Lithology substitution in a sand/shale sequence

Richard Uden*
Rock Solid Images, USA
r.uden@rocksolidimages.com

Jack Dvorkin
Rock Solid Images, USA
j.dvorkin@rocksolidimages.com

Joel Walls
Rock Solid Images, USA
j.walls@rocksolidimages.com

Matt Carr
Rock Solid Images, USA
m.carr@rocksolidimages.com

SUMMARY

Geophysics as well as inversion of seismic data has improved considerably over the last decade. So much so that elastic inversion is rapidly becoming a commodity data product that oil companies understand and use for risk reduction. Many examples have been shown where the elastic impedance is used to estimate porosity, for example using a statistical regression on well data.

This paper reviews the use of Rock Physics Diagnostics applied to log data to illustrate a relational model between porosity, clay and saturation. These relations are used to estimate porosity from elastic impedance attributes. Using statistical fits may work locally around the property values experienced by a well for example but away from the well a systematic approach is required to improve the confidence and thereby reduce the risk associated with such predictions.

Such a systematic approach is Rock Physics Diagnostics presented as a methodology considered essential for predicting rock properties from seismic data.

The main task of this case study was to identify productive sands from seismic away from well control. It was assumed that the sedimentary environment away from the well was the same as at the well. The well data (onshore North America) indicated the presence of blocky oil sand and down-fining cycle below.

Using this well log data as input identified robust empirical models to describe the Vp and Vs behavior of the pay sands and surrounding shale. These models were then used to transform acoustic impedance and elastic impedance volumes into a pay sand porosity volume.

Key words: Rock-Physics, Lithology, Porosity, Impedance and Seismic.

INTRODUCTION

Examination of trends in the impedance versus porosity rock physics domain can often reveal distinct relationships between shale and sand. Not so for this data, which exhibits both porosity and lithology influencing the impedances. These relationships have been reported by Han (Han et al 1986) among others and normally follow the relationship that the more clay you have the lower the velocity.

To uncover the effects of clay and porosity on impedance the data is first brought to a common fluid denominator, in this case by theoretically fluid substituting the in-situ pore fluid with the formation brine for the elastic log and density log data measured in the well bore. The wet condition elastic logs are shown in Figure 1 together with relevant supporting curves.

DETERMINISTIC ROCK PHYSICS MODELING

The use of empirical statistical fitting is commonly used as a method to relate impedance to rock properties. While good examples of this practice exist, one draw back is that extrapolating outside the statistical range may be invalid and therefore misleading. A deterministic based method can be either empirical or effective medium based, but must be predictive.

One such model based on extensive empirical data is the Raymer model (Raymer et al 1980), which states that p-wave sediment velocity in a function of mineral velocity and the fluid velocity, and depends on the total porosity. Another such model is the mud-rock model (Castagna et al 1985) that linearly relates the p-wave velocity to the shear wave velocity.

Figure 2 shows the data points from Figure 1 in the impedance versus porosity domain with curves derived from the two models superimposed on the data points. The “pure sand” data lie between the 0.0 and 0.2 clay content curves being best described by the 0.1 clay curve. As the clay content increases, the clean sand becomes shaley sand and the data move towards lower porosity. The turning point is approximately at 0.4 clay content and 0.1 porosity, known as the critical point. Increasing the clay content further increases the porosity to approximately 0.22, the porosity of “pure shale,” which at more or less the same porosity, has lower impedance than the sand.

DEPOSITION IMPOSED RELATIONSHIPS

The models used in Figure 2 imply a very large number of possible combinations of differing values for porosity, clay content and water saturation. In this fluvial system the number of allowable combinations can be significantly reduced. Consider Figure 3, where a clear relationship is seen between the total porosity and clay content. This is a further representation of the “horseshoe” shape impedance responses of Figure 2. The relationship is explained by the lower panel, which shows that as the clay content increases the dispersed shale particles gradually fill the pore spaces between the relatively large sand grains until we reach the critical point. Now the sand grains no longer maintain grain contact and are separated by the clay particles, until we reach the pure shale case on the right.

