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Evaluating the Possibility of Seismic Anisotropy in the Taubaté Basin

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Abstract Summary

This study evaluates the possibility of seismic anisotropy effects related to the Tremembé Formation in the Taubaté Basin. In order to investigate such effects, two crossing 2D seismic lines acquired in the basin were processed and analyzed. The preliminary results are encouraging and may indicate the presence of anisotropy associated with the up to 200 m thick shale successions characteristic of this formation. However, further investigation is required, as discussed in the following sections.

Introduction

Seismic anisotropy can be defined as the angular dependence of the seismic velocity. It can be seen as a large-scale expression of small-scale ordered heterogeneity, with the seismic wavelength serving as the standard of comparison (Thomsen, 2014). Therefore, whenever the seismic wavelength is large compared to the scale of the ordered heterogeneities, the wave propagation is anisotropic.

From a geological perspective, common causes of seismic anisotropy include rock stratification, aligned fractures or cracks, anisotropic stress fields in the Earth's crust, and mineral alignment (Wang, 2002). These are, in fact, the mechanisms of small-scale heterogeneity. While mineral alignment is responsible for the intrinsic anisotropy of some rocks, such as shales, the other mechanisms are sources of extrinsic anisotropy.

The effects of seismic anisotropy are usually small. However, since their impact on seismic data can be significant, accounting for such effects can improve the accuracy of velocity models and the quality of seismic imaging (Cetale Santos et al., 2003).

The purpose of the present study is to investigate the potential occurrence of seismic anisotropy in the Taubaté Basin, which is located in the eastern portion of São Paulo state, Brazil (de Andrade et al., 2022). The sedimentary fill of this basin comprises four formations belonging to the Taubaté Group, including the Tremembé Formation (Fm.). This Paleogene unit consists predominantly of fine-grained siliciclastic rocks, such as claystones, siltstones, and shales, typically exhibiting tabular geometry and variable thickness. Due to its depositional structures, this formation is expected to exhibit effects of seismic anisotropy that may be observable in seismic data. To conduct this study, two crossing seismic lines were reprocessed, and a preliminary analysis was performed. The theoretical foundation for such analysis, along with the results and some future research objectives, are presented in the following sections.

Theory, Data and Method

The simplest realistic case of seismic anisotropy is polar anisotropy, which has a single pole of rotational symmetry. This type of anisotropy is typically associated with horizontally layered thin-bedded sequences or laterally extensive massive shales, if those are unfractured. This is because cracks, fractures and joints destroy the symmetry around the polar axis. Any deviation from polar anisotropy is called azimuthal anisotropy, whose simplest (realistic) example is orthorhombic anisotropy (Thomsen, 2014).

Another way to usually refer to polar anisotropy is to call it ”transverse isotropy”. Therefore, when the symmetry axis is vertical, it may be called “vertical transverse isotropy” (VTI). In this situation, seismic velocity depends on the angle relative to the vertical. VTI model is usually attributed to fine layering within sedimentary basins. When the symmetry axis is not vertical but tilted, polar anisotropy is usually referred to as ”tilted transverse isotropy” (TTI). This form of anisotropy is commonly associated with dipping beds and folded structures, and can lead to azimuthal effects.

The effects of seismic anisotropy on P- and S-waves are distinct. Since the analyzed data contain only P-waves, the discussion is limited to the theory related to this wave type.

As previously discussed, seismic velocity in a VTI model varies with the angle relative to the vertical (polar angle), but remains constant with respect to the horizontal azimuth. In fact, the speed of P-waves is greater in the direction parallel to the isotropy plane (i.e., horizontal) and decreases as the propagation direction approaches the vertical. This means that wave speed is greater at long offsets than at short ones, which leads to a distortion in the moveout at far offsets.

In seismic processing, normal moveout (NMO) correction assumes that P-waves reflection travel times increase with offset in a hyperbolic manner. However, this approximation is strictly accurate only if the reflector is flat and the medium is homogeneous and isotropic. The travel time $t(x)$ of a reflection event follows a hyperbolic curve given by

$$t^2(x) = t_0^2 + \frac{x^2}{V_{NMO}^2}, \tag{1}$$

where t_0 is the zero-offset time, x is the source-receiver offset, and V_{NMO} corresponds to the seismic velocity of the homogeneous and isotropic layer. In a homogeneous VTI medium, the hyperbolic approximation still holds for near offsets. However, the NMO velocity is now given by $V_{NMO} \approx V_{P0}\sqrt{1+\delta}$, where V_{P0} is the vertical wave velocity, and δ is an anisotropic parameter related to the curvature of the P-wave wavefront. At far offsets, nonetheless, traveltimes are shorter than those predicted by the hyperbolic approximation. This is directly related to the fact that the horizontal wave velocity exceeds both V_{P0} and the moveout velocity, resulting in a non-hyperbolic moveout.

Given the layered sedimentary structure of the Taubaté Basin, and particularly of the Tremembé Fm., the VTI model seems appropriate to describe it, at least in its flatter regions. Furthermore, the basin's sedimentary content and depositional history favor the occurrence of anisotropy, especially considering that the Tremembé Fm., a clay-rich unit, was deposited in a lacustrine system, a setting that promotes the horizontal alignment of clay minerals.

Therefore, a key approach in investigating anisotropy in the Taubaté Basin seismic data is to examine non-hyperbolic behavior at far offsets. Although the dataset consists of only two crossing seismic lines, limiting the study of azimuthal anisotropy, it still allows for important analyses at the intersection point and along each line. At the intersection, the validity of the VTI model can be tested by comparing velocity behavior from different azimuths. Along each line, the objective becomes to identify the occurrence of non-hyperbolic moveout, which could indicate the presence of polar anisotropy.

