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Depth induced impedance variations: implications for predicting lithology and fluid distributions, offshore Brunei Darussalam

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Acoustic impedance (the product of rock density and the velocity of sonic propagation through rock) is the fundamental property that links together well geology and seismic data. Formation geology and fluid content define acoustic impedance, while seismic data responds to variations in impedance. But formation density and velocity of sonic propagation are affected by pressure and compaction. Hence acoustic impedance is sensitive to depth. With increasing depth, impedance characteristics of the formation change. The seismic response to lithology and fluid therefore changes with depth. Since seismic data and their attributes (including impedance) are often used to extract information regarding reservoir property and fluid distributions, it is important to know which of the fundamental petrophysical properties the seismic data is responding to at any depth. A study of acoustic impedance and its behaviour with depth is therefore crucial in determining what information can be extracted from seismic data.

This research studied the acoustic impedance characteristics of hydrocarbon bearing sheet sand reservoirs at various depths in a field currently under development (Fig. 1). Wireline sonic and density logs (Fig. 2) from this field show (1) trends that increase with depth, and (2) a separation between sand and shale packages. The separation narrows with depth and converges at around the onset of overpressuring, beneath which the sonic trend remains either constant or shows a slight reversal in the overpressured formation. Six hydrocarbon-bearing sand layers were selected for investigation (Fig. 2), chosen so as to sample the various sand intervals and pressure regimes in the formation. Wireline analysis of the sand layers included detailed cross-plots of the sands and surrounding shales (Fig. 3), and calculation of reflection coefficients at their upper interfaces. The wireline impedance logs were correlated with 3D seismic data via synthetic seismograms (Fig. 4). The seismic data volume was inverted into an acoustic impedance volume using the trace based constrained sparse spike inversion algorithm. Impedance maps were extracted for each sand from the seismic-derived impedance volume to study lateral impedance variations.

Integrated evaluation of the wireline, seismic and impedance volume data provided the following inferences. At structurally shallower levels, impedance varies independently and linearly with gamma-ray for sand and shale components. Hydrocarbon (gas) occurrence lowers sand impedance to unique, fluid discriminatory threshold values (Fig. 3, Sand A and Sand B). Overpressured shales occur relatively infrequently and have little or no influence on this impedance threshold. Impedance therefore works as both an indicator of lithology as well as fluid type. Inverse modelling results in pseudo-impedance traces that agree very well with wireline impedances (Fig. 5, impedances below 7e+06 kg/m^3*m/s). At these shallower levels, impedance maps display areas of hydrocarbon occurrence very prominently, and in addition, reveal possible variations in reservoir type and quality, as well as indicate background regional impedance variations (Fig. 6, Sand A and Sand B). Maximum contrasts of acoustic impedance are provided by a normally pressured shale in contact with a gas filled sand. The seismic response to hydrocarbon is therefore a brightening of amplitudes.

With increasing depth, overburden effects reduce the impedance contrast between sand and shale, so that the potential of impedance to act as a discriminator of lithology decreases (Fig. 3, Sand C). Additionally, overpressured shales assume increasing importance. Hydrocarbon occurrence lowers impedance to values that are no longer unique. Low impedance overpressured shales progressively impinge below the gas-sand impedance threshold (Fig. 3, Sand D). The potential of impedance to act as a discriminator of fluid type therefore successively decreases. Inverse modelling still produces a good match between pseudo-impedance traces and wireline impedances (Fig. 5, impedances below 8e+06 kg/m^3*m/s). On impedance maps, areas of low impedance signifying hydrocarbon occurrence are not as prominently displayed as before, and overlap with areas of low impedance shale, thereby creating considerable interpretational uncertainty (Fig. 6, Sands C, D and E). The seismic response to tops of gas sands is marked less by amplitude brightening and more by a reversal in waveform polarity. Overpressured shales in contact with clean sands would create similar seismic responses.

As overpressuring becomes pronounced with increasing depth, the interference between gas-sand and soft shale increases until there is complete overlap in their impedance values (Fig. 3, Sand E). At completely overpressured depths, impedances overlap for all types of lithology and fluid (Fig. 3, Sand F). Impedance responds, not to fluid type, but to fluid pressure instead. The occurrence of overpressuring is unpredictable and discordant to stratigraphic dip. Both seismic and wireline data quality may be adversely affected in overpressured formation. Inverse modelling shows a deterioration in agreement between the derived pseudo-impedance trace and the corresponding wireline impedance log (Fig. 5, impedances above 8e+06 kg/m^3*m/s). Impedance maps provide no indications of lithology or hydrocarbon (Fig. 6, Sand F). The seismic data, at this depth, responds to pressure and not to lithology or fluid type.

This analysis has considerable implications to hydrocarbon production and further exploration in Brunei The focus for further exploration in Brunei is shifting to the deep water environment. The principal data for deep water exploration is seismic. In Brunei, the top of undercompaction related overpressures is encountered at subsequently younger (and therefore shallower) stratigraphic levels from the onshore to the distal offshore. Hence overpressure induced uncertainties will manifest at progressively shallower depths offshore on seismic data. In addition, the onset of overpressuring is lifted to shallower levels along deltaic growth fault associated roll-over anticlines. Where the seismic response to overpressuring is a brightening of amplitude and where this brightening occurs conformable to anticline structures, considerable potential exists for misinterpreting the cause of the amplitude brightening to be the occurrence of hydrocarbon.

This study has demonstrated that the inverse modelling derived impedance volume can, at shallower levels, separate out fluids but has limited potential in differentiating lithology. With increasing depth, the capacity of impedance to separate out both lithology and fluid distributions decreases as a result of overburden effects and overpressure induced uncertainties. Direct hydrocarbon indicators on seismic data change from amplitude brightening at shallower levels to polarity reversals at deeper levels with increasing uncertainty brought about by overpressured shales. Full stack seismic data is increasingly inefficient in differentiating between sand and shale, and between gas-sand and low impedance shale. Alternative data and workflow are required. These may include comparison of Vp/Vs ratios for the different lithology and fluid combinations, analysis of angle dependent impedance (elastic impedance), and stochastic simulations of lithology and porosity distributions using the impedance volume as guide. Impedance, in combination with offset data and/or alternative workflows may still constitute an important tool in obtaining lithology and fluid distributions to build reservoir models that aid development and production.