Also, in the upper right of Figure 3, the water saturation increases with increasing clay content. As the sand grains make way for increasing clay particles, the pore size reduces and the capillary forces increase. The translation to 100% water saturation rapidly takes place even before the critical point is reached.

These dependencies between lithology, total porosity and water saturation define the deposition-imposed constraints in the forward model scenarios. For example, no clean oil saturated sand of 10% porosity can be present in this fluvial environment.

LITHOLOGY SUBSTITUTION

In order to perform lithology substitution, the dependencies expressed by the depositional constraints must be adhered to. In Figure 4 the oil sand has been substituted by shale, where the gamma ray value is about 80, then according to Figure 3, the total porosity is about 15%, and the water saturation is 100%. Given these conditions, the empirical models (Raymer and Castagna) are used to estimate the elastic and density responses shown in Figure 4.

The p-wave impedance curve shows that seismic stack data is very unlikely to discriminate shale from pay sand whereas the Poisson's Ratio curve clearly shows discrimination.

PAY DELINEATION AND POROSITY PREDICTION

The rock physics model shown here can also be used with impedance inversion attributes. Firstly Poisson's Ratio is computed from the p-wave and s-wave impedances. Small values of Poisson's Ratio characterize the presence of pay sand. Then secondly, the Raymer base transform is used to predict the porosity from the p-wave impedance as illustrated in Figure 5.

CONCLUSIONS

Fluid substitution is well known, but the key to lithology substitution is the rock physics model that links the changes in lithology, porosity and pore fluid to changes in the velocities and density. The model must be predictive, such that it works outside the data range spanned by the measured data. Application of rock physics analysis to the measured well log data quantitatively explains the observed variations in the elastic properties versus porosity and lithology.

A further critical fact of lithology substitution is the link between the sediment properties and conditions such as porosity, clay content and fluid saturation that follow the rules of geology and deposition.

Rock physics diagnostics requires an understanding of the rock if reliable predictions of rock properties from seismic data are required. The relationships between clay content porosity and water saturation influence the impedance response have been shown. The rock physics modeling method provides a rational and systematic basis for seismic attribute generation and interpretation and the application of these models can often help in an otherwise underdetermined state, which is often the case.

REFERENCES

Castagna, J. P., Batzle, M. L., and Eastwood, R. L., 1985, Relationship between compressional and shear-wave velocities in clastic silicate rocks: Geophysics, 50, 551-570.

Han, D. H., Nur, A., and Morgan, D., 1986, Effects of porosity and clay content on wave velocities in sandstones: Geophysics, 51, 2093-2107.

Raymer, L. L., Hunt, E. R., and Gardner, J. S., 1980, An improved sonic transit-time-porosity transform, Society of Professional Well Log Analysts, 21st Annual Logging Symposium Transactions, paper P.

