Explorational rock physics of post-rift sediments in the Southern Santos Basin, Brazil

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Abstract

A rock physics study focusing on sands and shales aged from the Campanian to the Eocene was conducted as part of a wider effort to exploit seismic amplitude information for the post-rift play in the Southern Santos Basin, Brazil. High confidence elastic property trends were established after recognizing (and removing) interference in the log datasets from intervals with abundant shell debris interspersed within the rock matrix. The sand trends show clear mechanical compaction behavior reflecting hydrostatic conditions and a lack of strong cementation. A clear distinction exists within the shale trends after the onset of the Eocene (55Ma) that may represent a change in provenance linked to the cessation of the Serra do Mar uplift event.

Introduction

Rock physics models are mathematical translations between a rock's (economic) physical characteristics and its elastic properties. They represent the link between what we can estimate from a seismic reflection's AvO and what we would like to know about in order to explore and appraise efficiently. Rock physics models need to be built using all available information and for all the potential reservoirs, seals, laminating rocks, 'exotic' rocks (volcanics, evaporites, coals, etc.) and fluids that are likely to be encountered in the study area.

There have been many different rock physics models published, although many can be grouped into common classes of techniques (Avseth, et al. 2005). Experience has shown that not all perform equally well when tested on high quality log datasets in clastics and carbonates (Dunne, 2010). Desired attributes of a rock physics model include:

1. a sound physical basis;

2. as few free variables as possible;

3. predicts measured V_P and V_S for any lithology, porosity, pressure, temperature and texture.

In an exploration quantitative interpretation (QI) study, we aim to predict a sediment's elastic properties from its burial depth (below mudline, Z_{BML}) and its dependence on relevant regional geologic controls. In predominantly clastic settings, such as the Santos Basin post-rift play, one way to achieve this is to establish an inter-related set of trends linking the elastic parameters (V_P; V_S; and Density) to burial depth (Z_{BML}). Density and porosity are easily linked to each other after establishing the grain density and fluid density of the rock. V_P and V_S can be linked to porosity (sometimes more naturally using the bulk and shear moduli) using trend fits or appropriate rock physics models. Porosity can be linked to burial depth using compaction curves.

When rock physics trends have been established for all the likely lithologies and fluids, it is possible to translate these into AvO attributes to provide a template that enables direct interpretation of the seismic AvO response. A 'Rock Physics Template' is essentially a model-based approach for interpreting seismic volumes, such as AI and V_P/V_S derived during an AvO inversion study (Avseth, et al. 2005). It is made to cover the depth range of interest and usually also includes hydrocarbon effects (via Gassmann fluid substitution on the models) and may also employ effective medium modelling to account for limited seismic resolution. These templates can be a great tool for discussing with interpreters which physical characteristics (of a rock) are possible to resolve using seismic amplitudes.

Armed with high confidence rock physics models, it may then be possible to achieve "tight integration" between structural mapping; pressure data; and seismic amplitude data. This could then be used to underpin predictions regarding potential exploration and appraisal outcomes, using Karoon's proprietary IQUITOS software.

Figure 1 *– Location map of the study area.*

This study focusses on the Southern part of the Santos Basin, where Karoon has a number of exploration permits (Figure 1). This area is aptly referred to as the "Salt Diapir and Minibasin province" (Modica and Brush, 2004). These authors, along with Thompson (et al., 1998) discuss the timing and spatial positioning of the igneous Serra do Mar uplift, noting a cessation of the uplift at the northern end of the Santos Basin at the start of the Eocene (55 Ma). Their observations highlight the possibility of a change in provenance for much of the Santos Basin at around this time.

Some other relevant observations on the regional geological setting include sand petrology studies for the wells used in this study (K. Jennings, *pers. comm.*, and Lanigan and Dunne, 2016) showing only minor variability in a broad mixture of different minerals that compose a typical sand in the study area. Depositional environments for the stratigraphic intervals considered are interpreted to be dominantly muddy-neritic (Modica and Brush, 2004). Drilling results at wells in the study area indicate hydrostatic conditions above the Santonian.

