

Investigation of core data reliability to support time-lapse interpretation in Campos Basin, Brazil

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Summary

A comparison between laboratory experiments and log measurements was done to investigate the effect of core damage on compressional wave velocities. This was done using 43 rock samples extracted from a 45 meters thick turbidite reservoir. We used Gassmann fluid substitution to obtain low-frequency saturated velocities from dry core measurements (thus mitigating the dispersion effects) taken at reservoir pressure. To mitigate the scale effect (or under-representation of reservoir properties by a number of small cores), we apply a correction for small mismatch between the core and log porosities. Comparison of these computed velocities with the sonic log measurements shows very good agreement. This confirms that for this particular portion of the reservoir the effect of core damage on ultrasonic measurements is below the measurement error. The results suggest that stress sensitivity of elastic properties as obtained from ultrasonic measurements is adequate for quantitative interpretation of time-lapse seismic data.

Introduction

Quantitative interpretation of time-lapse seismic data requires an understanding of how seismic velocities are affected by changes in reservoir properties, in particular by changes in fluid saturation and pressure. Effect of fluid saturation is usually adequately modeled using Gassmann's equations. There is no such simple methodology for modeling the effect of pressure. Instead, the influence of pressure changes on seismic velocities is usually estimated from laboratory measurements of elastic wave velocities on core samples.

The validity of this methodology is limited by a number of factors:

- Under-representation: Core samples are small and core extraction is usually extremely sparse compared to the volume of rock sampled by seismic waves. Furthermore, cores are more easily taken from well consolidated intervals, while more friable samples fall apart. Thus core samples may not be representative of the entire formation interval.
- Dispersion: Core measurements are usually performed at ultrasonic frequencies (0.25-1 MHz) and may not be representative of the properties at seismic frequencies (10-100 Hz) due to dispersion (variation of elastic wave velocity with frequency).
- Core damage: Cores may be irreversibly damaged during the drilling and extraction processes.

Specifically, these processes can induce the creation of cracks which will increase the stress sensitivity of the cores as compared to the intact formation (Holt *et al.*, 2000, 2005).

In order to assess the adequacy of the core sample measurements to the properties of the intact reservoir rocks, it is necessary to compare them to *in situ* measurements. The most reliable *in situ* measurements of elastic properties of rocks are provided by the sonic log. The aim of this paper is to assess the adequacy of ultrasonic measurements on core samples by comparing measured ultrasonic velocities at reservoir pressures with sonic log data from a well in an oil field in Campos Basin, offshore Brazil.

The well was chosen because of an unusually large number of core sample measurements: 43 samples of sandstone were available from 45 meters of the turbidite reservoir, providing a relatively good representation of reservoir properties. The under-representation is further mitigated by applying a correction for porosity mismatch between log and core measurements.

In order to mitigate the effect of dispersion we use only dry measurements (as in dry rock the dispersion is usually small). Gassmann equation is then applied to compute the properties of the saturated samples (Nes *et al.*, 2002), which is expected to give the static limit of the elastic properties. By using dry measurements we avoid the errors associated with the dispersion between sonic and ultrasonic frequencies. Still, the difference may occur due to dispersion between low-frequency (Gassmann) velocities and sonic log velocities measured at KHz frequency range.

By mitigating the effects of under-representation and dispersion we can focus on the effect of core damage. To assess the magnitude of this effect, we compare the saturated low frequency elastic wave velocities at reservoir conditions (computed from the laboratory measurements) with sonic log data recorded in the well.

Field Description

The well logs and cores analyzed were obtained in the south portion of Campos Basin, around 100Km off the coast of Rio de Janeiro (southeastern Brazil), in a water depth of approximately 700 meters. In this basin there are more than 40 oil fields from different ages, representing a mosaic of reservoir properties. Each field and each reservoir has its own characteristics in terms of lithology, grain size, and cementation. In deep and ultra-deep water projects, it is important to avoid costly workovers;

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therefore programs of pressure maintenance are frequently used (Bruhn *et al.*, 2003). Close to the water injector wells pore pressure can significantly increase, whereas in other positions it could decrease due to depletion, resulting in higher effective pressure. Considering the vast range of reservoir properties and the lateral variation of effective pressure within the reservoir, local and specific petrophysical studies should be done to guide 4D interpretations.

