Shales, interbedded lithologies and its anisotropic properties

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This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

Seismic anisotropy has received recently more attention in the oil industry. Anisotropy effects can be extremely hazard to the seismic horizons positioning and amplitude recovering, on well log processing, interpretation and seismic tie. Nowadays, geophysicists have some tools to estimate and correct the anisotropy effects on seismic data. However, the solution of this problem is still beyond from its exhaustion.

In this paper we discuss the anisotropic properties of shales and interbedded sequences based on laboratory and log results and, also, some issues on anisotropy upscaling.

Introduction

Geophysicists have become increasingly aware on the effects of seismic anisotropy. Anisotropy studies are leaving the pure academic environment and becoming applicable on seismic and well log processing and interpretation in the daily work on the oil industry. Due to the strong anisotropy of shales, the most abundant rock on sedimentary basins, we might have serious troubles on the correct positioning and true amplitude recovering of the seismic reflectors. Currently, there are some reasonable algorithms available in order to try to solve those problems. Nevertheless, regarding the innumerous difficulties in sampling and handling shale cores, we don't have a good understanding of the anisotropic properties of shales. Int his paper we present one of the first results of anisotropy measurements on Brazilian shales.

Transversely Isotropic Media Characterization

A transversely isotropic media (TI) is isotropic in one plane (e.g., the bedding plane in sedimentary rocks). Therefore we must know five elastic constants to describe the stress-strain relations and wave propagation in such media (e.g. Goodman, 1989). Figure 1 shows a cartoon scheme of a TI media. The z-axis refers to the direction parallel to the symmetry axis (e.g., perpendicular to the bedding plane of a sedimentary rock) and the x and y-axis are two orthogonal symmetry directions contained in the plane perpendicular to the symmetry axis. Actually, on this picture we have a VTI media: the symmetry axis of the transversely isotropic media is oriented along the vertical direction.

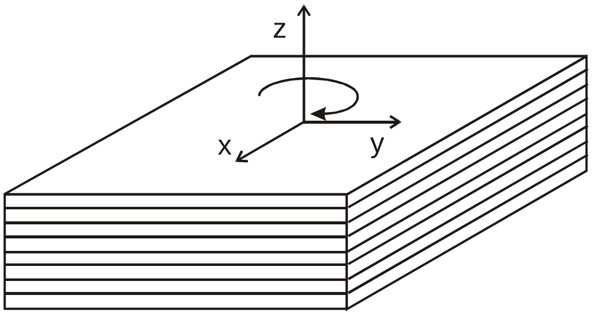

Figure 1 – Representation of a transversely isotropic media with symmetry axis along the z direction.

Recalling the generalized Hook's law, $\sigma = C\varepsilon$, for a VTI media, we can describe its elastic tensor (in the Voigt two-index notation) as

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix} \qquad (1)$$

where $c_{66} = \frac{1}{2}(c_{11} - c_{22})$.

We can reconstruct the VTI elastic tensor by means of seismic pseudo-velocities. To obtain the five elastic constants, we must know the (pseudo) velocities of (quasi) compressional and (quasi) shear waves at least along three different directions, taking into account the distinct polarizations of the shear waves.

Dealing with laboratory measurements, we must have at least three rock samples. In the case of cylindrical samples, if the sample orientation is referred to the cylinder axis – one will be parallel to the anisotropy symmetry axis (vertical sample), the second one will be perpendicular (horizontal sample) and the third one with the axis at 45º with the anisotropy symmetry axis, pursuant the scheme in figure 2 – the elastic constants is given by (Yin, 1992; Liu, 1994):

$$\begin{aligned}
c_{11} &= \rho(V_P(0))^2 \\
c_{33} &= \rho(V_P(90))^2 \\
c_{44} &= \rho(V_{SV}(0))^2 = \rho(V_{SH}(90))^2 \\
c_{66} &= \rho(V_{SH}(0))^2 \\
c_{13} &= \sqrt{4\rho^2(V_P(45))^4 - 2\rho(V_P(45))^2(c_{11}+c_{33}+2c_{44}) + (c_{11}+c_{44})(c_{33}+c_{44})} - c_{44} \\
c_{12} &= c_{11} - 2c_{66}
\end{aligned} \tag{2}$$

