Well log and seismic data analysis using rock physics templates

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Introduction
Rock physics is an integral part of quantitative seismic data analysis and is fundamental for fluid- and lithology-substitution, for AVO modelling, and for interpretation of elastic inversion results. Traditionally, rock physics interpretation of well logs and seismic data has been carried out by rock physics experts. As the demand for more quantitative results increases there is a need for easy-to-use interpretation tools for geoscientists that are not experts in the field of rock physics. In this paper we describe how a broad range of geopracititioners can use intuitive Rock Physics Templates (RPTs) as a toolbox for efficient lithology- and pore fluid interpretation of well log data and elastic inversion results.

Rock physics templates
The well log example presented in Figure 1 illustrates the typical challenges in rock physics interpretation. It shows acoustic impedance (AI)- and Vp/Vs logs for a 100m interval, and the corresponding Vp/Vs vs. AI cross-plot. The logs are colour coded based on the four populations defined in the cross-plot domain, and the cross-plot points are colour coded using the Gamma Ray log (not shown).

Four populations can easily be identified in the log cross-plot domain, and a separate lithology can be attributed to each of the four populations based on additional log information: two different shales, gas sand and brine sand. The cross-plot interpretation would have been much more difficult without the additional log information, and this is typically the case for elastic inversion results. This is where the motivation behind the RPTs comes in. Instead of using additional log data to aid the interpretation, we can use theoretical rock physics trends for the different lithologies expected in the area.

The generation of the RPTs is typically done by rock physics experts familiar with the various rock physics models and theories. When the expert has calculated and compiled a catalogue/atlas of RPTs, the practitioners can select the appropriate RPT(s) for the zone and area of interest, and perform the interpretation of elastic inversion results without in-depth knowledge about rock physics theory. If a compilation of relevant RPTs is available for the area under investigation, the ideal interpretation workflow becomes a fairly simple two-step procedure:

- Use well log data to verify the validity of the selected RPT(s). (If no appropriate RPT exists, the user should provide the rock physicist with local geologic input, so that new RPTs can be created for the area under investigation).
- Use the selected and verified RPT(s) to interpret elastic inversion results.

Figure 1: AI- and Vp/Vs logs (right) and Vp/Vs vs. AI cross-plot (right). The logs are colour-coded based on the populations defined in the cross-plot domain, and the cross-plot points are colour-coded using the Gamma Ray log (not shown). The interpretation is based on all available log data.

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RPT interpretation of well log data may also be an important stand-alone exercise, for interpretation and quality control of well log data, and in order to assess seismic detectability of different fluid and lithology scenarios.

**Rock physics modelling constrained by local geology**

This paper is primarily directed towards seismic interpreters and geo-practitioners; hence this section gives a descriptive summary of the key steps in the modelling behind the RPTs.

The first step in the modelling of RPTs is to calculate velocity-porosity trends for the expected lithologies, for various burial depths, and this requires geological and petrophysical input. Well log data and lab-based rock physics results, if available, are typically used as input to the generation and validation of RPTs. Hertz-Mindlin contact theory (Mindlin, 1949) can be used to calculate the pressure dependency at the high porosity end member. The other end-point is at zero porosity and has the bulk and shear moduli of the solid mineral. These two points in the porosity-moduli plane are connected with a curve given by Hashin-Shtrikman (1963) bounds (bulk and shear moduli) for the mixture of two phases: the original porous phase and the added solid phase. Porosity reduction related to packing and sorting, where smaller grains enter the pore space between larger grains, is modelled by the lower bound. For cemented rocks, we apply the Hashin-Shtrikman upper bound model.

The next step is to calculate the elastic bulk moduli of brine and hydrocarbon saturated rocks. The dry rock properties calculated from the combined Hertz-Mindlin and Hashin-Shtrikman models are used as input into Gassmann’s equations to calculate the saturated rock properties, assuming uniform saturation. From these we can calculate the Vp, Vs and density of brine or gas saturated rocks, and finally the AI and Vp/Vs ratio. AI and Vp/Vs estimates are among the typical outputs from elastic inversion of seismic data, and this is the main reason for presenting the rock physics templates in the Vp/Vs vs. Al cross-plot domain. An example of an RPT is shown in Figure 2. It includes a background shale trend, a brine sand trend, and curves for increasing gas saturation as a function of sand porosity.