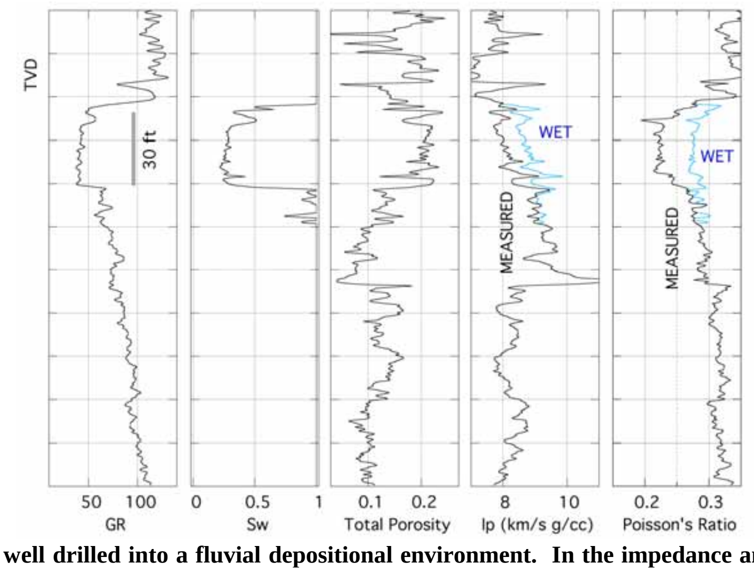

Figure 1: Curves from a well drilled into a fluvial depositional environment. In the impedance and Poisson's Ratio frames, black is used for the in-situ measurements while blue is used for the theoretically computed wet condition.

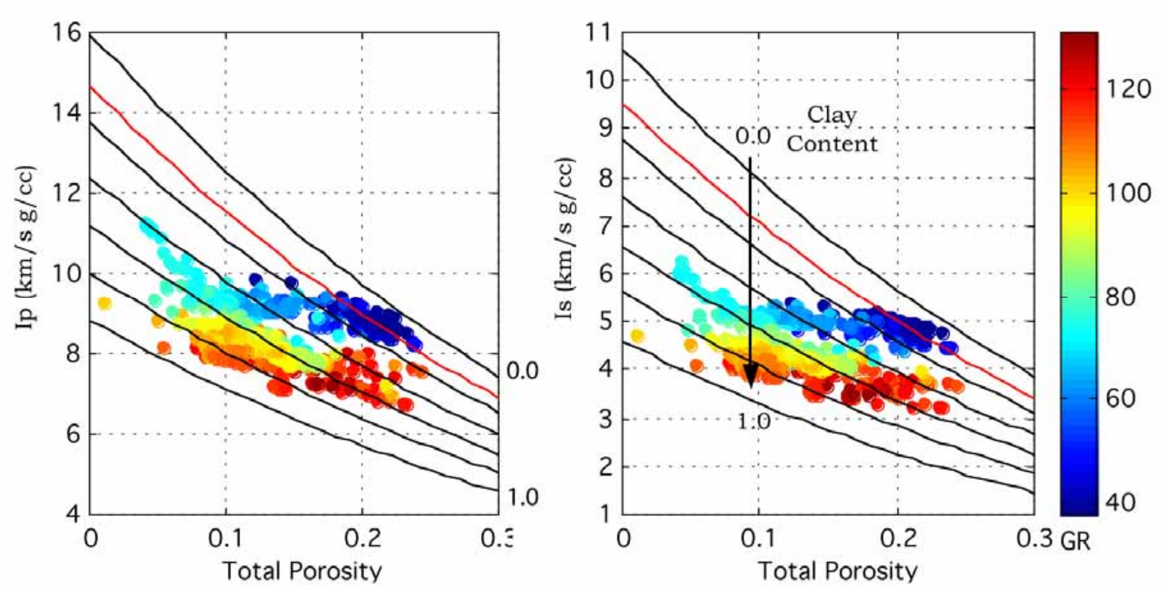

Figure 2: Formation water substituted wet condition – p-wave impedance (left) and s-wave impedance (right) versus total porosity for the log data shown in Figure 1 color coded by gamma ray values. The curves are for the Raymer- Castagna rock physics model, plotted for constant clay content in steps of 0.1 from 0.0 (upper) to 1.0 (lower). The red curve is for clay content 0.1.