This paper begins by reviewing the seismic petrophysics applied to prepare well-log data ahead of the rock physics trend formulation for end-member sands and shales. Rock physics templates lead into the design of seismic attributes for highlighting porefill and lithology effects from seismic AvO data. The study represents the necessary pre-work enabling subsequent integration between pressure and seismic datasets, which is based on structural mapping; event amplitudes; and flatspots.

Method

The study was based on 10 wells that fall within the BM-S-7 seismic survey, each of which possesses a full, high quality log suite. The well logs were put through a consistent 'seismic petrophysics' workflow involving steps such as outlier editing; depth matching; auxiliary log creation (e.g., differential caliper, normalized gamma ray; logarithm of resistivity; total porosity; total saturation; volume of shale from Neutron-Density); Gassmann fluid substitution to brine conditions; and automated blocking/squaring.

Some specific points to note for this study include:

• Fluid properties (Table 1) were assigned regionally, with oil properties based on typical oils encountered in the Karoon wells.

• Normalizing the gamma ray logs suggests that the shales in the Eocene have a different clay mineralogy. This appears to be supported by cuttings descriptions, where the Eocene shales tend to be described as "light grey" and "amorphous" while the older shales are often described as "dark grey" and "micaceous".

• V_{Shale} was set using a Neutron-Density crossplot with the 'shale line' adjusted for each major stratigraphic unit as a result of the observation made above.

• The final trend crossplots only include brine-saturated points to avoid any dependence on Gassmann fluid substitution given uncertainty in the porosity and saturation evaluation.

For the wells logged using the Sonic Scanner tool, it was necessary to perform editing at calcareous sands and shales in order to improve seismic-well ties. Visual inspection of the raw waveforms confirmed that this new tool produces accurate, high resolution P- and S-wave sonic logs. However, a VSP corridor stack showed a better tie to the seismic data than to a synthetic from which the calcareous intervals had *not* been edited. This suggests that our seismic dataset does not resolve most of the calcareous material.

T Surf °C	T Grad °C/m	Pressure	Salinity ppm	Oil °API	Oil GOR scf/stb	Gas Grav fract
15	0.031	Hydrostatic	75,000	35	500	0.7

Table 1 *– Regional fluid properties.*

An internal petrology study showed that the calcareous content appears mainly in the form of shell debris. Most of the time, these calcareous intervals appear as thin, resistive hard steaks (~1-2m thick) on the logs so they are unlikely to have much lateral extent (according to Walther's law). As a result, they were filtered from the rock physics crossplots (using the logarithm of resistivity and normalized gamma ray auxiliary logs) to derive rock physics trends that correspond to pure sands and shales.

The functional form and fitting parameters of the linked rock physics trends are shown below, starting with the porosity versus Z_{BML} trend formulation (based on Athy, 1930):

$$\varphi = \varphi_0 e^{-kZ_{bml}}$$

The V_P and V_S versus porosity trends are formed indirectly via the bulk (K) and shear (μ) moduli using the Sun rock physics model (Sun, 2004). The Sun rock physics model can be most simply expressed in terms of dry rock moduli, with Gassmann fluid substitution applied as a second step to form saturated rock elastic properties:

$$K_{dry} = K_{grain}(1-\phi)^{\gamma_K} \qquad \gamma_k > 1$$

$$\mu_{dry} = \mu_{grain}(1-\phi)^{\gamma_\mu} \qquad \gamma_\mu > 1$$

$$\rho_{dry} = \rho_{grain}(1-\phi)$$

Frame flexibility factors
(control pore-space stiffness)

Grain properties in the Sun model can be estimated using an effective medium approach to accommodate rocks that are not mono-mineralic. The frame flexibility factors relate to the texture, or internal fabric, of the rock. For the Sun model, they modulate a smooth transition between the Reuss and Voigt bounds, thereby always predicting physically valid rocks. Low frame flexibility values represent stiffer rocks while larger values can be used to model unconsolidated (or unloaded) rocks.