Moreover, the RPTs are site (basin) specific and honour local geological factors. Geological constraints on rock physics models include lithology, mineralogy, burial depth, diagenesis, pressure and temperature. All these factors must be considered when generating RPTs for a given basin. In particular, it is essential to include only the expected lithologies and fluid types in the models. The RPTs show end-member velocity trends for various lithologies and fluid saturations, and the models are constrained by depth-related pressure, mineralogy, critical porosity, and fluid properties.

![Figure 2: A rock physics template (RPT) in the Vp/Vs vs. Al cross-plot domain includes rock physics models locally constrained by depth (i.e., pressure), mineralogy, critical porosity, and fluid properties. The template includes porosity trends for different lithologies, and increasing gas saturation for sands (assuming uniform saturation). The black arrows show various geologic trends (conceptually): 1) increasing shaliness, 2) increasing cement volume, 3) increasing porosity, 4) decreasing effective pressure, and 5) increasing gas saturation.](image)
for the area under investigation when generating the rock physics templates. A siliciclastic system will comprise different lithofacies than a carbonate system. In this paper we show examples for siliciclastic environments, hence we expect the following lithologies: shale, shaly sands and clean sands. But even for a siliciclastic system, the mineralogy can be highly variable. The sands can be either quartz-rich (Arenite) or feldspar-rich (Arkose). Quartz and feldspar have very different elastic properties, and this must be considered in the rock physics modelling. Other minerals may also be of significance. Shales are dominated by clay minerals such as smectite, illite, kaolinite or chlorite. Silty particles of quartz and feldspar are also very common in shales. Mavko et al. (1998) list elastic properties of common minerals. The sands modelled in the RPT in Figure 2 represent clean, quartz-rich sands (Arenite), while the shales are assumed to be smectite-rich.

In consequence, the shale trend will typically be basin-specific, whereas the clean brine sand trend will typically have a more general validity.

The water depth and the burial depth determine the effective pressure, pore pressure and lithostatic pressure. The pore pressure is important for the calculation of fluid properties, and to determine the effective stress on the grain contacts of the rock frame carrying the overburden. Porosity reduction associated with rock compaction and diagenesis are directly related to burial depth. At great depths, quartz-rich sands tend to be quartz cemented whereas smectite-rich shales will go through illitization and the release of bound water. Avseth et al., (2001) showed how to calculate expected seismic properties at a given depth, based on local porosity-depth trends for different lithologies. In Figure 2 the effective pressure is 20 MPa. If the pore pressure is hydrostatic, this represents approximately 2 km burial depth.

In the modelling of the RPTs we also need to know the acoustic properties of mud-filtrate, formation water and hydrocarbons in the area of investigation. Required input parameters include temperature, pressure, brine salinity, gas gravity, oil reference density (API), and oil GOR. In areas where hydrocarbons have yet to be encountered, gas gravity can be assumed (normally between 0.6-0.8). However, oil API is more uncertain. Also, the seismic response of oil can be difficult to distinguish from that of brine. Thus, in the templates presented in this paper we consider only gas and brine saturated sands. One should, however, expect oil to show similar values as low gas saturation in AI vs. Vp/Vs ratio cross-plots. Regarding the saturation distribution, we have assumed uniform distribution in the modelling of the templates, which gives the infamous effect where residual amounts of gas will cause almost the same seismic properties as commercial amounts of gas. However, a patchy distribution of gas would have shown a more linear change in seismic properties with increasing gas saturation.

We apply a three-level selection hierarchy to find the appropriate RPT(s) from our pre-computed compilation:  
- Area / basin (i.e. shale trend selection)  
- Pressure regime (i.e. burial depth corrected for possible overpressure)  
- Expected sand reservoir (quartz-rich (Arenite) / feldspar-rich (Arkose) / clean compacted / shaly compacted / quartz-cemented ...)

One should address the most likely geological scenario to be modelled, but alternative pit-fall scenarios should also be considered. Silica ooze and opal A-CT transitions, volcanic tuff, salt intrusions, calcite cement, and shallow overpressure all represent potential pit-falls that are typically not included in the models. However, the RPTs may help discriminate some of these anomalies from hydrocarbon-related anomalies.

**RPT analysis of well log data**

The reliability of RPT interpretations depends on the validity of the lithological trends for the area under investigation. Well log data, if available, should be used to verify the validity and guide the selection of RPTs. If necessary, the seismic interpreter should interact with the rock physicist in order to update or create new RPTs, if no appropriate RPT already exists.