The dataset analyzed in this study was provided by the National Agency for Petroleum, Natural Gas and Biofuels (ANP) and comprises 11 seismic lines covering nearly the entire extent of the basin, as shown in Figure 1, where the two processed lines are highlighted. Data were acquired using a Vibroseis source array operating in the frequency range of 12 to 56 Hz, with a sampling interval of 4 ms. A split-spread configuration with 120 recording channels was used, with a minimum offset of 50 m and receiver spacing of 25 m.

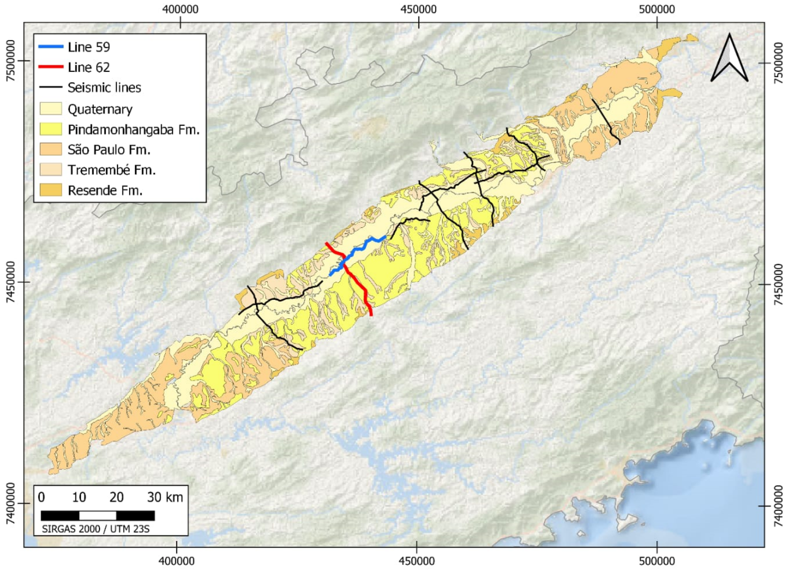

Figure 1: Map of the Taubaté Basin indicating the two lines processed and analyzed in the present work. Author: Guilherme Lenz.

The seismic lines selected for processing are located close to one of the basin's depocenters, where the sedimentary package is thickest and all formations of the Taubaté Group are expected to be present. The processing was performed in Epos software (AspenTech) and followed a conventional workflow (deconvolution, stacking and migration). After spiking deconvolution, semblance analysis was performed on the CDP (common depth point) gathers near the intersection of the two lines.

Results

Figures 2(a) and 2(c) show velocity analysis for the two gathers near the crossing point of the reprocessed lines. It is easy to see that the NMO velocity functions are very similar for both gathers ($\approx$ 1900 m/s for the basement). This suggests that the VTI model is valid in this case, at least locally.

Figures 2(b) and 2(d) show the gathers after a hyperbolic NMO correction where an isotropic medium was assumed. It can be observed that, for short offsets, the reflectors were reasonably well flattened, which was not the case for longer offsets (note the behavior beyond the refracted wave, particularly in CDP gather 1303). An ”excessive correction” can be seen, in addition to the usual NMO stretch. This could be an indication of anisotropy. However, it is important to notice that non-hyperbolic behavior at far offsets may result from the intrinsic anisotropy of rocks, but also from the layering of isotropic beds, or even from anisotropic coarse-layered sequences. Therefore, further investigation is required to determine the true nature of the observed effects, including a deeper geological understanding of the basin.

Conclusions

Two crossing seismic lines from a survey conducted in the Taubaté Basin were reprocessed to investigate the possibility of seismic anisotropy. The observed results may indicate the presence of

VTI-type anisotropy, probably associated with the Tremembé Fm.. However, further investigation is needed to better understand the nature of the observed non-hyperbolic moveout, which may also be influenced by lateral heterogeneity and the crooked geometry of the line.

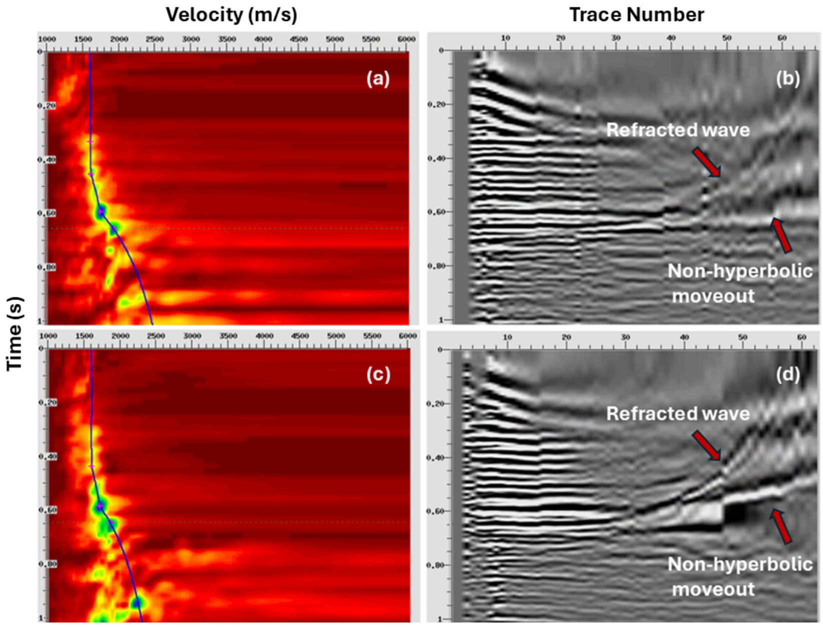

Figure 2: (a) NMO velocity function and (b) corrected gather for CDP gather 950 (line 59); figures in (c) and (d) show the same for CDP gather 1303 (line 62).

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