The reservoir is comprised of gravel to sand rich lobes from confined turbidities related to a Cretaceous Period (Santonian / Campanian) marine transgressive megasequence. Figure 1 shows a representative thin section of the reservoir rock which can be classified as arkosic sandstone. This 45 meters reservoir is comprised by the amalgamation of 6 turbidites events with thickness from 2.5 to 14.5 each and grains size from sand conglomerate in the base to medium / coarse sandstone in to the top.

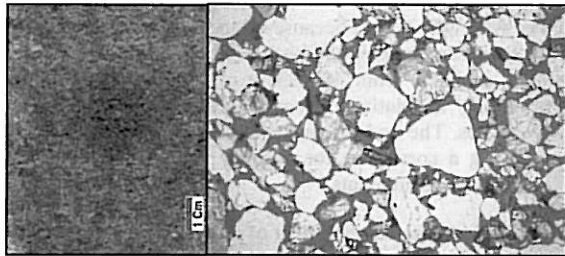


Figure 1 (courtesy of H.E. Voelcker and M.P. Franco, Petrobras) - Coarse sandstone representative of confined turbidities present in this field in Campos Basin. In the left: core; in the right: thin representative section from the analyzed reservoir showing mineralogical composition (quartz 39.5%; feldspar 25.5%; rock fragments 10.5%; other minerals (biotite/granade) 1.5%; cement 0.5%; and porosity 22.5%.

After the discovery in 1984, oil production started in 1985 and the reservoir has been depleted by natural water aquifer and water injection. There are 25 wells producing 29 API oil, permeability is 1500mD and temperature 89°C. The current and forecast recovery factors are 38 and 55%, respectively, and reservoir monitoring is important to locate unswept areas. The reservoir pressure (pore pressure) was initially close to 3700 psi and the average oil saturation in the interval under investigation is 90%.

Methodology

a) Logs and core measurements

Gamma ray, saturation, sonic (velocity), porosity, density, resistivity and caliper logs were used to characterize the reservoir zone (Figure 2).

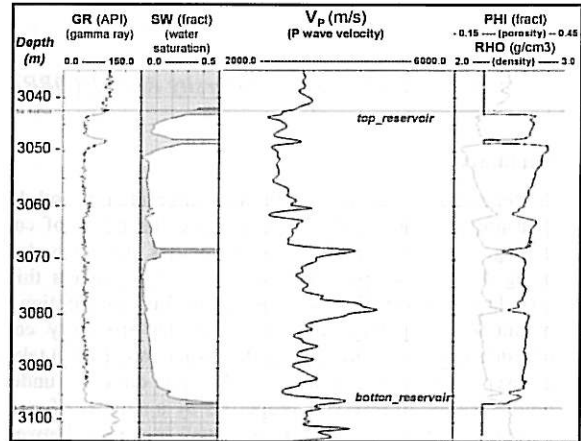


Figure 2 - Gamma ray (a), water saturation, P-wave velocity, porosity and density from the studied well.

Cores were extracted continuously from 49.5 meters of rocks in and close to the reservoir zone. Core measurements were obtained positioning samples between 2 pairs of piezoelectric transducers (for P and S-waves), and all together were immersed in a pressure chamber with hydraulic oil (Figure 3).

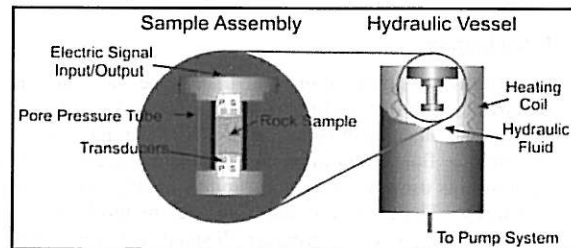


Figure 3 - Measurement system device (courtesy of Vasquez, G.F., I.A. Simoes Filho, C.H.L. Bruhn and L.D. Dillon, Petrobras).

The effective pressure was increased up to 6000 psi with steps of 500 psi from 500 up to 3000, then with steps of 1000. A sinusoidal pulse with the frequency range 250-500 KHz was propagated through and for each step of pressure increment velocities were determined from the travel time and the length of each sample (courtesy of J.E. Lira, A. Sobrinho and J. Pinheiro, Petrobras).

b) Reservoir's effective pressure estimation

To estimate the effective pressure (P_{effec}) at the reservoir we used the following equation:

$$P_{effec} = P_{over} - P_{por}, \quad (1)$$

where P_{por} is the pore pressure and P_{over} is the overburden pressure calculated as

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$$P_{over} = Ah_w + B(h_r - h_w), \quad (2)$$

where A and B are ocean water and lithostatic pressure gradients; h_w and h_r are water and reservoir depths, respectively.