A subtle point with regards to parameter fitting revolves around the estimate of grain density, which is perhaps better regarded as an initial assumption. Parameterization of the Sun model is most naturally done using porosity on the X-axis, however this porosity (unless calibrated to stressed-core porosities) is typically evaluated from the density log using an assumed grain density in the first instance. As a result, this assumed grain density will need to be maintained for the Sun model, even if the estimated grain V_P and V_S values suggest that mineralogy may be quite different to what was assumed during the 'seismic petrophysics' workflow. This minor incongruity in the workflow tends to occur in an exploration setting when core data may be unavailable but quality checking the model against the actual logs (as acquired) will confirm that internally-consistent predictive models have been built, albeit with provisional (and possibly incongruous) grain densities.

Results

The sand trends appeared quite well-behaved after the majority of calcareous sands were filtered from the various trend-fitting crossplots (Figure 2). When compared to global analogues, the porosity-Z_{BML} trend matches typical hydrostatic and lightly-cemented sandstones. The Sun model does an excellent job of modelling both the P- and S-wave velocity data, with frame flexibility factors that suggest that the sands are moderately stiff and so perhaps have some minor cements around the grain contacts. Quartz grain properties were used although the petrology study (mentioned earlier) suggested a mineral mixture that would fall in the center of a QFL Ternary chart.

The shale trends also made more sense after high-resistivity calcareous shales were filtered from the trend-fitting crossplots. The porosity-Z_{BML} crossplot shows two distinct trends when colored by normalized GR and when the Eocene shales are highlighted with a different symbol shape to the other shales (Figure 3). There are several hundred meters of overlap in depth (or temperature) between the trends and points on the "high GR" trend correspond to temperatures as low as 60°C. Both of these observations suggest that shale diagenesis may not be the primary reason for the different trends.

The Sun model was again accurate in modelling the P- and S-wave velocity data for both the Eocene shales and Paleocene to Campanian shales. The grain properties used (Table 2) were taken from published examples of Montmorillonite-rich clays (for the Eocene) and a 60/40 mixture of Illite and Smectite (for the Paleocene to Campanian). XRD data would be helpful here and, once available, it should lead to a revision of the grain properties used along with corresponding adjustments to the frame flexibility factors, which seem quite low for the Eocene shale (when compared to global analogues).

More shale data is needed in order to build predictability beyond the depth ranges of the current dataset. Cuttings taken from some wells indicate color and textural differences between shales above and below the base Eocene. A study from the nearby Campos basin suggests that the classic Smectite-Illite transition may not be as important in offshore Brazil as it is in the Gulf of Mexico (Anjos, 1986). Other studies mentioned earlier pinpoint the cessation of the Serra do Mar uplift (at least onshore) at the start of the Eocene (55 Ma). Upcoming drilling and coring (with XRD analysis) will undoubtedly refine our thoughts on shale mineralogy.

