**Petrobras’ Rock Physics Laboratory: 35 Years Squeezing and Shacking Rocks**

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# Abstract

The Petrobras’ Rock Physics Laboratory first activities begun 35 years ago. In this paper we will register some highlights of the experimental research developed in the laboratory, in parallel with the international investigations in experimental rock physics.

# Introduction

Dillon and Oliveira (1987) registered the very first laboratory velocity measurements made in Brazil, at the Petrobras Rock Physics Laboratory. In this internal publication the authors also point out some limitations of the available equipment. They went forward and made a project of an in-house ultrasonic velocity measurement apparatus with pressure, temperature and saturation capabilities in collaboration with a submarine engineering company (Consub). This equipment was fully operational until around 2010, and other velocity equipments were added in this meantime.

The seismic response of rocks is closely linked with the saturating fluid. So, in the 90’s the team dedicated efforts in fluid acoustic velocity (e.g., Vasquez e Dillon, 1993). This work front was essential in supporting seismic monitoring feasibility studies, especially those related to steam or hot water injection (e.g., Dillon and Vasquez, 1993; Vasquez et al., 1999). Of course, in parallel, a lot of elastic wave measurements in rock samples were done to assist the technical feasibility studies.

Laboratory studies were largely used in supporting seismic interpretation in field development and exploratory scenarios (Dillon et al., 2003).

Nowadays, the Petrobras Rock Physics Laboratory is equipped with several commercial and hybrid measurement systems with hydrostatic and axisymmetric stress capabilities. Some other high quality rock physics laboratories were established in Brazil, mainly in universities, and the involved teams present excellent scientific production, with publications in international congresses and renowned journals.

We have “official” laboratory velocity data from 396 wells, encompassing 9335 rock samples, which would sum up if aligned one after other 397.2 meters! This counting does not include outcrop samples and some internal testing and calibration results.

Our objective is to draw a brief history of the Petrobras Rock Physics Laboratory studies with some examples and illustrate the international rock physics context in parallel. We will divide our description by topics, instead of a chronological review.

# First 4D Feasibility and Fluid Acoustics Studies

In the 90’s there were already some successful seismic production monitoring results published on the literature, although the technology was in its infancy. At this time, the Petrobras’ geophysical team identified some interesting candidate fields to 4D seismic campaigns. Some of these were onshore fields from Reconcavo (e.g., Fazenda Alvorada, Fazenda Belém and Dom João) and Potiguar (e.g., Alto do Rodrigues and Estreito) sedimentary basins, producing heavy oil and were object to steam injection or hot-water injection. In some cases, the oil is not so heavy, but high viscous due to the paraffin content.

At this time Dillon and Vasquez (1991, 1992) released some results from the Fazenda Alvorada field, the first laboratory 4D feasibility study in Brazil. The "Fazenda Alvorada" oil has 20oAPI in average and is very paraffinic. The best production unit is an eolic sandstone with good permeability and porosity, and the reservoir is quite shallow (few hundred meters). An interesting result is that they observed a high temperature dependence of the crude oil velocity, and high velocity dispersion in oil saturated rock samples. At ambient pressure and temperature, the oil is like a wax. Only at 65oC it behaves really like a liquid phase. Coincidently, only few years before, Drs. Amos Nur and Zee Wang (1987) proposed that even only temperature changes could be detected in 4D surveys. At first sight this proposal was not widely accepted by the geoscience community (personal communication). Figure 1 illustrate compressional-wave velocity results for a sandstone from Fazenda Alvorada field saturated with oil for different temperatures. A huge velocity decrease (about 16%) is observed as the temperature rises from 35oC to 90oC, quite impressive.

Unfortunately, due to practical and economic issues, some of these on shore 4D surveys were left behind. Later, Gomes et al. (1999) mapped the steam front in Alto do Rodrigues, and their interpretation was guided by some laboratory experiments. The example in Figure 2 illustrates the velocity of a rock sample from Alto do Rodrigues fully saturated with crude oil from the field, as a function of temperature. In the same graph we have the acoustic-wave velocity for the pure oil, as a function of temperature. It seems that the oil behavior with temperature is the main governing factor of the observed rock velocity behavior.