Let us again consider the well-log data in Figure 1. Figure 3 is basically the same cross-plot as in Figure 1, superimposed onto the appropriate RPT. It includes porosity trends for different lithologies. The white shale-trend line represents pure shale while the black sand-trend line represents clean compacted brine filled quartz sand. Increasing gas saturations are included for the clean sands. Note that the two ‘shale’ populations fall exactly on the shale trend, and assuming that the trends are valid for the area, the obvious interpretation is that these two populations represent shales with different mineral compositions.

![Figure 3: Vp/Vs vs. AI cross-plot, with theoretical rock physics trends for pure shale and clean compacted brine filled quartz sand superimposed. The trends are plotted as functions of total porosities. The effects of different gas saturations are added below the brine sand trend. The colour coding is the same as in Figure 1.](image-url)
total porosities. The ‘brine sand’ population sits just above the theoretical brine sand trend, and again assuming that the trends are valid for the area, the interpretation is that the brine sand is slightly shaly. The ‘gas sand’ population plots well below brine sand trend and roughly along the dotted lines indicating the effects of increasing gas saturation. For the ‘gas sand’ population it is possible to estimate the corresponding clean brine sand porosities, but little can be inferred about the shaliness of the gas sand (but this is a fundamental limitation in seismic data analysis).

Figure 4 shows examples of RPTs for different types of sands. The upper plot represents unconsolidated clean sand, whereas the lower one represents cemented sandstone. For the unconsolidated sands we observe that the Vp/Vs ratio drops dramatically with just a little increase in gas saturation, whereas the acoustic impedance drops more moderately. For the cemented sandstones, which have a stiffer rock frame, there is a much smaller fluid sensitivity. The Vp/Vs ratio shows a very little decrease with increasing gas saturation. However, the acoustic impedance still shows a marked decrease due to the density effect of the gas.

Log data for two different wells from offshore West Africa have been superimposed onto the templates in Figure 4. The logs represent the same Oligocene interval, but different burial depths; one well penetrated the Oligocene with approximately 1200 m overburden (top RPT in Figure 4), the other with approximately 2400 m overburden (bottom RPT in Figure 4). Hence, the sands and shales in the second well have been compacted more than in the first well, and the sands in the second well are cemented whereas the sands in the first well are unconsolidated. Quartz cementation tends to occur at temperatures exceeding approximately 80 °C, corresponding to burial depths of about 1.5-2 km. The sands in first well (top RPT in Figure 4) show a much bigger fluid response than in the second well (bottom RPT in Figure 4), even though the sands are from the same stratigraphic level. This illustrates the value of the RPTs. Even for the same basin, and the same stratigraphic level, different rock physics models will apply for different burial depths. Moreover, the RPTs indicate that the expected seismic response of hydrocarbon-saturated sands will be different at the two wells.

For the shallow sands in the first well, we expect an AVO Class II for oil-saturated sands, whereas the gas sands will be Class III. For the deeper, cemented sands in the second well, the oil sands will be predominantly AVO Class I, whereas gas sands will be AVO Class II. Hence, the AVO response of hydrocarbons will be different at the two locations because of local diagenetic changes. This example of RPT analysis confirms how rock physics depth trends must be taken into account during AVO analysis (c.f., Avseth et al., 2003).

Interpretation of elastic inversion results

Below is an example of the full workflow of RPT selection using well log cross-plot analysis followed by rock physics interpretation of elastic inversion results using the selected template. Figure 5 illustrates the template verification step. The log interpretation is partially based on additional log data, and the AI and Vp/Vs logs have been colour-coded according to the zones defined in the AI vs. Vp/Vs log cross-plot. The red zone includes two different shales, and the yellow zone contains a shaly sand (or silty shale). The chalk constitutes a small and clearly separate cluster in the high AI zone (violet). The points representing oil and brine sand sit inside the blue and green zones respectively, but note that the oil-water contact appears to coincide with an apparent change in lithology. The brine sand has higher AI-values than the oil sand, as expected, but lower Vp/Vs-values, which is the opposite of the expected change. The interpretation is that the sand below the oil-water contact is slightly cemented and/or denser packed. The log data match the theoretical trends fairly well. The oil in this example is fairly heavy (19° API) and a large deviation from the brine sand trend is not expected. Assuming that the selected rock physics template is
valid for this area, the oil sand appears to have about 22-25% porosity, and the brine sand 17-21% porosity.