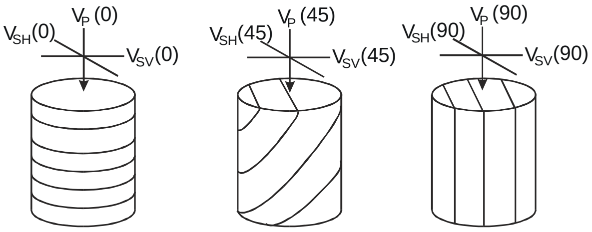

Figure 2 – Scheme of the different velocities measured for the calculation of the elastic constants of a VTI media (modified from Vernik & Liu, 1997).

Thomsem (1986) proposed the use of three parameters for describing the anisotropy of a media with weak anisotropy, that is:

$$\begin{aligned}
\varepsilon &= \frac{c_{11} - c_{33}}{2.c_{33}} \\
\gamma &= \frac{c_{66} - c_{44}}{2.c_{44}} \\
\delta &= \frac{(c_{13} + c_{44})^2 - (c_{33} - c_{44})^2}{2.c_{33}(c_{33} - c_{44})}
\end{aligned} \tag{3}$$

With these three parameters Thomsem estimated the wave velocities as a function of the angle between the wave propagation direction and the plane of symmetry of the VTI media (the angle with the normal to the bedding plane):

$$\begin{aligned}
V_P(\theta) &\approx \alpha(1 + \delta \mathrm{sen}^2\theta \cos^2\theta + \varepsilon \mathrm{sen}^4\theta) \\
V_{SV}(\theta) &\approx \beta\left(1 + \frac{\alpha^2}{\beta^2}(\varepsilon - \delta)\mathrm{sen}^2\theta \cos^2\theta\right) \\
V_{SH}(\theta) &\approx \beta(1 + \gamma \mathrm{sen}^2\theta)
\end{aligned} \tag{4}$$

Anisotropy Measurements in the Laboratory

We have measured seismic velocities at the PETROBRAS Rock Physics Laboratory by the ultra-sonic pulse transmission technique (Vasquez *et al.*, 2000) on cylindrical samples with 1 and 1.5-inch diameter. It is very hard to prepare good shale samples, owing that, first of all, we rarely have cores sampling shale sequences. Furthermore, it is very difficult to find well-preserved shale samples. Due to the bedded nature of these rocks, the recovering ratio is very small, mainly for horizontal and 45º core sampling.

We present here the results on the anisotropy of hydrocarbon source rocks and also on Sergipe and Campos Basin shales.

Hydrocarbon Source Shales

We estimated Thomsem's ε and γ parameters from a large hydrocarbon source shale sample set. In this case we got only vertical and horizontal samples available because of serious problems on the oblique samples preparation. The average results for the vertical compressional and shear velocity and ε and γ parameters are listed on table 1.

We obtained extremely high anisotropy parameters, which disagrees with the weak anisotropy assumption. This could be due to the lack of pore pressure equilibration on the experiment (Rice and Cleary, 1976), to very high organic matter content or, most probably, due to a combination of these two conditions. Vernik and Nur (1992) report anisotropies as high as 50% on compressional velocities of kerogen-rich shales.

Table 1 – Anisotropy parameters ε and γ of hydrocarbon source shales.

Pressure (psi)	Vp (0) (km/s)	Vs (0) (km/s)	ε	γ
1000	2.98	1.86	0.60	0.53
2000	3.00	1.88	0.59	0.55
3000	3.04	1.90	0.58	0.56
4000	3.07	1.91	0.57	0.55
4500	3.08	1.91	0.58	0.52

Shales from Sergipe Basin

We measured the anisotropy of non-source shales sampled from one deviated well at Sergipe Basin. This shale didn't show a very pronounced apparent bedding. Insuring that we had prepared the sample set at the right directions, we measured each sample velocities at various orientations with respect to the shear transducers polarization. With these velocities we found out the principal axis of each sample. Figure 3 presents the compressional and shear velocities measured on this shale as a function of confining pressure. The anisotropy parameters are summarized on table 2 and the phase velocity surfaces are presented in figure 4. It is important to point out that the signal quality at low pressures was very poor.