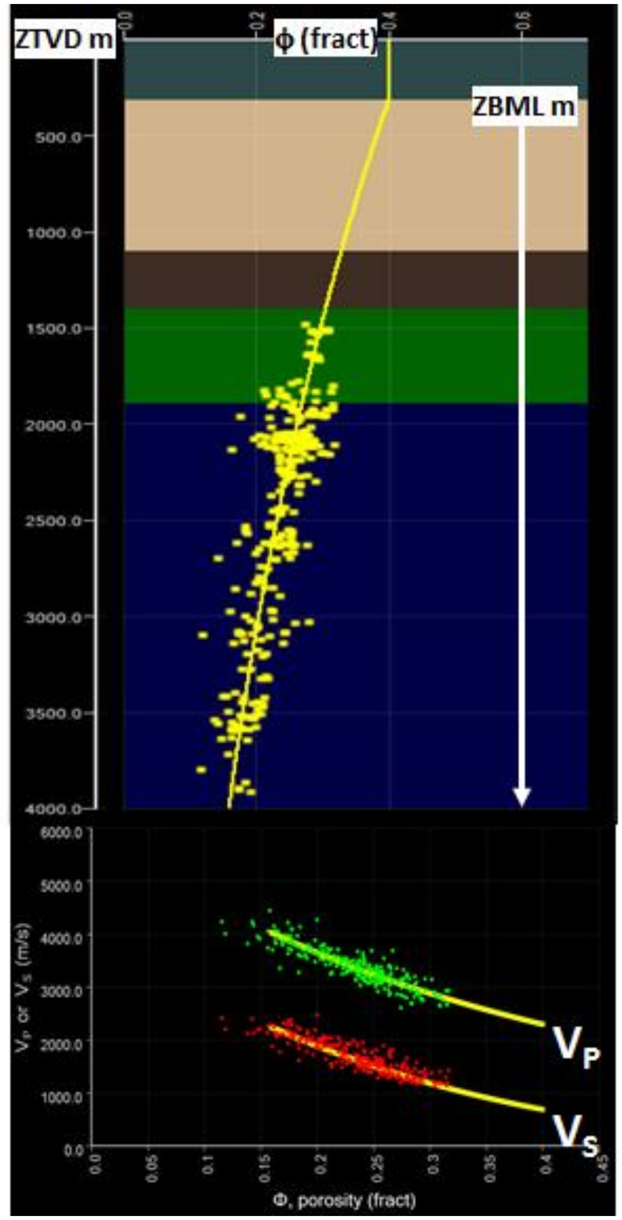

***Figure 2** – Brine sand trend formulation using the Sun rock physics model.*

Separate rock physics templates were created for both shale types using the Lambda-Rho and Mu-Rho attributes (Figure 4). These templates were used to design a depth-independent porefill attribute by de-trending the Lambda-Rho attribute. However, overlap of the shale and oil sand trends noted at some depth ranges highlights the potential for false positive anomalies, especially for the Eocene shale. Derivation of a lithology attribute is more complex because of crossing trends and the need to first allow for hydrocarbon effects.

Despite the caveats above, the depth-independent porefill attribute has provided the clearest images yet of oil sands in known fields. These images show excellent structural conformity where sands exist and in many cases they confirm oil-water contacts that match predictions from pressure data (where it exists).

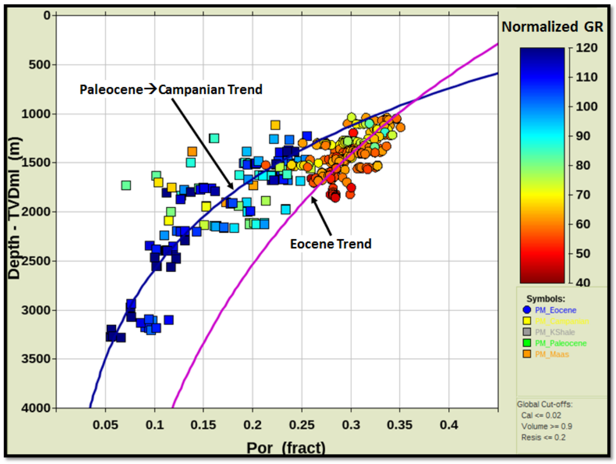

Figure 3 – *Shale porosity burial trend formulation using the Athy model, showing overlap in depth (temperature) and clustering based on formation age.*

These rock physics models play a central role in building an integrated amplitude-based interpretation of our prospects and fields. They underpin attempts to model and calibrate the seismic AvO response at the crest of a proposed target; along the flanks (which may be substantially deeper for steeply-dipping post-salt plays); in the aquifer; and at flatspots.