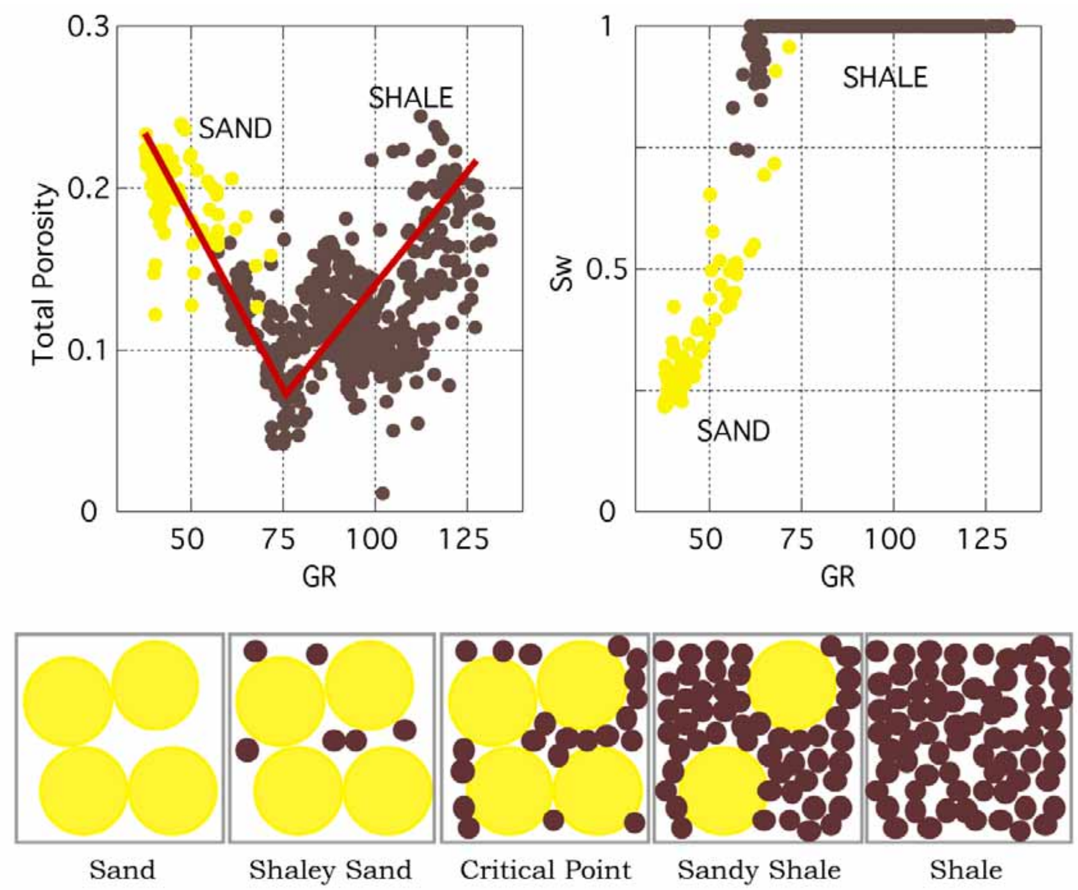

Figure 3: Top – total porosity and water saturation versus gamma ray (clay content measure), with the pay zone highlighted in yellow. Bottom – cartoon of the porosity change in the dispersed clay depositional model.