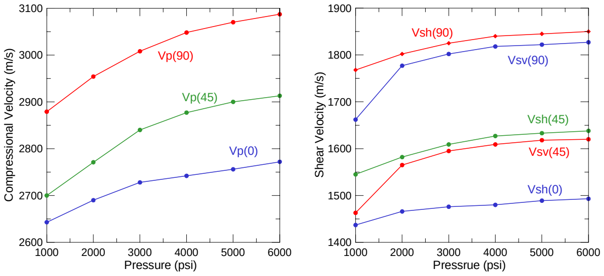

Figure 3 - Compressional (left) and shear (right) wave velocities for the Sergipe Basin shale.

Table 2 – Anisotropy parameters of Sergipe Basin shales.

Pressure (psi)	ε	γ	δ
6000	0.126	0.117	0.064
5000	0.126	0.117	0.071
4000	0.123	0.118	0.060
3000	0.114	0.116	0.038
2000	0.108	0.114	-0.005
1000	0.099	0.150	-0.026

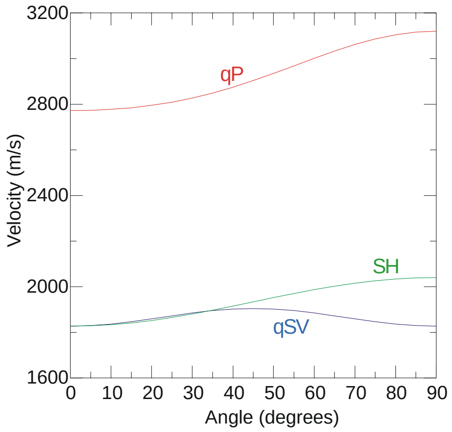

Figure 4 – Phase velocities surfaces for the Sergipe Basin shale in the angle range 0-90º to vertical axis.

Shales from Campos Basin

We had prepared two samples set from the neighborhood of a particular Campos Basin oil field. One set came from a brown, very clay-rich shale. The other set was prepared from a light-gray, quite competent carbonate-rich shale, as shown on figure 5. The Thomsem parameters for these shales are listed on tables 3 and 4.

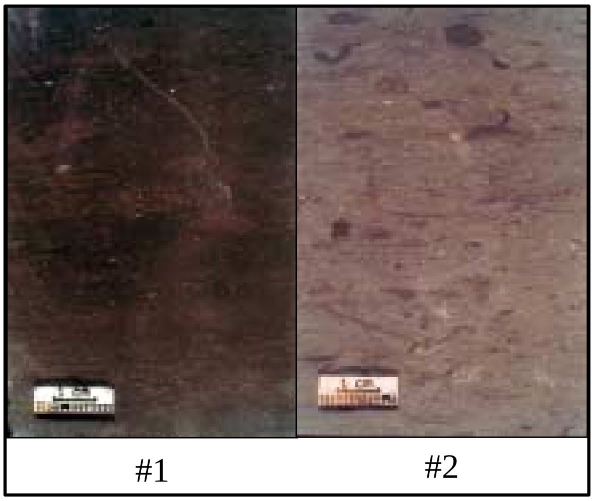

Figure 5 – Whole-core photography from Campos Basin shales.

As expected, the cemented shale (#2) exhibits less anisotropy: the cementation tends to “glue” the clay sheets, giving a strong coupling and masking its anisotropy in some degree.

Figures 6 to 8 illustrate the comparison of the anisotropic parameters of the Sergipe and Campos Basin shales.

Table 3 – Anisotropy parameters of the Campos #1 shale.

Pressure (psi)	ε	γ	δ
6000	0.179	0.076	0.084
5000	0.177	0.074	0.079
4000	0.180	0.076	0.082
3000	0.183	0.075	0.072
2000	0.190	0.075	0.070
1000	0.204	0.078	0.086

Table 4 – Thomsem parameters of the Campos #2 shale.