Lithology	φ_0 fract	k	Grain ρ g/cc	Grain VP m/s	Grain VS m/s	γ_K	γ_μ
Sandstone	0.4	-2.5e-4	2.65	6050	4090	4	7.5
Eocene Shale	0.55	-3.6e-4	2.71	4453	2512	6	5
Pal→Camp Shale	0.7	-7.5e-4	2.71	4904	2688	12	7

Table 2 – *Final rock physics model parameters using a linked trend approach that combines the Athy burial trend for porosity and the Sun rock physics model for P- and S-wave velocities.*

Other applications include the search for gas-caps updip of oil discoveries in conjunction with top seal analysis. In the latter application, the rock physics model can be used to estimate the overburden (confining) pressure. This can be converted into an estimate of the fracture pressure and using a goal-seeking approach the maximum column height can be estimated for a range of porefill scenarios. The rock physics and fluid properties models act to enforce self-consistency between quantitative interpretation results and trap integrity studies.

Conclusions

Well-behaved rock physics trends exist within Cretaceous and Tertiary sequences of the Southern Santos basin. Shale rock properties indicate a clear mineralogy change near the start of the Eocene and the cause is speculated to relate to the cessation of the Serra do Mar uplift. Shale XRD analysis may help to resolve this when core is acquired during upcoming drilling. Rock physics templates were constructed to define depth-independent attributes for highlighting porefill and lithology. The resultant attribute maps have improved the understanding of field sizes and exploration and appraisal targets within our exploration permits.

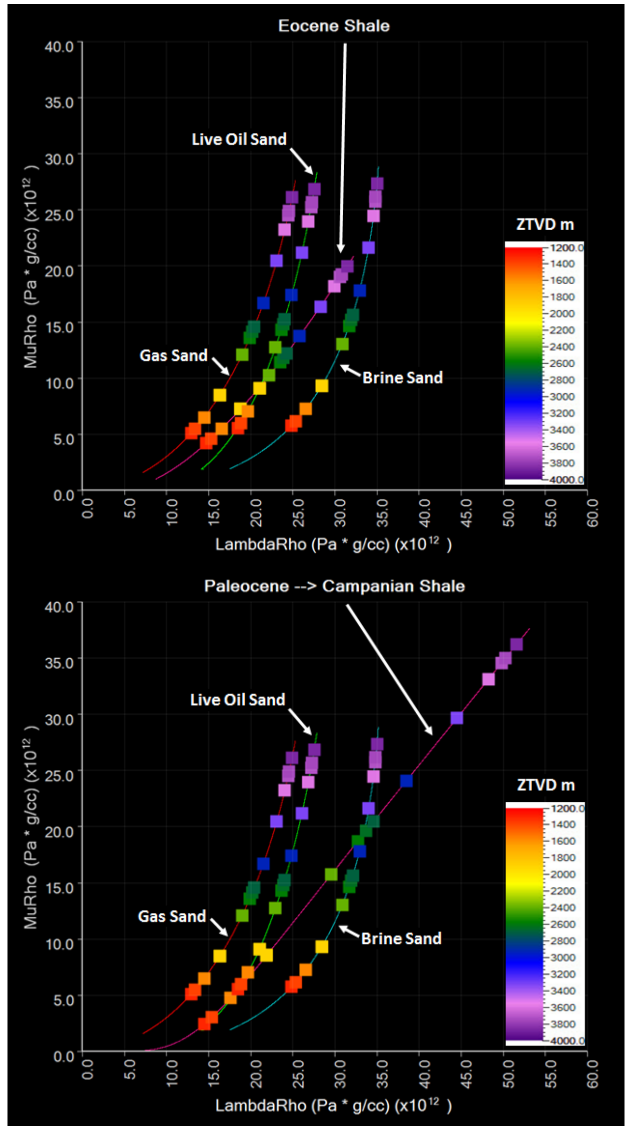

Figure 4 – *Rock physics templates formulated in terms of Lambda-Rho vs Mu-Rho and separated by shale type.*

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