Incorporating depth-dependency in quantitative interpretation through statistical rock physics

Sagar Ronghe and Anne Locke, DownUnder GeoSolutions

Introduction

Quantitative interpretation calibrates elastic properties (P-impedance, Vp/Vs) derived through simultaneous inversion of seismic angle stacks to a rock physics model in order to characterise the formation. The rock physics interpretation framework comprises probability density functions (PDFs) that define the range of elastic properties associated with different lithology and fluid types. The PDFs are often calculated from cross-plot samples of upscaled elastic well logs. Simultaneous inversion results, sometimes from large vertical intervals, are then compared against the cross-plot derived PDFs to predict the occurrence of different kinds of lithologies and fluids. This approach has two fundamental problems: cross-plot samples may not be representative of the complete possible range of elastic properties associated with the lithologies and fluids of interest; and the implications of depth trends on elastic properties is ignored. In this paper we highlight a workflow that uses statistical rock physics to understand the depth-dependent population behaviour of the rock types, and incorporates depth dependency in the criteria for predicting lithology and fluid distributions from seismic AVA and elastic property derivatives.

Building a rock physics interpretation framework using the extents of recorded or synthesised elastic logs has significant limitations. Formation lithologies and fluids of interest may have been intersected over narrow depths relative to the logged intervals. The length of acquired elastic logs may be short. Elastic properties vary with depth, usually as a function of overburden pressure. Elastic log measurements of lithologies and fluids are therefore only valid at the depths that they are encountered. Changes in structural geology away from the wells may cause lithologies of interest to occur at depths outside the logged intervals and have elastic properties that fall outside the logged ranges of values. Using elastic log measurements of intersected lithologies and fluids to characterise formations outside the logged intervals is inaccurate.

Wells may be few in number and preferentially drilled to intersect specific lithologies. Cross-plots of wireline log samples may not be representative of the complete range of elastic properties possible for the lithology at the intersected depth. Calibrating seismic derived elastic properties with well logs needs to overcome differences in resolution. This is usually undertaken by filtering the well logs to the bandwidth of the derived elastic properties before cross-plotting. Filtering reduces the density of samples on the cross-plot. Using a filtered subset of samples risks establishing interpretation criteria that do not appropriately reflect the properties of the formation of interest.

Statistical rock physics

Statistical rock physics provides an understanding of the population behaviour (the complete likely range of elastic property responses) of lithology and fluid combinations as a function of end-member rock types, fluid content, reservoir quality and depth. The workflow, described below, comprises analysis (end-member picking and trending) and modelling (statistical sampling of the end-member trend information). A depth-dependent interpretation framework can be created in elastic property space and in interface reflectivity space (Lamont, *et al*., 2008, Thompson *et al*., 2011).

Statistical rock physics analysis involves picking end-member lithology types from logs and establishing end-member trends (Figure 1). End-members are the cleanest logged examples of any lithology defined using distinct elastic properties. End-member intervals (picks) are selected on logs and their elastic properties are upscaled to form single values. The data points are cross-plotted, and end-member trends are established for each lithology type. The end-member trends, along with their standard deviation corridors, specify the relationships between the elastic properties, between elastic properties and reservoir porosity, and show the effect of depth.

Statistical rock physics modelling samples the rock property distributions defined by end-member trends and associated standard deviations to derive large numbers of data points representative of the population behaviour for each lithology and fluid mixture at any depth. Prior to sampling, reservoir and non-reservoir trends are proportionally mixed to represent formation characteristics consistent with petrophysical evaluations; and fluid mixture properties are obtained for these lithologies using Gassmann fluid substitution. The statistically sampled data are cross-plotted for elastic properties (e.g. P-impedance versus Vp/Vs) and are characterised using PDFs for each lithology and fluid mixture at depth increments. The result is a depth-dependent interpretation framework in elastic property space (Figure 2). Similarly, a depth-dependent interpretation framework can be established in interface property space by sampling the contrasts between lithology and fluid mixtures for reflectivity. Cross-plots are created for reflectivity (e.g. near [10 deg] vs far [30 deg] reflectivity) and are summarised using PDFs (Figure 3). In reflectivity models, PDFs explain AVA behaviour. PDFs will plot in different regions of near vs far reflectivity space for the different classes of AVA. PDFs can span multiple classes. The PDFs enable an understanding of the range of seismic AVA responses possible from an interface given the statistical rock physics model.

