Rockphysics: Applications for Reservoir Studies

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Summary

Knowledge about porosity and permeability is essential to evaluate fluid content, fluid flow and recovery rates in a formation. Information about subsurface formations is generally gathered at different scales, which vary in resolution, spatial coverage, and number of parameters measured. There is a need to up- or downscale to increase reliability of prediction.

This paper shows applications of rock physics data to calibrate observations made in the field. I first present current state of the art in the discipline and then show many various possible applications to understanding reservoir properties.

Introduction

In seismic exploration, the data gathered at a seismic and well-logs scale consists mainly of velocity, impedance, resistivity, porosity, shale volume. However, the major requirements for successful recovery are measuring, monitoring, and verifying the efficiency and risks of reservoir production at in situ conditions. Since directly measured in situ physical properties rocks are not always available, seismic measurements are our principal source of information for reservoir properties. Seismic surveys can give us data on structures, velocity, and impedance. In recent times, these seismic measurements have proven to be powerful tools in reservoir management. Remotely measured changes in seismic attributes are used to map and identify bypassed oil and gas and to quantify saturations in various reservoir rocks. Although we can use well logs to obtain information on velocity, impedance, resistivity, porosity, and volume of shale, for complete reservoir characterization, we require information on the porosity and permeability distributions as well as lithology, depositional environment, and in situ stresses in the reservoir. Thus, the success of the time-lapse seismic methods has depended largely on laboratory-derived relations between seismic attributes and fluid saturations. In this paper, I will show the applicability of rock physics and experimental geophysics to reservoir characterization, monitoring and verification studies.

In this paper, I shall discuss rock physics allows us to understand empirical and theoretical trends based on experiments on rocks in controlled environments, calibrate seismic response using experimental data, and show the different petrophysical controls on seismic properties in sediments and rocks, for example, porosity, permeability, cementation, pore-filling, saturation, and compaction. I will also show how the rock physics analyses can be implements to diagnose unknown data sets, calibrate well log data, for pressure prediction, and for modeling response of clay-sand mixtures.

Major rock physics trends

Velocity - porosity variations

The porosity - velocity relation for rocks can be divided into two domains: one in which the rock has a stiff matrix that acts as the load-bearing part. The second domain is where the rock particles are suspended in a fluid and the fluid is the load-bearing part. Nur et al. (1995) have defined this transition from fluid-supported suspension to matrix-supported rock as the critical porosity. Figure 1 shows the range of data on velocity - porosity relations below critical porosity and the additional controls that define the wide range velocity can have for any single porosity.

Below the critical porosity, the largest variation in velocity in rocks can be described by porosity variations. In the simplest case, the upper and lower Hashin-Shtrikman (Hashin and Shtrikman, 1963) model can be used to put bounds on velocity in a binary system. These bounds describe velocity variations between two end-points, one where the velocity is that of one mineral phase and the other where velocity is that of the second mineral phase or the pore fluid. The lower bound describes the softest arrangement with the softer phase (or pore fluid) being load-bearing and the upper bound describes the stiffest arrangement with the stiffer phase being load-bearing. The actual arrangement of the two components can lie between these two extremes. The Hashin-Shtrikman model can help to conceptually explain and model the data scatter seen in Figure 1. A sub-set of the data from

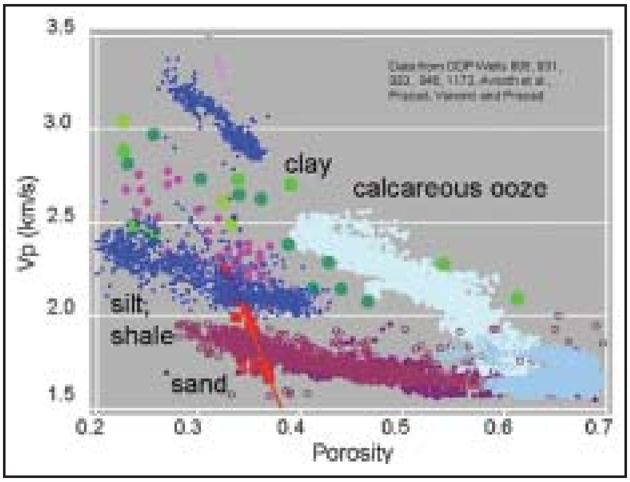

Fig. 1: Velocity - porosity relations in various revervoir rocks. The critical porosity of a quartz sand system is marked by the red line (from Prasad, 2002a).

