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CHARACTERIZATION OF SEISMIC ANISOTROPY IN SHALES USING GEOPHYSICAL WELL–LOG DATA

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Resumo – O modelo ANNIE permite uma estimativa da anisotropia sísmica em folhelhos laminados através de dados de perfilagem sônica em poços. ANNIE consite de uma aproximação para isotropia transversal (TI) com eixo de simetria vertical. A simplicidade e robustez da aproximação reside na sua capacidade de descrever um material TI por completo, com apenas 4 módulos elásticos independentes. Essa redução no número de módulos elásticos é possível porque o parâmetro de Thomsen δ, que controla as velocidades de empilhamento para as ondas P, é aproximadamente nulo na maioria das rochas sedimentares. Assumindo as restrições impostas a ANNIE, os módulos elásticos são calculados para conhecidos intervalos de folhelhos laminados em um poço produtor de óleo na bacia de Campos, Brasil. O perfil sônico de ondas P existente é usado para calcular o módulo de rigidez (normalizado pela densidade) a_{33}, associado ao quadrado da velocidade de fase vertical da onda qP. Devido à indisponibilidade do perfil sônico de ondas S no poço, o módulo de rigidez correspondente a_{44} é estimado por meio de uma metodologia que utiliza o perfil sônico de ondas P como informação principal. Análise de dados reais recentemente publicados revela que a razão de Poisson num material TI aproximado pelo modelo ANNIE é cerca de 15% menor que no caso isotrópico. Essa restrição adicional fornece uma maneira de determinar a_{11} (rigidez associada à propagação horizontal da onda qP) a partir de a_{13}, que é diretamente calculado a partir de a_{33} e a_{44}. O relacionamento imposto a ambos os módulos a_{12} e a_{13} conduz ao computo do quadrado da velocidade de fase horizontal da onda qSH, a_{66}. O uso da abordagem ANNIE nos intervalos de folhelhos escolhidos conduziram à construção de perfis de módulos de rigidez em função da profundidade. A intensidade de anisotropia nos intervalos de folhelhos é medida através dos parâmetros de Thomsen ϵ e γ, que, para o modelo ANNIE, são quantidades sempre positivas. O intervalo de variação observado em ambos os perfis ϵ e γ está de acordo com dados experimentais de rochas sedimentares moderadamente anisotrópicas. Os resultados sugerem que projetos de aquisição de dados sísmicos multicomponentes na bacia de Campos podem ser beneficiados com estudos preliminares de anisotropia sísmica usando dados de perfis sônicos.

Palavras–Chave: Anisotropia sísmica, perfilagem geofísica de poços, folhelhos turbidíticos.

Abstract – The ANNIE model allows estimating seismic anisotropy in laminated shales by using well–log sonic data. ANNIE consists of an approximation for transverse isotropy (TI) with vertical axis of symmetry. Both simplicity and robustness of the approach reside in its capability of fully describing a general TI material with only 4 independent elastic moduli. This reduction in the number of elastic moduli is possible because the Thomsen's δ, which controls P–wave normal–moveout velocities, is nearly null in most sedimentary rocks. By assuming the constraints imposed to ANNIE, the stiffnesses are calculated for known laminated shale intervals in an oil–producing well in Campos basin, Brazil. The existing P–wave sonic log is used to calculate the density–normalized elastic stiffness a_{33}, associated to the square of the vertical qP–wave phase velocity. Due to the unavailability of the S–wave sonic log in the well, the corresponding stiffness a_{44} is estimated by a methodology which utilizes the P–wave sonic data as main information. Analysis of real data recently published reveal that Poisson ratio in a TI material approximated by ANNIE is nearly 15% less than in the isotropic case. This additional constraint provides a way to determine a_{11} (stiffness associated to horizontal qP–wave propagation) from a_{13}, which is directly calculated from a_{33} and a_{44}. The relationship imposed to both a_{12} and a_{13} moduli leads to the computation of the squared horizontal qSH–wave phase velocity a_{66}. The use of ANNIE approach in the chosen shale intervals led to the construction of logs of stiffnesses as a function of depth. The strength of anisotropy in the shale intervals is measured by calculating Thomsen's parameters ϵ and γ, which, for the ANNIE approach, are always positive quantities. The range of variation observed in both ϵ and γ logs is in agreement with experimental data from sedimentary rocks moderately anisotropic. The outcomes suggest that projects of multicomponent seismic data acquisition in Campos basin can benefit from preliminary studies of seismic anisotropy using well–log sonic data.