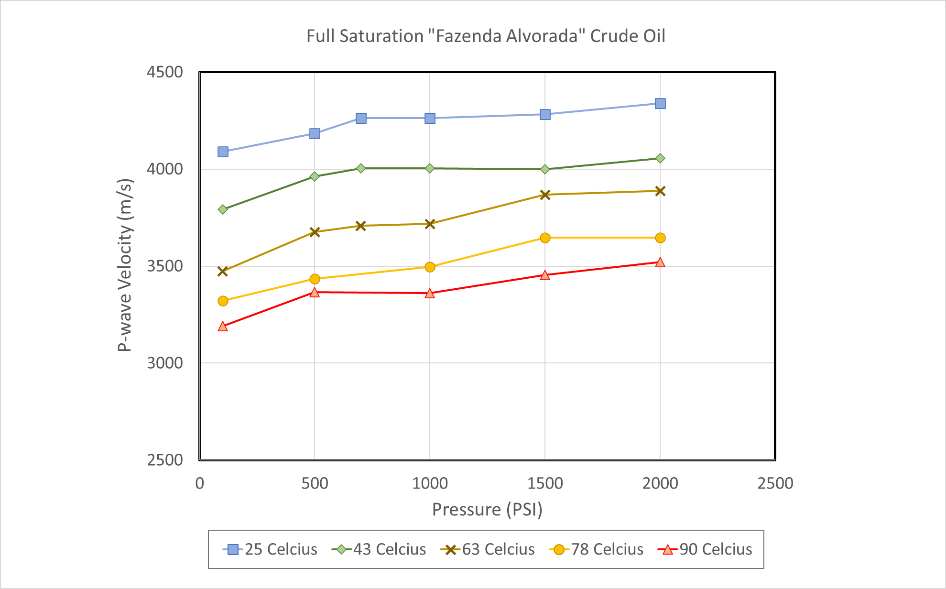


Figure 1: Compressional-wave velocity as a function of confining pressure for a reservoir sample from Fazenda Alvorada field saturated with the original crude oil, at different temperatures (modified from Dillon & Vasquez, 1991).



Figure 2: Compressional-wave velocity in oil saturated rock from Alto do Rodrigues field (brown diamonds and green triangles) and on the pure crude oil (blue discs), from Vasquez et al., 1999.

The first offshore 4D example from Brazilian basins was done in the Marlim giant field (Aggio and Dillon, 1999, Filpo et al, 1999, Johann et al, 2009). The feasibility and seismic interpretation studies were also supported by series of laboratory measurements.

It is well known that time lapse seismic can be influenced by pressure changes and fluid substitution. Thus, it is very important to know the oil acoustic properties, and we dedicated some effort on measurement of acoustic wave velocity in crude oils (e.g., Vasquez and Dillon, 1993). Batzle and Wang (1992) published an excellent review of tools for predicting the seismic properties of pore fluids. The continuous line shown in fig. 2 along with the laboratory data is not a best-fit line, it is the estimate of oil velocity from this classical reference. We observed good agreement between laboratory results and the prediction of Batzle and Wang’s paper for oils with different API degrees. Thus, it seemed that it was not necessary to care about experiments on fluid acoustics, because Batzle and Wang’s paper was a holy grail that would give the fluid acoustic properties given the ambient conditions and some fluid characteristics. Lately, Batzle (from Colorado School of Mines) and Han (from University of Houston) noticed that some extremely heavy oil and condensates was not adequately “predicted” by the old equations, as well as brines which compositions was not dominated by NaCl. They invested a lot of effort with collaborators to fill this gap in predicting fluid acoustic properties (e.g., Han and Batzle, 2000, Sun and Han, 2009).

# Seismic Wave Absorption: Attenuation and Dispersion

The experience with viscous oil reservoir revealed the importance of seismic velocity dispersion and attenuation, in the combined phenomena known as absorption. In the laboratory, wave velocity could be higher at ultrasonic frequencies than at lower frequencies. Due to the (difficult) relative motion between frame and saturating fluid, the wave could lose energy, and the waveform and its frequency spectrum could change as they propagate through the rock.

This observation was not fresh news, Winkler (1985), Murphy (1982) and other notable rock physicists had already observed and studied wave dispersion and attenuation. But a good picture of the problem was not clear in the 90’s. Indeed, it still needs attention even nowadays.