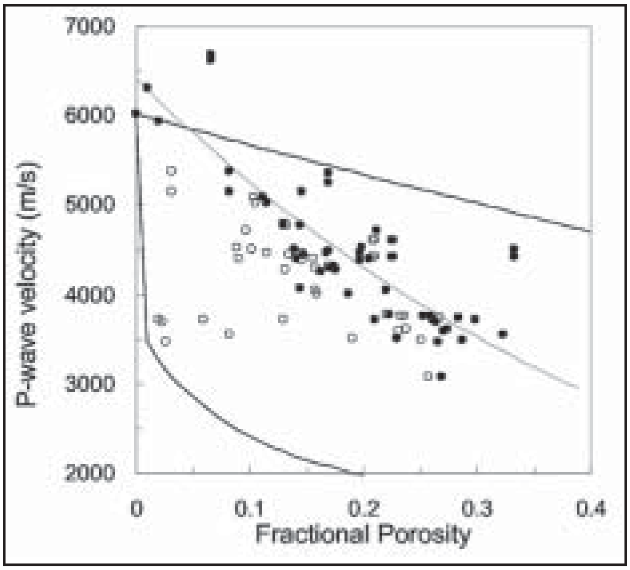

Fig.2: Velocity - porosity relation. Open symbols denote measured porosity, solid symbols represent modified porosity. The solid gray line is an exponential fit through the solid symbols. The solid black lines are the Hashin-Shtrikman upper and lower bounds calculated for a quartz - water system. Note that some points lie above the upper bound, because they are either pure carbonates or they contain significant amounts of calcite and or dolomite (from Prasad, 2003).

Figure 1 is shown in Figure 2 bounded by the Hashin-Shtrikman model plotted as solid black lines.

Velocity - clay variations

The simple velocity - porosity relation is further complicated by presence of clay minerals that alter the elastic and plastic behavior of rocks significantly. Thus, a large part of the scatter observed in Figure 1 is due to presence of clay in the rocks. Figure 2 show how velocities are reduced in clay-rich sandstones when the clay is load-bearing (Tosaya, 1982; Han et al., 1986). Using acoustic microscopy images of sandstones, Prasad (2002b) has shown that the clay in contact zones has significantly lower impedance than the quartz it cements.

Galmudi et al. (1998) introduced the concept of modified porosity to describe the velocity scatter due to presence of clay. Modified porosity accounts for the observation that the measured porosity in clay-rich rocks is lower than total porosity, because unconnected pore space in clay minerals is usually underestimated. Galmudi et al. (1998) suggest that the clay porosity (porosity of clay, 0.6, factorized by the clay content) should be added to the measured rock porosity. In Figure 2, the open circles are plotted for measured porosity, while the closed circles are plotted for modified porosity. The solid lines are the Hashin-Shtrikman upper and lower bounds and the gray line is an exponential fit through the data.

The variation in velocity with clay content can be used to diagnose data in unknown formations as shown in Figure 3. Here, the velocity - porosity data from Han et al. (1986) is plotted as a function of clay content. By superimposing the unknown data on this calibration data set, we can assess the amount of clay in the unknown formation.

