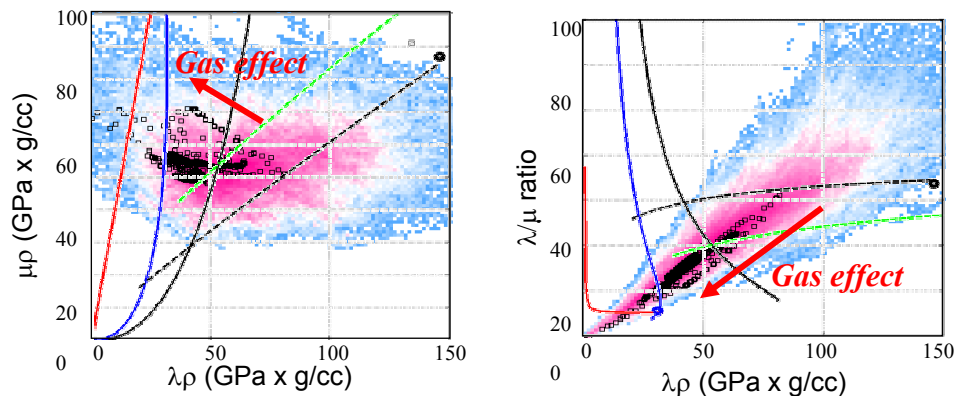

Fig. 6, Crossplots of the inverted elastic properties for a gas charged dolomite reservoir.

properties are interpreted using the crossplot template developed from clastics, most populations of the data points will be mistakenly interpreted as either shale or shaly sand.

Incorrect treatment of the amplitude of CDP gathers, incorrect scaling at any stage of data processing, or incorrect background information (velocity and density) in the AVO inversion may alter the values of the inverted rock properties and consequently displace the data points into a biased location in the crossplot space. This will lead to a misinterpretation and as indicated, the worst case would be that the criteria for a clastic non-reservoir are used.

A flow chart for the calibration and interpretation of carbonates using AVO is given in Figure 7, showing two main branches for AVO modeling and seismic processing. Geological information needs to be used in the interpretation stage and in the final QC calibration stage. Either a tight limestone or well-defined background geologic units can be used to check if the inversion was performed correctly.
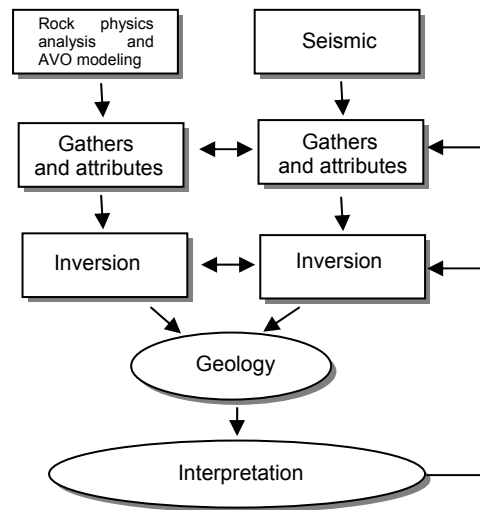

Fig. 7, Flowchart of AVO processing and interpretation for carbonate reservoirs.

Pitfalls
In addition to proper care in amplitude preserving processing, there are pitfalls in interpretation to be aware of. An often-encountered pitfall is the similarity of rock properties between porous carbonate (or porous gas charged carbonate) and shale. As shale often coexists within carbonates, it could be interpreted as either gas charged reservoir or vice versa. Figures 1, 4 and 6 all indicate this fact, i.e. with increasing porosity, carbonate rocks merge into the shale crossplot space. In this kind of situation,

geological information becomes crucial in constraining the interpretation. In addition, converted wave interference may manifest itself as good class II AVO anomalies, and shale and carbonate interfaces may produce class III AVO anomalies. Multiples are also an issue degrading the quality of pre-stack gathers. Finally, factors involving structural complexity and imaging amplitude preservation should be considered and tested for AVO robustness.

Conclusions

With better understanding of carbonate rock properties and advances in seismic data processing, calibration and correct interpretation becomes important. With correct data processing, AVO modeling, geologic input, and awareness of pitfalls, the risk of using AVO technologies in carbonate reservoir exploration can be reduced.

Acknowledgments

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