Keywords: Seismic anisotropy, geophysical well logging, turbiditic shales.

1. Introduction

Shales are clay–rich rocks with widespread occurrence in sedimentary basins. It is well–known that such rocks play a major role in the control of the processes of generation, migration and entrapment of hydrocarbon accumulations (Best and Katsube, 1995). Kerogen–rich shales act as source rocks from which oil and/or gas are generated. Due to their very low permeabilities, shales work as flow barries to migration of hydrocarbons to upper formations. It is this sealing property that controls the origin and development of abnormal pore–pressure zones, which represent hazard to well–drilling operations.

Exploration activities also rely on an accurate characterization of the petrophysical properties of shales. Of crucial importance is the knowledge of the compressional–wave and shear–wave phase velocities along the sedimentary column under study. Seismic data processing requires stacking velocities with low extent of uncertainties (Winterstein, 1986), while calibration of seismic data depends on velocity measurements. More critically, if amplitude–versus–offset (AVO) analysis is performed at far offsets, erroneous predictions will be obtained if velocity anisotropy is neglected (Wright, 1987). As a result, if shales are involved in the amplitude anomaly, an evaluation of seismic velocity anisotropy in these rocks must be accomplished.

Although rocks are formed by minerals with intrinsic elastic anisotropy, it is the effective anisotropic response that"is accounted in experiments. For instance, transverse isotropy (TI) is the common approach applied to compute anisotropic effects in laminated composites. This goal is fulfilled with all subclasses of TI discussed in Lyakhovitskiy (1984). Nevertheless, a particular case of TI, which is named ANNIE (Schoenberg et al., 1996), is proposed as a best approximation for laminated shales. For its simple formulation and accurate estimation of the elastic parameters, ANNIE is used in this research in order to characterize seismic anisotropy in two shale intervals along a hydrocarbon–producing well. The existing P–wave sonic log is used as the main source of information for the computation of the density–normalized elastic moduli. The unavailability of S–wave sonic data is compensated by a methodology which allows estimating vertical S–wave velocity logs from P–wave sonic data (Castagna et al., 1985). By using the constraints imposed to ANNIE, the stiffnesses of both shale intervals are predicted. With ANNIE's elastic matrix formed, phase velocities are evaluated at chosen depths within both intervals. Further, measures of anisotropy proposed in Thomsen (1986) allows evaluating dependence of anisotropy with depth. The methodology is described below and seems to be quite promising in evaluating seismic anisotropy in large intervals of laminated shales with reasonable accuracy.

2. Transverse Isotropy

Transverse isotropy is used as a good approximation for characterizing the effective anisotropy response due to regular sequence of thin layers (Backus, 1962; Berryman, 1979). This long–wavelength approach is well acceptable in seismics, where the frequency bandwidth attains the order of 10^2 Hz. The TI approach is still valid for the investigation of samples of laminated shales by means of ultrasonic methods. In this case the axis of symmetry is considered perpendicular to the planes of lamination, along which elastic properties are invariable.

The existence of a TI solid is governed by stability conditions which impose positiveness to the strain energy function. Further, the strength of anisotropy in a TI material can be evaluated by the so-called Thomsen's (1986) parameters, which are known to be within small ranges ($\ll 1$) in sedimentary rocks. These topics are summarized below, as well as the constraints for the application of ANNIE approach to laminated shales.