Avseth (2000) has shown, however, that within a single lithology, velocity depends not only on the cement type but also on its location. Thus pore filling will reduce

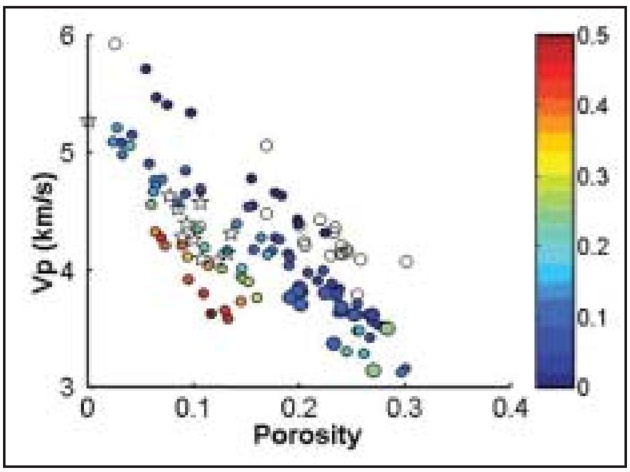

Fig. 3: Velocity - porosity relation with varying clay content given by the color coding on the right. Open symbols mark unknown data. At same porosity, higher clay content (warmer colors) reduces the velocity.

porosity and not effect velocity much, contact cement will increase velocity and not reduce porosity much (Figure 4 from Avseth, 2000).

Basin analysis models

Once the basic relations between seismic and petrophysical properties are understood, we can use them to build realistic and reliable basin models that would honor the observed seismic signatures. In doing so, we need to first develop site-specific trends and understand the possible causes for variations in seismic signatures. The site-specific trends can be used for inversions and for interpretations as shown here.

Developing Site-Specific Velocity - Porosity Trends: In addition to understanding the scatter in velocity - porosity plots, the data can be used to develop site specific velocity - porosity relation. For example, Mantilla (2001) has shown that the empirical relations derived from ultrasonic data can be used to invert for porosity (Figure 5). They predict porosity using seismic impedance as soft data and well log and cores data as hard data. By using this approach they mapped permeability-controlling deposition features based on seismic.

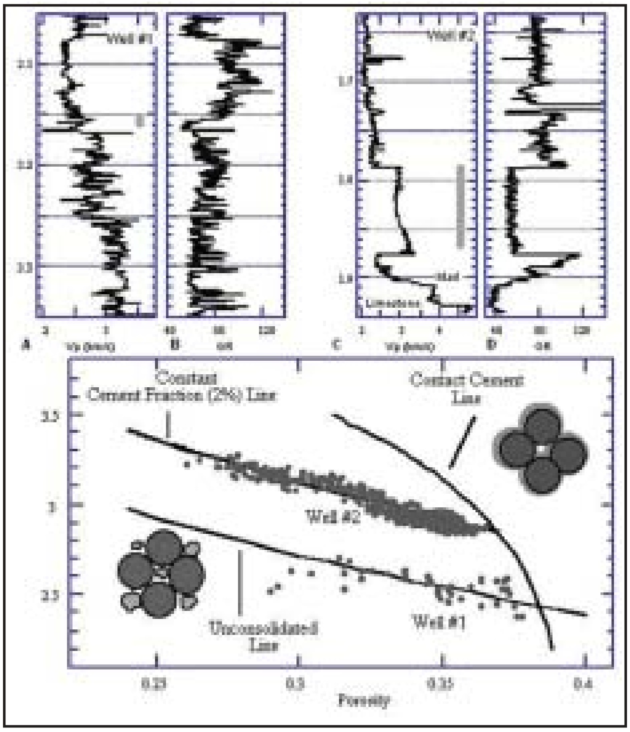

Fig. 4 Top: Vp and Gamma Ray (GR) response at two different sites from well logs. Bottom: Velocity - porosity relation showing that at well #1, the cement exists as pore filling whereas at well #1, the cement acts to stiffen the matrix (from Avseth, 2000).

Developing Site-Specific Velocity - Pressure Trends: As rocks are buried they undergo compaction and cementation. This effect can be understood from Figure 6, which shows the increase in velocity with pressure in sandstones. There is a difference in rate of increase in velocity in horizontal and in vertical directions for the different samples. In some cases, a large velocity anisotropy at low pressure decreases to near zero at 25 MPa. In other samples, e.g., samples 10, 11, and 19, velocity anisotropy remains high even at pressures of 25 MPa.

In most samples, rate of change of Vp is greater at low pressures (up to 15 MPa); at high pressures, Vp changes only slightly. The different behavior of Vp gives an indication of the type of pores in the samples. A steep increase in Vp at low pressures is indicative of the closing microcracks or pores with large aspect ratios (Wepfer and Christensen, 1990).