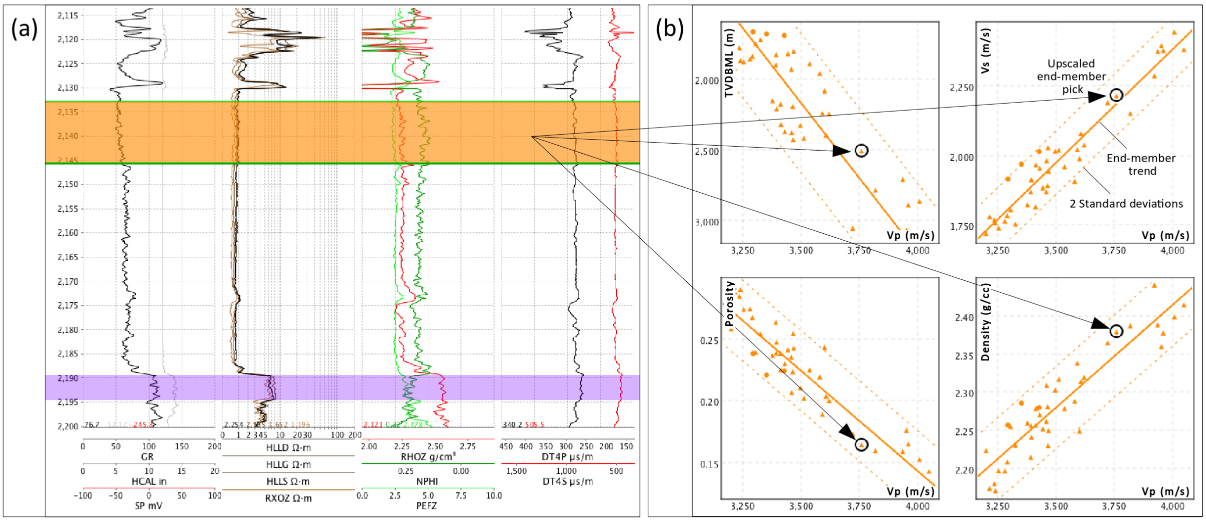

Figure 1 *End-member picks and trends. (a) Two intervals representing different end-member picks are highlighted on well logs in orange and purple. (b) An end-member pick is upscaled to form a single point on cross-plots. End-member pick distributions are used to define end-member trends and standard deviations for each end-member lithology.*

Discussion

Depth trends affect interpretation criteria in both elastic property and interface reflectivity space. For the dataset displayed in Figure 2, a number of changes can be observed with increasing depth: the properties of the individual PDFs change; the size of the PDFs reduce due to decrease in reflectivity; and the associations between different PDFs vary. At 700 m TVDBML the Brine Sandstone PDF is completely overlain by the Claystone PDF, whereas the PDFs associated with the hydrocarbon sands show little overlap with the other PDFs. In contrast, at 1,900 m TVDBML, the Brine Sandstone PDF shows increased separation from the Claystone PDF and hydrocarbon sand PDFs show increased overlap with the other two. In between these depths is a continuum of change. This demonstrates that the range of elastic properties that can classify a particular lithology or fluid type at a depth are invalid in classifying the same lithology or fluid at a different depth.

Similar effects are seen in interface reflectivity space. For the dataset in Figure 3, at 1,000 m TVDBML, the PDF representative of the Claystone / Gas Sand interface has a strong Class II or Class III AVA signature. This transitions to subtle Class III to Class IV between 3,000 and 4,000 m TVDBML. At 6,000 m TVDBML, the response is a strong Class IV. Note also how the associations between the PDFs change with depth and the implications of decreasing reflectivity with depth. It is therefore important not just to know the likely range of AVA responses associated with the top of a gas sand, but also the depths at which these responses are expected. It is crucially important to incorporate and apply depth dependency in the interpretation criteria for both simultaneous inversion results as well as seismic AVA.