Pore pressure was obtained from well (RFT) measurements which were made at the time when logs were acquired, and provided constant values over the reservoir interval. The resulting value of effective pressure was 5000 psi for the interval under investigation.

c) Calculation of elastic modulus

Once the laboratory measurements were made on dry cores, the saturated bulk modulus K_{sat} was computed using Gassmann equation:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{min}}\right)^2}{\frac{\phi}{K_{fluid}} + \frac{1 - \phi}{K_{min}} - \frac{K_{dry}}{(K_{min})^2}}, \quad (3)$$

where

$$K_{dry} = \rho_{dry} \left(V_{Pdry}^2 - 4V_{Sdry}^2 / 3 \right) \quad (4)$$

is the bulk modulus of the dry rock, K_{min} is effective modulus of the solid grains, K_{fluid} is effective modulus of the saturating fluid, V_{Pdry} and V_{Sdry} are the compressional and shear wave velocities measured in dry sample, ϕ is the porosity and ρ_{dry} is the density of the dry sample.

As a saturation log was available, it was taken into account to calculate the fluid bulk modulus using Wood equation:

$$\frac{1}{K_{fluid}} = \frac{1 - S_w}{K_o} + \frac{S_w}{K_w}, \quad (5)$$

where S_w is water saturation, K_o and K_w are the bulk moduli of the oil and water phases. Finally, the saturated compressional velocity $V_{P,sat}$ was obtained using the equation

$$V_{P,sat} = \left(\frac{K_{sat} + \frac{4}{3}G}{\rho_{sat}} \right)^{1/2}, \quad (6)$$

where $G = V_S^2 \rho_{dry}$, is the shear modulus of the rock, $\rho_{fluid} = S_w \rho_w + S_o \rho_o$ is the composite fluid density and $\rho_{sat} = \rho_{fluid} \phi + \rho_{dry}$ the density of the saturated rock.

According to Mavko (1995) and Winkler (1986), the dry rocks generally have little or no velocity dispersion, at least relative to the large dispersion that occurs when pore

liquids are introduced. Therefore the velocities computed from dry measurements using Gassmann equations can approximately be considered as measured in the low frequency (quasi-static) limit.

As a result of this calculation, elastic moduli and saturated velocities were obtained for 43 samples for each effective pressure step (500 to 6000 psi). As an example, Figure 4 shows the dependency of velocities on effective pressure for 6 samples. To compare with log measurements, we selected velocities corresponding to the estimated effective pressure present *in situ* (5000 psi).

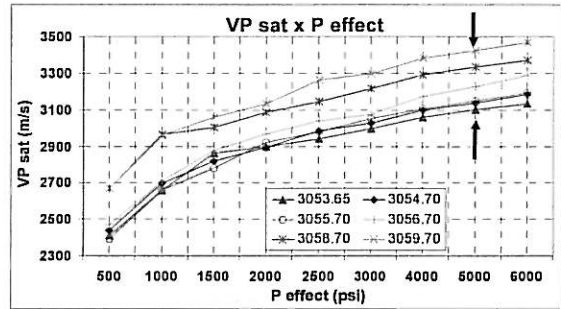


Figure 4 - Velocity dependence in effective pressure for samples (cores) in different depths.

d) Quality control and selection of subset

Considering the large number of cores available, it was possible to discard some samples deemed to be non-representative of the reservoir properties. As can be seen in Figure 5, the reservoir interval contains a few low-porosity zones which are related to the presence of concretions containing large amounts of calcite cement either as small balls or levels. These concretions usually form very thin layers which are under-sampled (smoothed over) by both porosity and sonic logs. At the same time, core samples can be taken both from concretions and from surrounding reservoir rock. In both cases this may result in large discrepancy between log and core porosities.

Therefore the porosity criterion was primarily used to discard the samples where the difference between the porosity measurement in cores and the neutron porosity log was greater than 3%. Figure 5 shows both measurements of porosity as well as the discarded samples (in gray). We also removed a few samples around these heterogeneous zones, even where porosity match was good, as porosity and sonic logs may have different vertical resolution and/or penetration depth.

From the original dataset of 43 we retain 27 samples which were considered representative of the reservoir sandstone and potentially comparable with log measurements.