2.1. Elastic Matrix, Stability Conditions and Measures of Anisotropy

In linear elasticity, Hooke's law controls the stress–strain relationship as follows (Einstein summation convention applied)

$$\tau_{ij} = c_{ijpq}\, e_{pq}, \tag{1}$$

where τ_{ij} and e_{pq} are the stress tensor and the strain tensor, respectively. The fourth-rank tensor c_{ijpq} represents the stiffnesses of the solid material under analysis. For a general anisotropic solid, the stiffness tensor has 81 elements. Nevertheless, the symmetry property of both tensors τ_{ij} and e_{pq} reduces the number of stiffnesses to 21. Using Voigt's condensed notation, the tensor c_{ijpq} can be written as a 6×6 matrix, which simplifies algebraic manipulations considerably.

For a general homogeneous TI material with vertical axis of symmetry (in shales, the vertical axis of symmetry is taken normal to the planes of foliation), the elements of the 6×6 elastic matrix are: a_{11}, a_{12}, a_{13},

$a_{22} = a_{11}$, $a_{23} = a_{13}$, a_{33}, a_{44}, $a_{55} = a_{44}$ and a_{66}, where $a_{12} = a_{11} - 2a_{66}$. For convenience, the stiffnesses are normalized by the bulk density ρ of the solid ($a_{mn} = C_{mn}/\rho$, with C_{mn} – capital letter – representing a stiffness c_{ijpq} in Voigt's notation). Giving the bulk density in g/cm^3 and c_{ijpq} in GPa, the density–normalized stiffnesses are measured in km^2/s^2. As a result, velocities along a certain direction of wave propagation are provided, in km/s, by the square root of the corresponding density–normalized elastic parameter.

For an elastic material, stability constraints guarantee positiveness of the strain energy. To derive the stability constraints, the determinant of the elastic matrix and of all its minor determinants must be positive (Helbig, 1994). If a general TI solid is considered, the following inequalities apply simultaneously

$$a_{11} > 0, \quad a_{33} > 0, \quad a_{44} > 0, \quad a_{66} > 0, \quad a_{33}(a_{11} - a_{66}) > a_{13}^2. \tag{2}$$

Note that the inequalities in (2) summarize those given in Postma (1955).

In seismic anisotropy studies, available measures provide a way of evaluating the strength of anisotropy for the material under investigation. As a consequence, the deviation of the data from isotropy can be studied as well since, in this case, these measures of anisotropy reduce to zero.

By considereing a TI material, Thomsen (1986) defines

$$\epsilon = \frac{a_{11} - a_{33}}{2a_{33}}, \qquad \gamma = \frac{a_{66} - a_{44}}{2a_{44}}, \qquad \delta = \frac{(a_{13} + a_{44})^2 - (a_{33} - a_{44})^2}{2a_{33}}. \tag{3}$$

The above dimensionless parameters are frequently used in experimental studies (Wang, 2002) and in seismic imaging in anisotropic media (Alkhalifah and Tsvankin, 1995). Calculation of ϵ, γ and δ in rock samples suggests that weak anisotropy ($|\epsilon|$, $|\gamma|$ and $|\delta| \ll 1$) is a rather common phenomenon in sedimentary basins (Thomsen, 1986). As expected, Thomsen's parameters ϵ, γ and δ constitute measures of anisotropy applicable to the ANNIE approach described below.

2.2. The Model ANNIE

The approach named ANNIE (Schoenberg et al., 1996) represents a particular case of a TI material which is fully characterized by only 4 stiffnesses. ANNIE is formulated as a best approximation for seismic anisotropy in laminated shales. The formulation of ANNIE takes into account that the parameter δ in (3), which controls P–wave normal –moveout velocities, is found to be nearly zero in most sedimentary rocks. Sayers (1995) gives the Taylor series expansion for δ as: $\delta = (a_{13} + 2a_{44} - a_{33})/a_{33} + (a_{13} + 2a_{44} - a_{33})^2/[2a_{33}(a_{33} - a_{44})]$. As a result, the following first equality constraint for ANNIE holds

$$a_{13} + 2a_{44} - a_{33} = 0. \tag{4}$$

By setting $\delta \to 0$, the zero-offset normal–moveout velocity is equal to the vertical velocity $\sqrt{a_{33}}$ in the TI material described by ANNIE.