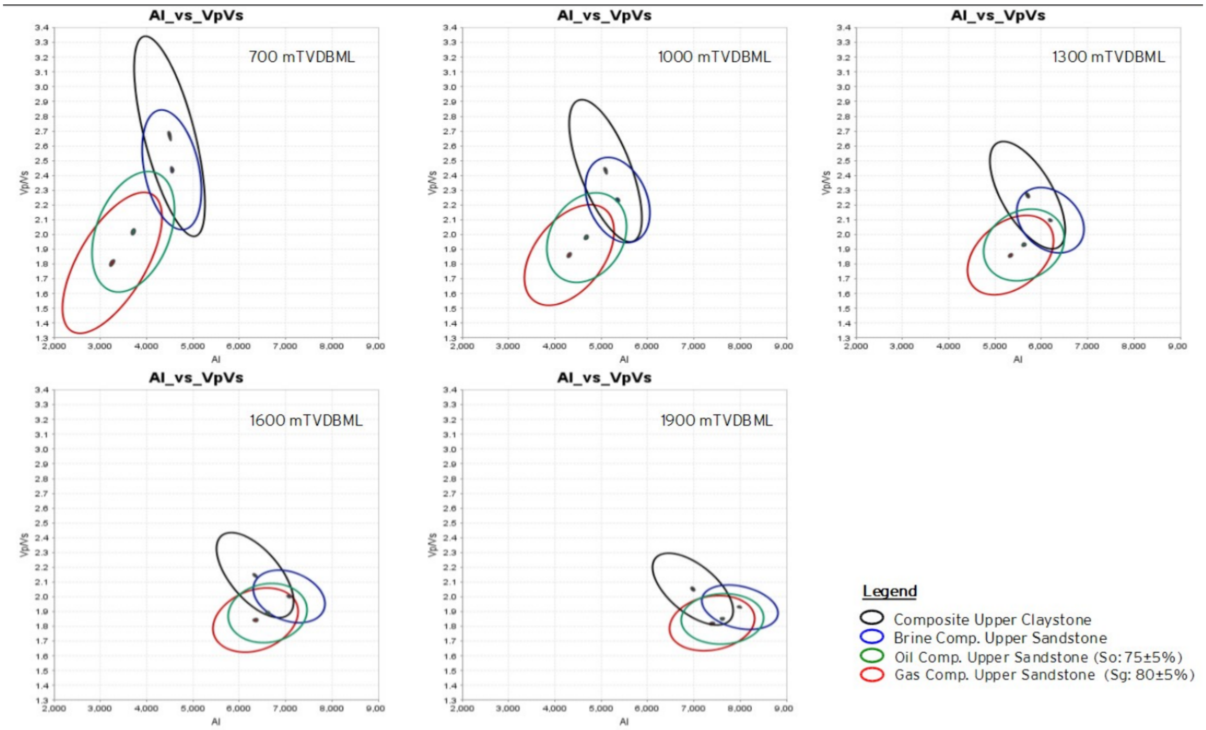

Figure 2 *A depth-dependent elastic property interpretation framework is displayed as P-impedance versus Vp/Vs cross-plots at various depths, each overlain by PDFs for mixtures of lithology and fluid. Each PDF is displayed using a mean point and a 2 standard deviation contour of the property distribution. The PDFs change in properties, size and associations with increasing depth.*