We made some studies of laboratory velocity dispersion and attenuation measurements using the spectral ratio technique (e.g., Vasquez et al. 1996, 2001). Figure 3 shows one example of attenuation as a function of temperature for a fluvial sandstone partially saturated with heavy oil. This rock presents 19.7% porosity and 514.6 mD permeability and was saturated with approximately 97% with a 28oAPI crude oil from the same well (the other fluid in the pore space is air). We interpreted that the result with QP/QS<1 was similar to the one obtained by Winkler and Nur (1979) for rocks partially saturated with water. While for the P-wave attenuation there is a decrease with temperature increasing like the observed velocity dispersion (except for the first data), S-wave attenuation increases. This oil is like a wax at 20oC, and maybe it can contribute to large dispersion but gives a good “acoustic coupling”, resulting in an attenuation not so high as would be expected.

The interest in attenuation is mainly because experiments and models suggest that it may be closely related to the type of saturating fluid (specially its viscosity) and to pore space properties.

In the literature there are several interesting results of dispersion and attenuation measurements at ultrasonic frequencies. We learned a lot from these experiments. However, it became evident that attenuation is highly frequency-dependent, and that the application of ultrasonic studies to seismic interpretation is difficult or even impossible with the current knowledge of the governing parameters and the phenomena itself. Moreover, low-frequency measurements in the laboratory (e.g., Adam et al., 2006; Spencer and Shine, 2016). So, ultrasonic attenuation studies suffered a sharp slowdown. Currently, we have close collaboration with PUC-Rio, they have a low-frequency apparatus built in collaboration with Curtin University (Chavez, 2021).

Gráfico, Gráfico de linhas

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Figure 3: Attenuation (1000/Q) of compressional and shear waves as a function of temperature for a fluvial sandstone partially saturated with heavy oil at the confining pressure 5000 PSI.

**Shear-wave Velocity Control**

In 1985 the first array sonic tool was introduced that allowed downhole digitization of the full waveform possible, and shear-wave logging became available for the industry (Close et al., 2009). However, in the 90’s shear-wave velocity control was still a hot subject. As may happen to any new technology, the community was not fully comfortable with S-wave sonic. Moreover, this information is absent in several old wells. Castagna et al. (1985) released some empirical relations between compressional and shear wave velocity in siliciclastic rocks which could be useful in the absence of S-wave logs, as well as a quality control for this curve in new wells. Later Greenberg and Castagna (1992) published a receipt to shear wave velocity prediction in sedimentary rocks with different compositions. Even nowadays, shear wave estimation is important. Some frontier areas, such as the Brazilian Equatorial Margin, presents several wells, most of which do not have shear wave sonic.

The tools developed by Castagna and collaborators are very useful, and maybe a “fine tune calibration” to particular areas of interest can improve the results even more. Lira et al. (1997) compared the application of three different procedures to estimate S-wave logs in wells with good and reliable shear wave velocity: Greenberg & Castagna (1992), Krief et al. (1990), and local calibration with laboratory derived VP-to-VS correlations. Lira and Pinheiro (1999) explored the S-wave velocity log generation using neural networks as well, and Pinheiro e Vasquez (2001) compared neural networks results with Greenberg-Castagna. Pinheiro (2005) also discussed the use of Greenberg-Castagna in different scenarios, with a seismic interpreter point of view. Indeed, this is a very good method to shear-wave velocity log estimation, as exemplified in Figure 4, and is considered as a kind of benchmark.

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Figure 4: Example of shear-wave log estimate with Greenberg and Castagna technique, from Pinheiro and Vasquez, 2001.

**Years 2K: new labs on the block**

We can find some rock physics studies in Brazilian universities before 2000, but it was relatively scarce. In the “new century” we observed an increase in rock physics investigations in the universities. As an example, Soares and Guimarães (2003), from UFRJ (Federal University of Rio de Janeiro), published conceptual and experimental investigations related to anisotropy in shales. Ceia and Misságia (2009), from UENF (North Fluminense State University), released interesting results of velocity measurements on natural and artificial sandstones. Later, they included physical modeling and rock physics measurements facilities on the laboratory. In 2012 another productive laboratory was established in UFCG (Federal University of Campina Grande): LabPetro-UFCG.