Velocity - permeability variations

Relationships between seismic velocity and permeability have been difficult to establish. Using a collection of velocity, porosity, and permeability data, Prasad (2003) has shown that, by grouping them in different hydraulic units based on pore space properties, a positive correlation between velocity and permeability can be established (Figure 7). The pore space parameters, grouped together as Flow Zone Indicator (FZI) values, are calculated from measured values of porosity and permeability. Velocity modeled with the Biot theory, by using FZI values for pore space properties agrees well with measured data. Thus, by defining hydraulic units for a specific site, flow properties can be controlled and predicted. Prasad (2003) showed velocity - permeability relation and modeling results for a large data set of laboratory measurements. The good match between calculated and measured data shows that this relation can be used to predict permeability from velocity in well logs by zoning the data from training wells into hydraulic units. One possible application is shown where, by using site-specific data, the velocity - permeability relation is vastly improved with a correlation coefficient, R2 of 0.9.

Basin models

Rockphysics relations are extremely useful to derive geologically and geophysically meaningful basin models. If

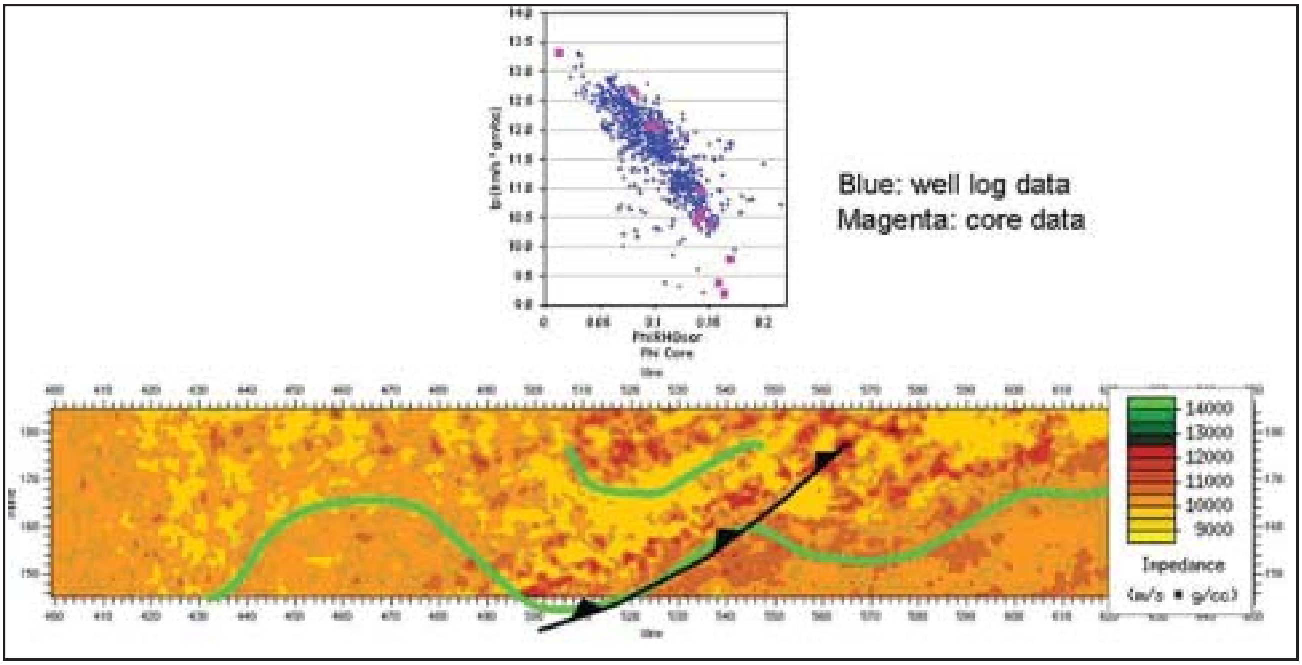

Fig. 5 : Top: P-wave impedance - porosity relation from well logs (blue) and cores (magenta). The good match between impedance and porosity allowed mapping the seismic data to porosity variations (bottom).