Pressure (psi)	ε	γ	δ
6000	0.039	0.031	-0.020
5000	0.041	0.032	-0.011
4000	0.042	0.035	-0.013
3000	0.044	0.043	-0.010
2000	0.044	0.045	-0.017
1000	0.045	0.049	-0.019

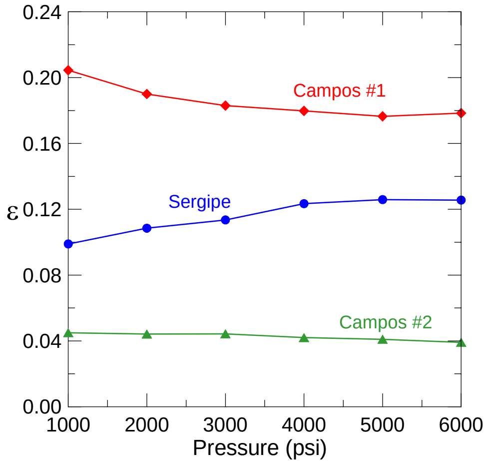

Figure 6 – Anisotropy parameter ε versus pressure.

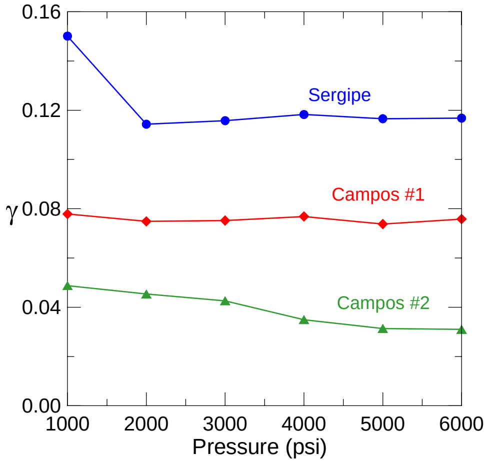

Figure 7 – Anisotropy parameter γ versus pressure.

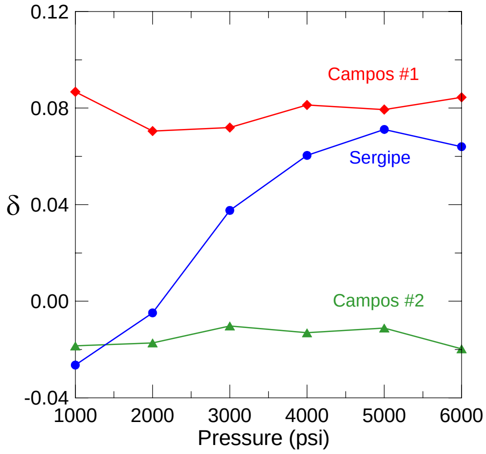

Figure 8 – Anisotropy parameter δ versus pressure.

Anisotropy Correction in Practice

At the field development stage, it is very common to drill deviated wells to optimize the production index. The well-to-seismic tie in this case is not so trivial as just projecting the well log curves to a true vertical when estimating synthetic seismograms. One of the various issues when dealing with non-vertical wells is the anisotropy of shales and interbedded intervals. Actually, the correction of seismic anisotropy in deviated wells is one of the most important steps to improve seismic-well tie (Vernik et al., 2002).

Based on our lab results, we applied anisotropy corrections on deviated wells of a particular Campos Basin field. We show on figure 9 one example of such a correction on the compressional velocity. Considering the deviation survey, we had estimated the angle between the tool and the shale symmetry axis, which is along the vertical axis in this case. Once we had the angle we could then apply the Thomsem's equations to correct the velocities to its vertical values.

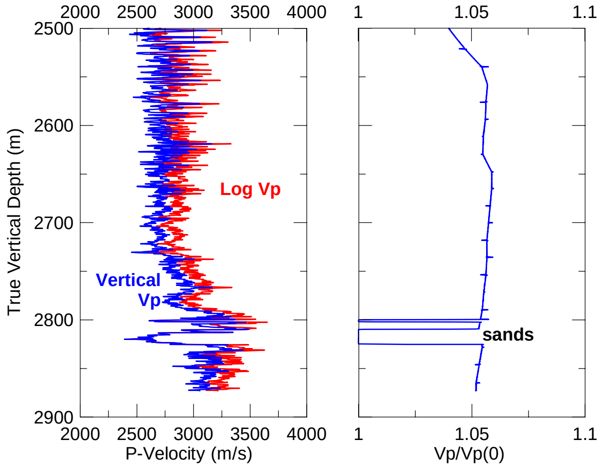

Figure 9 – Compressional velocity correction applied to a deviated well in Campos Basin.