The additional equality constraint imposed to ANNIE is $a_{13} = a_{12}$. Thus, the combination of the relation for a_{12} with Eq. (4) leads to

$$a_{11} - a_{33} = 2\,(a_{66} - a_{44}), \tag{5}$$

which relates all horizontal and vertical waves (qP, qSV and qSH) propagating in the material.

ANNIE is further subjected to additional inequalities constraints as follows

$$\frac{a_{66} - a_{44}}{a_{44}} > 0, \qquad 0 < \frac{a_{44}}{a_{33}} \le \frac{1}{2}. \tag{6}$$

By considering the previous restrictions imposed to ANNIE, the following relation is obtained

$$\gamma = \frac{1}{2}\frac{a_{33}}{a_{44}}\,\epsilon, \tag{7}$$

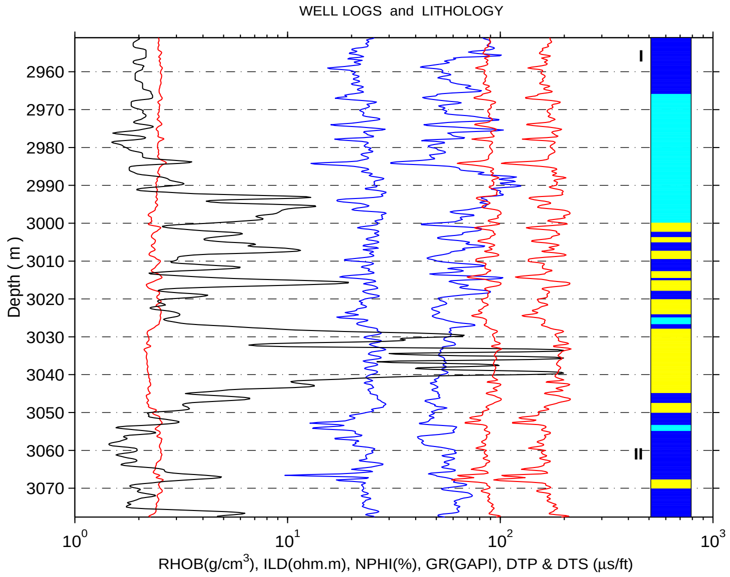

Figure 1: The well chosen for the accomplishment of a seismic anisotropy study. Log properties are assigned in order of occurrence in the plot. The lithologic column at the right depicts turbiditic shales (dark color), oil–bearing sandstone reservoirs (light color) and carbonate-rich shales and calciluties (light–to–dark color). The shales assigned I and II are known to be laminated rock composites.

where, in view of Eqs. (5) and (6), γ and ϵ are always positive quantities. In addition, $\gamma > \epsilon$ since $a_{33} = a_{44}$. The relation in (7) seems to be quite useful for the study of anisotropy in samples of laminated shales which anisotropy is approximated by ANNIE.

3. Application of ANNIE to Real Data

The use of ANNIE in approximating seismic anisotropy in shales implicitly assumes thin clay laminae forming the microstructure of the rock. Application of this model to real data is restricted to ultrasonic data. In Schoenberg et al. (1996) experimental data at increasing confining pressure are used to estimate the stiffnesses of the corresponding ANNIE models. The present study, however, focuses on applying ANNIE for the prediction of elastic moduli in two laminated shale intervals. Sonic logs rather than ultrasonic data are the main source of information used for elastic stiffnesses calculation.

3.1. Description of the Data

The well chosen for the present anisotropy study is shown in Figure 1. The lithologic column displays oil–bearing sandstone reservoirs encased in turbiditic shales and in other mixed lithologies as carbonate-rich shales and calcilutites. The displayed lithology was constructed with the help of all available logs and observation of cores at corresponding depths. The absence of the S–wave sonic log for this well was compensated by the use of a methodology given in Castagna et al. (1985) for estimating S–wave logs from P–wave sonic data. Both extremes (I and II) of the lithologic column depict shales which are reported to be clay–laminated composites. For these shales, predominance of horizontal foliation supports the assumption of vertical axis of symmetry. Prediction of elastic moduli in both shale intervals was accomplished according to the methodology described below. Results are shown only for the shale interval II.