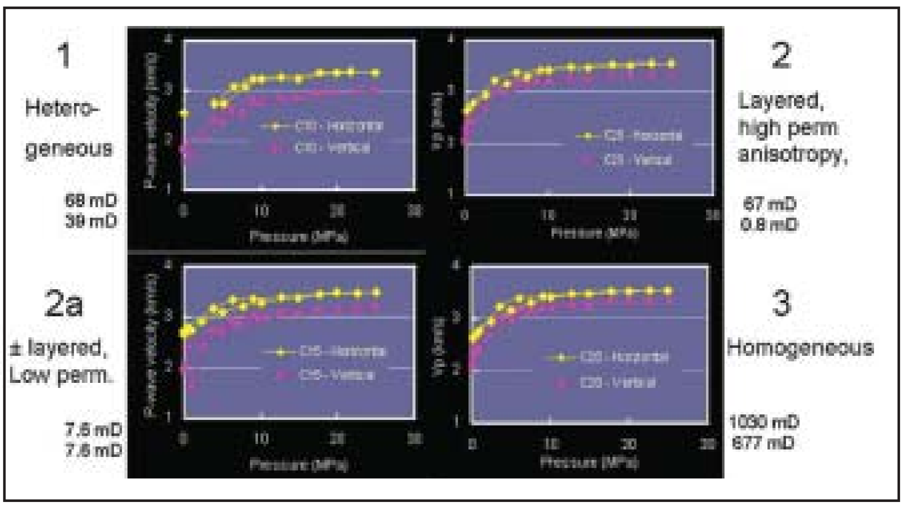

Fig. 6: P-wave velocity - pressure trends for various sandstones measured in two directions. The velocity and velocity anisotropy - pressure relations depends on the texture and pore space.

we take the porosity - permeability - velocity relations shown in Figure 7, we can build reasonable models of the depth - physical property trends that would honor the different events in the basin history.

Consider for example, a marine sediment with a "normal" compaction trend, as shown in Figure 8. Depending on the depositional environment, the sediment will have a certain velocity and porosity. The corresponding velocity - permeability trend is governed by the geometric distributions of the pore space at the time of deposition. As it undergoes burial, this sediment compacts and porosity decreases and velocity increases along lines A-B in Figure 8. We do not expect the corresponding FZI to change and so, velocity change with depth can be used as analogs for a permeability change. However, if the sediment experiences a pore-filling event (point C), then porosity will decrease considerably without much change in velocity (line C-C').