If there are a couple of deviated wells penetrating the same shale formation, one can also apply the inversion scheme as proposed by Hornby *et al.* (2003).

Sometimes the application of the anisotropy correction relies on the assumption that the shale interval is quite homogeneous and uniform, which is not always true.

It is very common in turbidity sequences the occurrence of stratigraphic units composed by a set of fine layers, mainly sand-shale, sand–mud rock and/or carbonate-shale interbedded units, which individual thickness is bellow the seismic or even the sonic log resolution. Backus (1962) showed that a sandwich composed of layers with less than one wavelength thick behaves as a VTI media, even if both components are isotropic. Generally, in this case the anisotropy due to the interbedding are stronger than that of each component (Pratt & Sams, 1996).

The scaling problem on anisotropy correction remains a interesting challenge. Regarding the different wavelength/heterogeneity ratios involved in lab, log and seismic studies, the anisotropy of same rock shall be different in each individual scale, and the application of one result to another investigation method is not so trivial.

Conclusions

We presented results of the first laboratory measurements of anisotropy on Brazilian shales. These results agree with those available in the literature. Coherently, it is observed that the anisotropy tends to fall with the degree of consolidation and cementation of the shales. Also, we observed very high anisotropy on hydrocarbon-source rocks.

Although there are some schemes for sonic log correction to improve well-to-seismic tie, there are some important issues on the upscaling of anisotropic properties.

Acknowledgements

We would like to thank PETROBRAS for supporting and permission to present this paper. Also, we must thank Marcos Leão, Antonio Freitas, Júlio and Jose Lira for their help in some measurements. We are thankful also to Angela Vasquez and Guenther Schwedersky for revising the manuscript.

References

Backus, G. E., 1962. Long-wave elastic anisotropy produced by horizontal layering. *J. Geophys. Res.*, **67**, 4427-4440.

Goodman, R. E. 1989. *Introduction to Rock Mechanics*, 2nd ed. John Wiley & Sons. 562 p.

Honrby, B. E., Howie, J. M. and Ince, D. W., 2003. Anisotropy correction for deviated-well sonic logs: application to seismic well tie. Geophysics, **68**, 464-471.

Liu, X., 1994. Nonlinear elasticity, seismic anisotropy, and petrophysical properties of reservoir rocks. PhD Thesis. Stanford University.

Pratt, R. G. & Sams, M. S., 1996. Reconciliation of crosshole seismic velocities with well information in a layered sedimentary environment. *Geophysics*, **61**, 549-560.

Rice, J. R., & Cleary, M. P., 1976. Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. *Reviews of Geophysics and Space Physics*, **14**, 227-241.

Thomsen, L., 1986. Weak elastic anisotropy. *Geophysics*, **51**, 1954-1966.

Vasquez, G., Filho, I., Bruhn, C. H. And Dillon, L., 2000, Viscoelastic behavior of a brazilian turbidite reservoir and its relationships with facies attributes, *70th Annual International Meeting: Society of Exploration Geophysicists*, 1927-1930.

Vernik, L. & Nur, A., 1992. Ultrasonic velocity and anisotropy of hydrocarbon source rocks. *Geophysics*, **57**, 727-735.

Vernik, L. & Liu, X., 1997. Velocity anisotropy in shales: a petrophysical study. *Geophysics*, **62**, p. 521-532.

Vernik, L., Fisher, D. and Bahret, S., 2002. Estimation of net-to-gross form P and S impedance in deepwater turbidites. The Leading Edge, **21**, 380-387.

Yin, H., 1992. Acoustic velocity and attenuation of rocks: isotropy, intrinsic anisotropy, and stress induced anisotropy. PhD Thesis. Stanford University.