A small set of 3D elastic inversion data exist around this well. Figure 6 shows the estimated AI and Vp/Vs results for a selected line in a 100ms time window. The selected time window corresponds roughly to the depth range cross-plotted in Figure 5, for which the selected RPT is assumed to be valid. The Vp/Vs vs. AI cross-plot of these data is shown in Figure 7, with the selected RPT superimposed.

We do not see the same well-defined clustering of points...
as for the log cross-plotting, which must be attributed to the lower depth resolution in the seismic data. But still the rock physics interpretation of Figure 7 appears to be straightforward. The population that sits along the theoretical shale trend is interpreted to represent shale. Note that the shale points appear to move closer to the sand trend for the highest AI values. This could reflect shales becoming increasingly more silty, and the points between the shale and brine sand trends are interpreted to be silty shales and/or shaly sand. The points close to the theoretical brine sand trend most likely represent clean sand. We do not expect to see a clear oil sand response, as the oil is fairly heavy in this case (19° API), but some of the data that plot significantly below the brine sand trend may be attributed to oil saturation. The sand appears to have total porosities in the range 22-28%.

Furthermore, we have found RPTs very useful for quality control of elastic inversion results, and RPT-cross-plotting has become an important tool for optimizing the elastic inversion parameters.

**Direct classification using rock physics templates**

RPTs can be used for direct and automated classification of AI and Vp/Vs data into porosities and clay-/gas-factor, by transforming each pair of AI and Vp/Vs data into a pair of porosity and clay-/gas-factor, according to how the data plot on the selected template. Figure 8 shows the results of this type of automated direct classification of the logs in Figure 1, using the RPT in Figure 3. The clay/gas factor is simply the normalized deviation from the theoretical brine sand trend, so that the clay/gas factor is exactly 0.0 along the brine sand trend, exactly +1.0 along the theoretical shale trend, and exactly –1.0 along the gas sand trend (e.g. 30% gas saturation). Deviations above the brine sand trend will have positive values, and we call this the ‘clay factor’. Deviation below the brine sand trend will have negative values and be called ‘gas factor’. The porosity classification will be based on the porosities of the shale, brine sand and gas sand trends and normalized by the deviation of a point from these three trends. In Figure 8, ‘Shale B’ has lower porosities than ‘Shale A’, but the clay-factor values are around 1.0 since both shales plot on the theoretical shale trend. The gas sand has gas-factor values around –0.7, plotting somewhat above the theoretical gas sand trend. The brine sand is slightly shaly and has clay-factor values slightly above 0.0. Note that the porosities for the gas sand appear to be slightly higher than for the (slightly shaly) brine sand. This is because the classification of the gas sand is related to the theoretical clean brine sand trend, and possible shaliness is not taken into account. The validity of the RPT classification is directly related to the validity of the selected RPT.

![Figure 7: Vp/Vs vs. AI cross-plot of the elastic inversion results shown in Figure 6, with the selected rock physics template superimposed. A rough interpretation is indicated.](image-url)
Conclusions

Rock physics templates (RPT) provide geoscientists with an easy-to-use ‘tool-box’ for lithology and pore fluid interpretation of sonic log data and elastic inversion results. The RPT technology includes two steps: 1) The first step is to calibrate and validate rock physics models to local geology using sonic and density well log data, by selecting the appropriate RPT that gives the best match with well log data while honouring local geologic constraints. The RPT can be taken from an existing catalogue or atlas, or one can create a new, updated RPT for the area or zone under investigation. 2) The second step is to apply the appropriate RPT to seismic data, more specifically elastic inversion results, and interpret/classify the observed trends and characteristic populations in the data. RPT analysis of well log data may also be an important stand-alone exercise, both for petrophysical interpretation and quality control of well log data, as well as assessment of seismic detectability of lithologies and fluids.

However, the templates must be used with care, and the reliability of the information extracted depends on the quality of the input data and the model assumptions. RPTs may not always be 100% valid, but can in most cases be used for enhanced qualitative interpretation of well log and seismic data. Moreover, one should be aware of potential scale effects distorting the similarities between well log data and seismic data. Nevertheless, the rock physics templates provide a very useful interpretation tool that can improve communication between geologists and geophysicists and can help reduce risk in seismic exploration and prospect evaluation.

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References