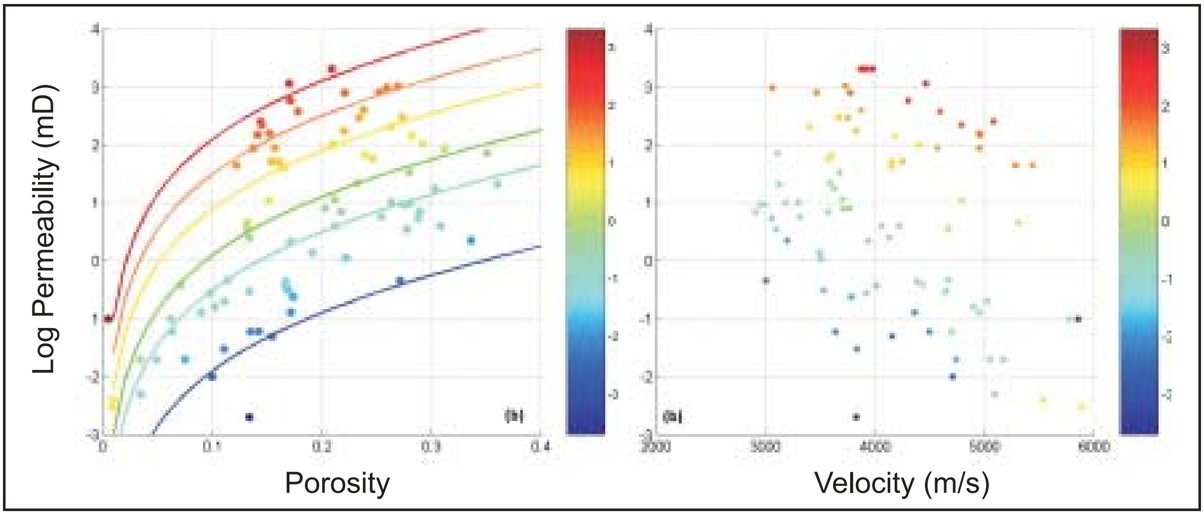

Fig. 7: Porosity - log permeability (left) and velocity - log permeability (right) relations within FZI intervals marked by different colors. The legend on the right gives the binning criteria for the hydraulic intervals. Clear relations can be observed between porosity, velocity, and permeability within narrow FZI intervals. The solid lines mark permeability calculated from using different FZI values marked by colors (fom Prasad, 2003)

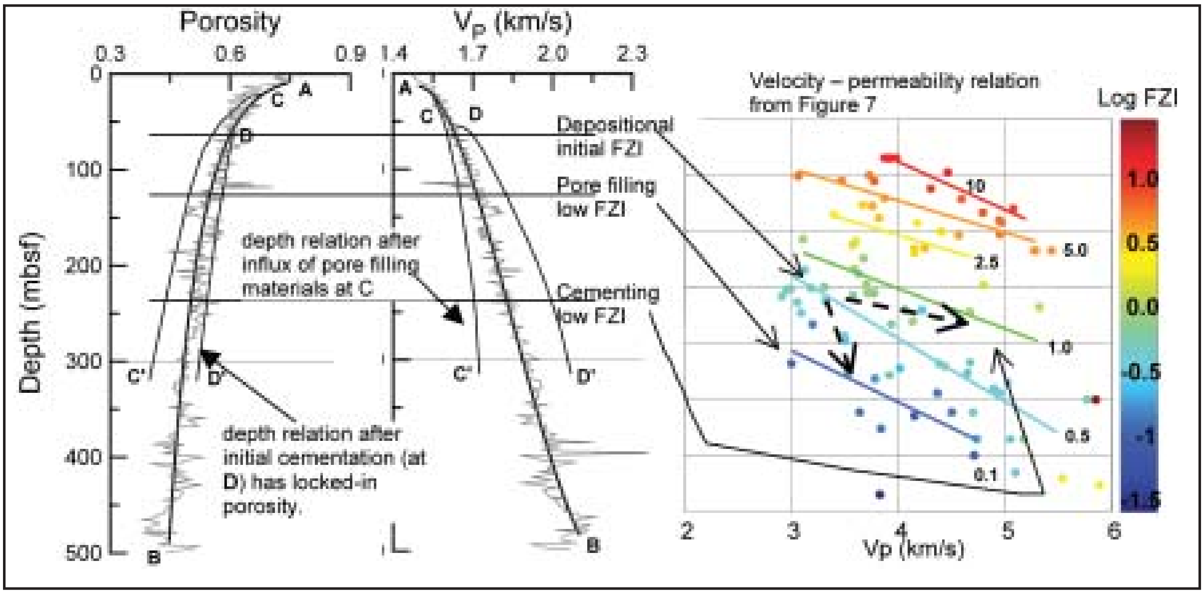

Fig. 8: Left: Depth trends for porosity and velocity from well logs. The curved line represents measured data, solid lines (A-B) are best-fit regression lines. C-C' represents the change in porosity and velocity due to a pore-filling event and D-D' represents the trend for a cementation event. Right: FZI plots corresponding to each environment. Thus, the initial velocity - permeability relation lies along the cyan line (FZI=0.5). At the depths shown by horizontal lines, the pore filling event moves the relation to FZI=0.1 and a cementing event moves it to FZI=1.0.

Correspondingly, we will see a reduction in FZI and the velocity - permeability trend will be different. On the other hand, in case of a cementation event (point D), velocity will increase considerably but porosity will not decrease much. The FZI will change again and we can expect higher permeability values.

Acknowledgements

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