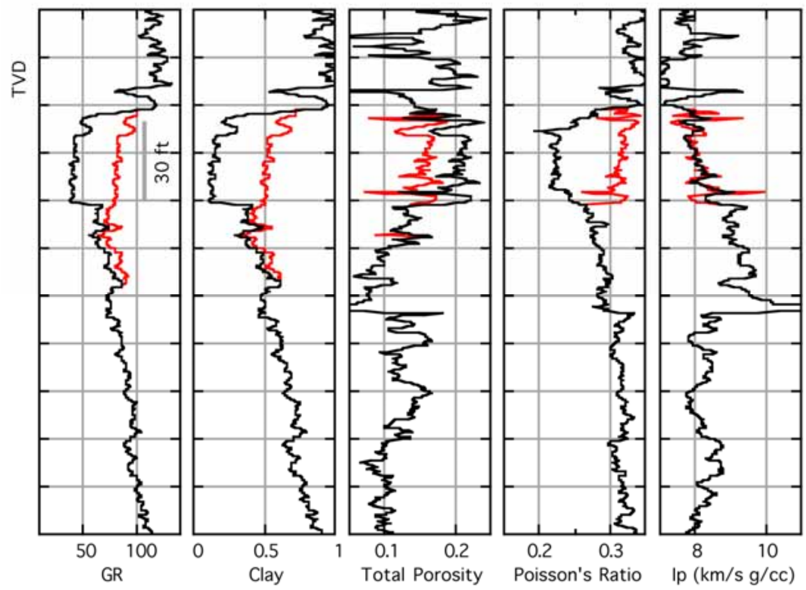

Figure 4: Curves from a well drilled into a fluvial depositional environment. Black is used for the in-situ measurements while red is used for the lithology substitution condition.

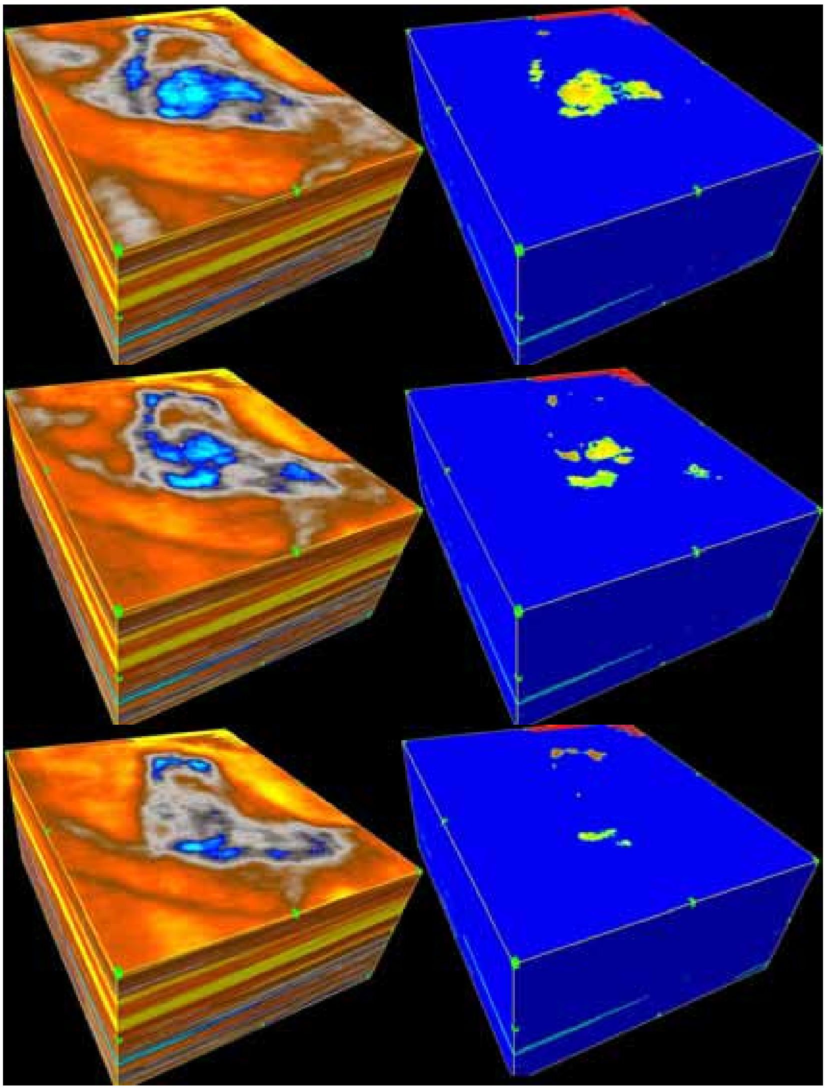

Figure 5: Three consecutive time slices through he pay zone. Left – Poisson's Ratio volume highlights the pay region. Right – Porosity prediction from the p-wave impedance – pure yellow indicates high porosity.