3.2. Methodology

The methodology used in this seismic anisotropy study can be summarized as follows:

1. Estimation of the vertical S–wave velocities from the existing P–wave sonic log. The methodology given in Castagna et al. (1985) is applied [$V_S = (V_P - 1.36)/1.16$ (km/s), where V_P is the vertical compressional–wave velocity and V_S the vertical shear–wave velocity].
2. Calculation of the elastic moduli $a_{33} = V_P^2$ and $a_{44} = V_S^2$. The density–normalized stiffness a_{13} is then estimated similarly as in the isotropic case [Eq. (4)].

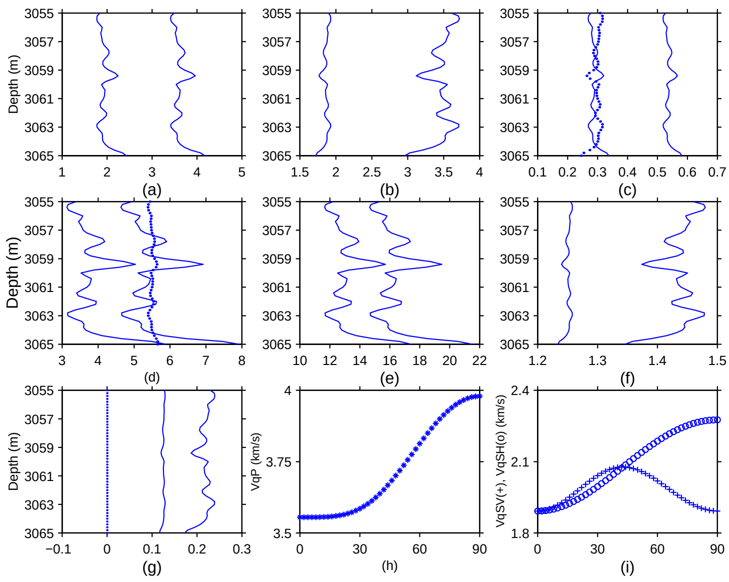

Figure 2: Results from the investigation of seismic anisotropy in the laminated shale interval II in Figure 1: (a) V_S and V_P vertical velocities (km/s); (b) V_P/V_S and V_P^2/V_S^2 ratios; (c) Poisson, V_S/V_P and V_S^2/V_P^2 (dotted) ratios; Stiffnesses estimated in the shale interval using ANNIE (d) a_{44}, a_{13} (dotted) and a_{66} and (e) a_{33} and a_{11} (km^2/s^2); (f) The ratios a_{11}/a_{33} and a_{66}/a_{44}; (g) Thomsen's parameters δ (dotted), ϵ and γ for the shale interval; (h) qP–wave (V_{qP}) phase velocity (km/s) as a function of phase angles (degrees) at 3057 m depth; (i) qS–wave phase velocities (km/s) at 3057 m depth [$V_{qSV}(+)$ and $V_{qSH}(\mathrm{o})$].