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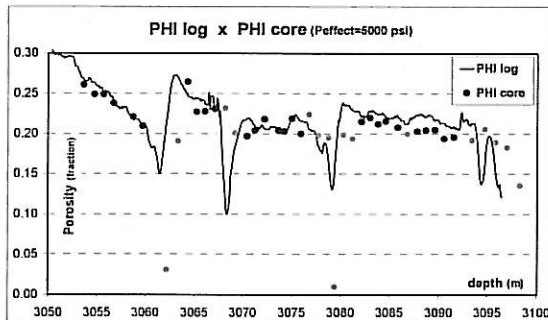


Figure 5 - Porosity from log versus porosity from cores showing the discarded samples (in gray) based mainly on the porosity criteria.

Results

Figure 6 shows the comparison of the saturated velocities computed for the selected subset from cores (blue dots) against corresponding sonic log data. We see a very good agreement between the two sets of data. Similar result was observed in Schiehallion Field by Meadows *et al.* (2005).

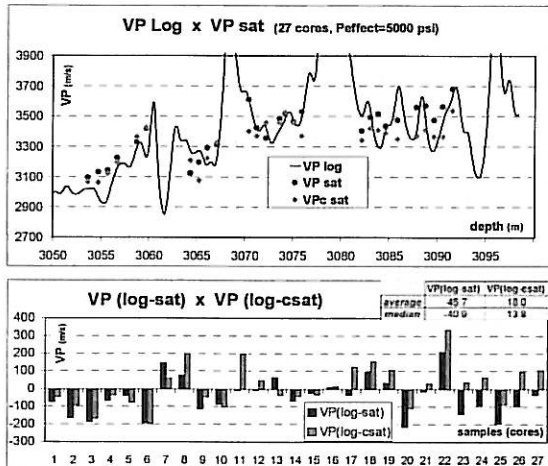


Figure 6 - Velocities from sonic log (VP log), and from cores: saturated using Gassmann (VP sat) and using scale effect correction (VPc sat). In the bottom graph we can see that both differences are predominantly smaller than 200m/s.

The average difference (systematic error) between the two sets is -46m/s (1.5%), similar to accuracy of the core measurements (1 - 3%). The root mean square of the differences between sonic log and the computed core velocities is 114 m/s.

One may notice that the higher (on average) core velocities correspond to lower (on average) core porosities, compared to the log data. In other words, the cores do not fully

represent the average properties of the formations as measured in logs. To reduce this effect, in Figure 7 we plot the velocity against porosity for our reservoir interval, construct a quadratic regression $V_{Pt}(\phi)$ and apply the correction to the core velocities:

$$V_{Pcor} = V_{Psat} + \Delta V_P, \quad (7)$$

$$\Delta V_P = V_{Pt}(\phi_{log}) - V_{Pt}(\phi_{lab}) \quad (8)$$

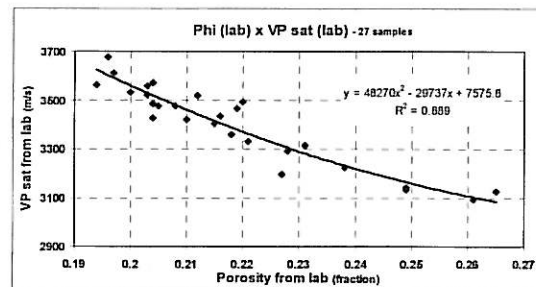


Figure 7 - Relationship between porosity measured in samples and compressional velocities using Gassmann theory.

The resulting corrected velocities are shown as red diamonds in Figure 6. After this correction, the resulting systematic difference between log and core velocities reduces to 18 m/s. Effectively, this procedure corrects for the effect of under-representativeness of core samples. We see that either with or without correction for porosity discrepancy, the sonic and core velocities are quite close.

Conclusions

We have described a methodology to assess the adequacy of ultrasonic velocities measured in the laboratory for use in sonic and seismic modeling (with view to use in time-lapse interpretation), focusing on the effect of core damage.

The main conclusion is that the saturated velocities computed from core measurements on dry samples match the sonic log velocities quite well. This means that the effect of core damage on the elastic properties of the core samples is small, that is, below the measurement errors.

The results of the study relate to a particular reservoir in the Campos Basin offshore Brazil. Similar studies in the same basin and other parts of the world are needed to verify how general this conclusion is.

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EDITED REFERENCES

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