With new rock physics laboratories and research groups in the universities the rock physics activities in Brazil experienced a widespread. The investigations were accelerated, with relevant thesis, dissertations and technical papers being published. Today we can find good research on rock physics experiments, models, and applications. Some groups from the universities develop activities also on geomechanics, digital rock physics (e.g., Vidal et al., 2016) and petrophysics. In the industry sometimes the exploration and production demand the concentration of efforts and some degree of specialization. For instance, there are other Petrobras groups investing their efforts in digital rock physics (e.g., Surmas et al., 2004; de Jesus et al, 2021) and they sometimes collaborate with the rock physics team. The same happens with geomechanics (e.g., Garcia et al., 2023).

After 2000 we experienced an increase on the demand for elastic velocity measurements, which increased even more with the discovery of presalt fields, after 2010. To attend the internal needs for elastic property results we made “semi commercial” automated systems and acquired some commercial (but customized) equipment. This transition to automated and third-party equipment let the researchers somewhat free to dedicate more time in experimental and theoretical studies.

Today we have velocity results from more than nine thousand samples in our data bank, comprising almost 400 meters of rock, which could be as tall as the Empire State Building.

**Rock physics and rock mechanics or geomechanics**

Since some decades ago, people are trying to use time-lapse seismic and geomechanics as an integrated tool for optimum drainage maintaining the reservoir’s integrity. Of course, it demands the collaboration between rock physics and rock mechanics experimental studies. New and sophisticated geomechanical models may take benefit of this collaboration as well.

In 4D studies applied to geomechanics the dilation factor, or R factor, is used very often by the geophysicists. However, some geoengineers argue that this parameter does not have a geomechanical meaning or, at least, we don’t know it. There are some studies trying to link this geophysical parameter to mechanical properties of rocks as the recently released by Garcia et al. (2023).

Another effort joining geophysicists and engineers is the construction of reliable geomechanical models. We are interested in the Biot’s coefficient (Morschbacher et al, 2023) and pore compressibility, two important model parameters often mis-considered.

The increasing number of publications in numerical or digital rock physics modeling, and the existing and new analytical rock physics tools also demand experimental support.

# Comments and Conclusion

We described a brief history of the Petrobras’ Rock Physics Laboratory and of the development of rock physics studies in Brazil, trying to mention the international trends as well.

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**References**

Adam, L., Batzle, M. and Brevik, I. 2006. Gassmann's fluid substitution and shear modulus variability in carbonates at laboratory seismic and ultrasonic frequencies. Geophysics, 71, F173-F183.

Batzle, M., Han, D-H and Castagna, J. 1999. Fluids and frequency dependent seismic velocity of rocks. SEG Technical Program Expanded Abstracts: 5-8.

Batzle, M.L., Han, D-H, and Hofmann, R. 2006. Fluid mobility and frequency-dependent seismic velocity — Direct measurements. Geophysics, 71, N1-N9.

Castagna, J.P. Batzle, M.L. and Eastwood, R.L. 1985. Relationships between compressional‐wave and shear‐wave velocities in clastic silicate rocks. Geophysics, 50, 571-581.

Ceia, M.A.R. and Misságia, R.M., 2009. Medidas Ultrasônicas em Amostras de Arenitos Naturais e Sintéticas. 11th International Congress of the Brazilian Geophysical Society.

Chavez, R.R.L., 2021. Determination of acoustic properties of carbonate rocks at low frequency. DSc Thesis Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio).

Close, D., Cho, D., Horn, F. and Edmundson, H. 2009. The Sound of Sonic: A Historical Perspective and Introduction to Acoustic Logging. CSEG Recorder, 34, 34-42.

Garcia, P.F.V., Rossi, D.F., Ferreira, F.H., Justen, J.C.R., Vasquez, G.F. and Lonardelli, J.N., 2023. Experimental and theoretical study of the dilation factor of sandstone analogues and pre-salt reservoir carbonates. Accepted for the 57th US Rock Mechanics/Geomechanics Symposium. Paper ARMA 23-0054.

Greenberg, M.L., and Castagna, J.P., 1992. Shear‐wave velocity estimation in porous rocks: theoretical formulation, preliminary verification, and applications. Geophysical Prospecting, 40, 195 – 209.

Han, D-H, and Batzle, M. 2000. Velocity, density and modulus of hydrocarbon fluids - data measurement. SEG Technical Program Expanded Abstracts: 1862-1866.