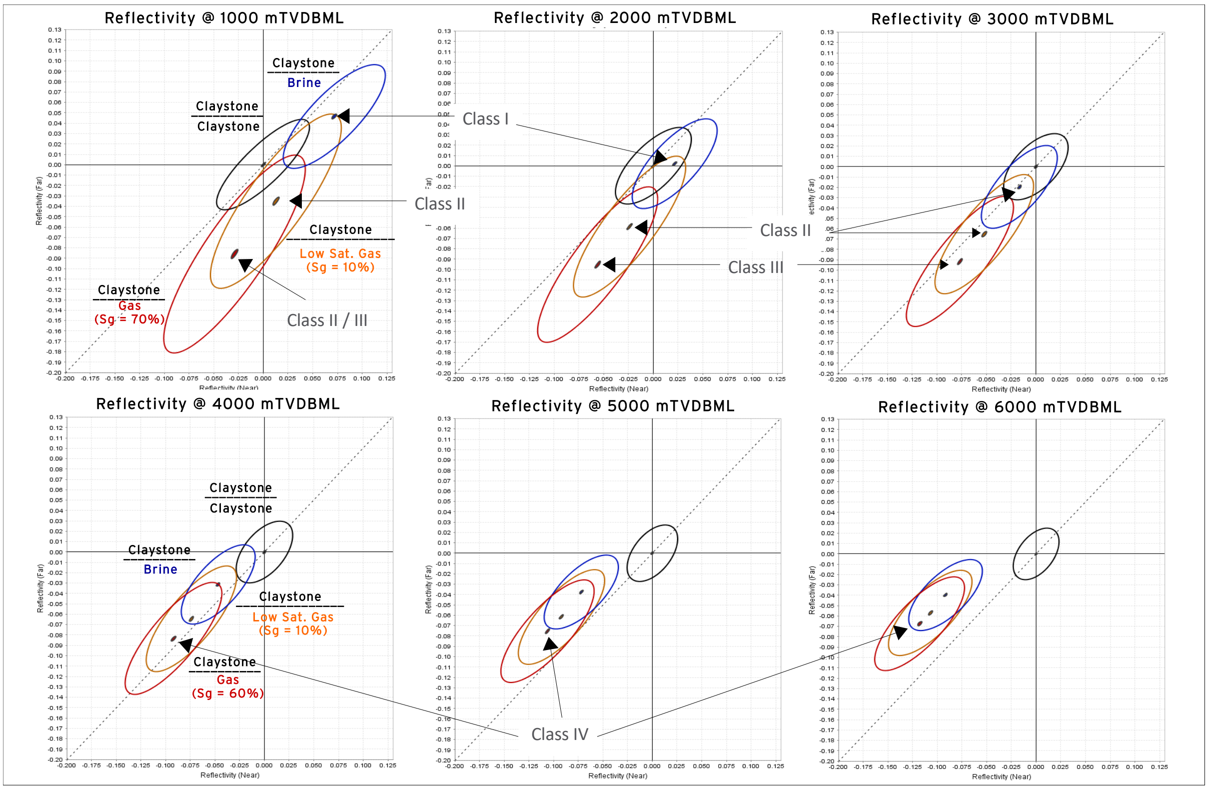

Figure 3 *A depth-dependent interface reflectivity interpretation framework is displayed as Near (10 deg) versus Far (30 deg) cross-plots at various depths, each overlain by PDFs for interface contrasts between lithology and fluid mixtures. PDFs change AVA character, size and associations with increasing depth.*

The statistical rock physics workflow overcomes limitations of traditional rock physics approaches. Depth trends can be extrapolated outside the logged intervals if appropriate, with due consideration to changes in structure and stratigraphy. This means that, unlike well log cross-plot based methods, it is possible to derive interpretation criteria outside the wells extents, with some caveats. Also, the differences in bandwidth between well and seismic data can be addressed by mixing end-member lithology and fluid trends in proportions representative of the resolution of the seismic data. The resulting modelled PDFs retain the population behaviour of the end-member lithologies and are in agreement with seismic. The loss of information inherent in cross-plotting frequency filtered logs to bridge the resolution gap between well and seismic data does not feature in a statistical rock physics model.

Conclusion

Cross-plotting of filtered well logs to define the framework for quantitative interpretation of AVA and inversion products is not appropriate as it reduces data density and ignores depth dependency. Statistical rock physics overcomes these limitations by defining the population behaviour of lithologies and fluids as a function of depth. The rock physics model can be extended and interpretation criteria established outside the logged intervals. Lithology and fluid trends can be mixed to define PDFs at seismic resolution. This does not require any data decimation that loses information. Interpretation of simultaneous inversion results and seismic AVA must incorporate depth dependency.

Acknowledgements

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References

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