3. For estimating the stiffnesses a_{11} and a_{66}, the indetermination shown in the relationship (5) is eliminated as follows. The isotropic Poisson ratio σ_{iso} is calculated. For a TI solid with vertical axis of symmetry, the Poisson ratio ($\sigma_{\mathrm{TI}} = \sigma_{32} = \sigma_{31}$) associated to both the transverse and the longitudinal deformations due to a stress applied along the axis of symmetry x_3 is given as $\sigma_{\mathrm{TI}} = a_{13}/(a_{11} + a_{12})$. In view of ANNIE's constraint $a_{13} = a_{12}$, one can write $a_{11} = \kappa_\sigma a_{13}$, where $\kappa_\sigma = 1/\sigma_{\mathrm{ANNIE}} - 1$. Thus, an estimate for the Poisson ratio σ_{ANNIE} in laminated shales allows calculating the density–normalized stiffnesses a_{11} and, consequently, a_{66}. By using the data published in Wang (2002), it is observed that σ_{ANNIE} is 15% less than σ_{iso}. Hence, the adoption of $\sigma_{\mathrm{ANNIE}} \approx 0.85\sigma_{iso}$ represent a reasonable choice for the calculation of κ_σ. The stiffness a_{11} is then computed with $a_{11} = \kappa_\sigma a_{13}$, and a_{66} with Eq. (5).
4. Test of the estimated stiffnesses for the stability constraints in Eqs. (2) and (6). In case of need, the relation between σ_{ANNIE} and σ_{iso} can be modified so a to honor ANNIE stability constraints.

3.3. Results

The outcomes of the investigation performed in the shale interval II are shown in Figure 2. The trend of the predicted shear–wave velocity log in Figure 2a is similar to the existing P–wave velocity log. This similarity indicates that the methodology of Castagna et al. (1985) is suitable enough for predicting S–wave velocities from P–wave data in this sedimentary region. The velocity ratios in Figures 2b and 2c display an acceptable range of variation for shales. For instance, if the ratio $V_P/V_S = 2$, the isotropic Poisson ratio will be 1/3. However, for the whole shale interval, σ_{iso} is below 1/3. Note that the ratio V_S^2/V_P^2 (dotted line in Figure 2c) is below the limit imposed by ANNIE's constraint in (6). This is certainly an indication that Castagna et al.'s (1985) methodology provides accurate S–wave velocities in this sedimentary region.

Figures 2d and 2e show logs of elastic stiffnesses as a function of depth. It can be observed that ANNIE constraints hold for the whole interval. Further, the average values for the ratios a_{11}/a_{33} and a_{66}/a_{44} in Figure 2f are nearly 1.25 and 1.45, respectively, which match previous assumptions made in Wright (1987). This is a quite surprising result since the cited author made no consideration on the anisotropic Poisson ratio for the determination of stiffnesses in shales.

Logs of Thomsen's parameters are plotted against depth in Figure 2g. As assumed in ANNIE's formulation, the parameter δ vanishes for the whole interval. The range of variation displayed by ϵ and γ are expected for sedimentary rocks with weak strength of anisotropy (Thomsen, 1986). For completeness of the study, Figures 2h and 2i show phase velocities at 3057 m depth as a function of incidence angle. The plots confirm the importance of taking into account seismic anisotropy effects at far offsets. At the chosen depth, qP–wave anisotropy starts affecting data from 25^o of incidence, while qS–wave anisotropy is observed for an incidence near 15^o.

4. Conclusions

Both compressional–wave and shear–wave sonic logs can be used for estimating elastic stiffnesses in horizontally–laminated shales. In using the ANNIE approach, the Poisson ratio serves as additional information to constraint computations of the elastic moduli in those rocks. By analyzing published laboratory data from world–wide sedimentary environments, it was observed that the Poisson ratio in the ANNIE model was 15% less than the Poisson ratio in the isotropic case. This relationship allowed evaluating ANNIE's elastic matrix at all depth positions in the shale intervals investigated. Although the estimatives are acceptable for sedimentary rocks, only use of laboratory measurements can lead to a thorough analysis. For instance, correlation of calculated with measured elastic moduli can reveal the extent of uncertainties in computations.

As far as the author is concerned, this research can be considered original in two senses. First, no previous work used sonic logs for calculating elastic moduli in laminated shales by means of ANNIE approach. Second, no similar seismic anisotropy study was accomplished in Campos basin with public data. As a consequence, this work represents the starting point for a research project on seismic anisotropy investigation in Campos basin. Available sonic logs will be used as the main source of information for calculating elastic moduli in shales. Future multicomponent seismic data surveys in this sedimentary scenario can benefit from the results of the proposed research project.

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