Jesus, C.M., Compan, A.L.M., R. Moreira Araújo, R.M., and Surmas, R. 2021. K-Image - Permeability Characterization Integrating Matrix and Non-Matrix Pore Scales on Pre-Salt Reservoirs. Second EAGE Conference on Pre-Salt Reservoirs.

Krief, M., Garat, J., Stellingwerff, J., and Ventre, J. 1990. A petrophysical interpretation using the velocities of P and S waves (full-waveform sonic). The Log Analyst, 31, 355-369.

Lira, J.E.M., Dillon, L.D., Vasquez, G.F., Bastos, A. and Soares, J.A., 1997. Métodos para Geração de Perfis de onda S: Urna Análise Crítica a partir da Correlação Rocha – Perfil. 5th International Congress of the Brazilian Geophysical Society.

Lira, J.E.M., and Pinheiro, J.E.F., 1999. Fluid Substitution Using Pseudo-Sonic Log Generated By Neural Networks: A Modelling Study. 6th International Congress of the Brazilian Geophysical Society.

Morschbacher, M., Vasquez, G., Justen, J., Figueiredo, M., Falcão, F., Maria, A.L. 2023. Laboratory Measurements of the Biot Coefficient of a Pre-salt Oil Field, Santos Basin. Submitted to the 18th International Congress of the Brazilian Geophysical Society.

Murphy III, W.F., 1982. Effects of partial water saturation on attenuation in Massilon sandstone and Vycor porous glass. The Journal of the Acoustical Society of America, 71, 1458-1468.

Nur, A., and Wang, Z. 1987, In-situ seismic monitoring EOR: The petrophysical basis: Presented at the SPE, SPE 16865.

Pinheiro, J.E.F., and Vasquez, G.F., 2001. Perfis Sintéticos de Vs: Greenberg Castagna X Redes Neurais. 7th International Congress of the Brazilian Geophysical Society, Oct 2001, cp-217-00228

Pinheiro, J.E.F., 2005. Aprendendo a confiar em Greenberg-Castagna. 9th International Congress of the Brazilian Geophysical Society

Soares, J.A., and Guimarães, M.S.B, 2003. Usando o modelo de Thomsen para análise da composição e estrutura interna de folhelhos. 8th International Congress of the Brazilian Geophysical Society.

Spencer Jr., J.W. and Shine, J. 2016. Seismic wave attenuation and modulus dispersion in sandstones. Geophysics, 81, D211-D231.

Sun, M. and Han, D-H. 2009. Velocity properties of CO2 saturated water and methane‐saturated water at temperatures up to 200 °C and pressures up to 138 MPa. SEG Technical Program Expanded Abstracts: 2095-2099.

Surmas, R., dos Santos, L.O.E., and Philippi, P.C. 2004. Lattice Boltzmann simulation of the flow interference in bluff body wakes. Future Generation Computer Systems, 20, 951-958.

Vidal, A., Soares, J., Medeiros, L., Borges, I., Raposo, G. and Barboza, A., 2016. Digital Rock Physics from Santana Formation, Araripe Basin. Third EAGE/SBGf Workshop 2016.

Vasquez, G.F., Dillon, L.D., 1993. Modulos Adiabático e Isotérmico de Óleos Brutos. 3rd International Congress of the Brazilian Geophysical Society.

Vasquez, G., Dillon, L., Agnelo, J. and Bastos, A. 1996. Velocity and attenuation in sandstones with temperature - Evidence of the local fluid flow. 58th EAGE Conference and Exhibition.

Vasquez, G., Neto, G., Dillon, L. and Aguiar, F. 1999. Viabilidade da Sísmica 4D em um campo terrestre: enfoque. 6th International Congress of the Brazilian Geophysical Society.

Vasquez, G., Simões Filho, I.A., Dillon, L.D., Bruhn, C.H.L., 2001. Velocity Dispersion and Attenuation in Brazilian Sandstones. 7th International Congress of the Brazilian Geophysical Society.

Winkler, K.W. and Nur. A., 1979. Pore fluids and seismic attenuation in rocks. Geophysical Research Letters, 6, 1-4.

Winkler, K.W. 1985. Dispersion analysis of velocity and attenuation in Berea sandstone. J. Geophys. Res., 90 (B8), 6793-6800.