Utilizing Conventional Well Logs to Determine Anisotropic Information of Clastic Rocks: A Feasibility Study

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Summary

A rock physics mapping method was developed to determine anisotropic parameters in vertical transverse isotropic (VTI) media by utilizing conventional well logs. This methodology is based on an assumption that anisotropic properties of rocks in the principal anisotropic directions are related, and that the horizontal velocity is a function of the vertical velocity and the volume of clay in rock. This assumption has been validated by lab measurements, which indicate that velocity anisotropy parameters have a linear relationship with clay volume that determines clay mineral orientation. Thus, the rock physics mapping method is established based on this relationship and existing anisotropic measurements. The prediction using this mapping method is compared with other methods.

Introduction

Anisotropic properties of rocks are of importance for seismic imaging (e.g., Vestrum and et al., 1999), seismic interpretation, and reservoir characterization. They also affect the quality of AVO analysis due to their effect on offset dependent amplitudes. The determination of rock anisotropic properties encounters numerous difficulties in association with cost, accuracy, and applicabilities of the existing methodologies. The measurements of rock anisotropic properties have been conducted mainly in laboratory (e.g., Jones and Wang, 1981; Johnston and Christensen, 1995; Vernik and Liu, 1995) and in situ through crosshole seismic or VSP (e.g., Winterstein and Paulsson, 1989; Byun et al., 1989) or seimic refraction (Leslie and Lawton, 1999). The link between rock physical properties, such as mineral orientation, and rock anisotropy properties in clastic rocks has been recognized (e.g, Liu, 1994, Johnston and Christensen, 1995). In a study of anisotropic properties of the Monterey shales, the origin of anisotropy of rocks has been described by Liu (1994) as preferred clay particle orientation, the micro laminated and lenticular kerogen-clay mixture. A SEM image by Hornby et al.(1994) illustrated that the platey clay minerals and silt in a shale were consistent with Liu's descriptions. A quantitative approach for describing direction dependent properties of shale was given by Johnston and Christensen (1995) who used orientation index determined by X ray diffraction patterns of minerals to measure the degree of alignment of clay minerals. A linear relationship between orientation index and velocity anisotropy was observed in their study. In this study, these relationships are examined for the purpose of linking conventional well logging measurements, which are measured in the vertical, to rock anisotropic properties. The expected output is rock anisotropic properties or anisotropic parameters. The ultimate goal is to develop a rock physics mapping method that can be used practically.

Rock Physics Background

Two important mineral compositions of clastic rocks are clay and quartz. The volume of clay is often considered equivalent to volume of shale in well log analysis. Their elastic properties, volume fraction, and orientations, control the effective properties of clastic rocks. The clay minerals often are flat and platy. Their orientations are affected by its volume fraction and the degree of compaction of the rock. Physically, anisotropy of rocks is determined by the orientations of minerals. It is further influenced by compaction of the rocks. Ocean bottom deposits and low velocity weathering layers may not display anisotropy even with high clay content. With increasing of compaction, clay minerals tend to align in the direction perpendicular to overburden. High velocity in the bedding direction is thus formed. Figure 1 illustrates the effect of clay volume and compaction on rock anisotropic properties.

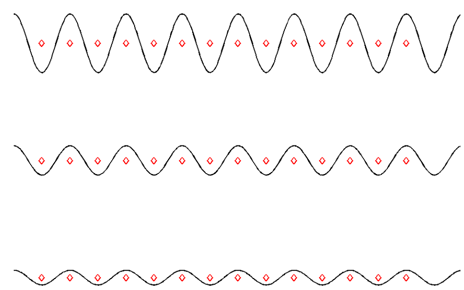

Fig 1. Compaction of rock results in alignment of clay minerals in horizontal direction. The alignment is affected by the amount of quartz grains in rocks.

Rock anisotropy can be described by the anisotropic parameters ε, γ, and δ, where $\varepsilon = (c_{11} - c_{33})/2c_{33}$, $\gamma = (c_{66} - c_{44})/2c_{44}$, and $\delta = \{(c_{13} + c_{44})^2 - (c_{33} + c_{44})^2\}/2\, c_{33}(c_{33} - c_{44})$. For weak anisotropy, Thomeson (1986) simplified these parameters to $\varepsilon = (Vp_{\parallel} - Vp_{\perp})/ Vp_{\perp}$, $\gamma = (Vs_{\parallel} - Vs_{\perp})/ Vs_{\perp}$, and $\delta = (Vp_{45^\circ} - Vp_{\perp})/ Vp_{\perp} - \varepsilon$, where "||" and "⊥" represent the directions parallel and perpendicular to the fast velocity direction. Figure 2 shows how these parameters influence phase velocities and slowness. Figure 2a illustrates weak anisotropic cases ($\varepsilon = 0.25$) and Figure 2b shows strong anisotropic cases ($\varepsilon = 0.5$). $\delta = \varepsilon$ (elliptical anisotropy), 0.0, and $-\varepsilon$. The values used here cover all possible anisotropic situations.

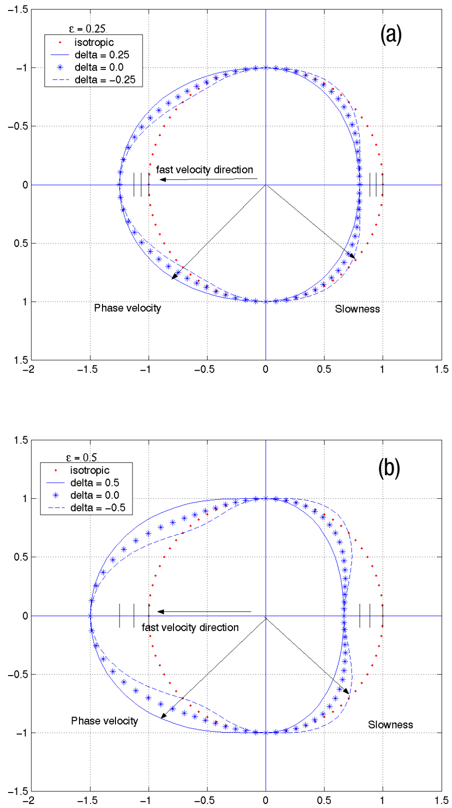

Fig. 2 Phase velocities and slowness: a) in weakly anisotropic media, and b) in strong anisotropic media.

A statistical approach was taken to evaluate the relationships between anisotropic parameters by using published anisotropic measurements (Thomsen, 1986; Vernik and Nur, 1991; Johnston and Christensen, 1995, Vernik and Liu, 1996). The crossplotting of ε vs. γ, δ, and ε–δ (Figure 3) indicates the following relationships: 1) ε and γ are approximately equivalent; 2) best fitting to δ yields a relationship of $\delta = 0.32\,\varepsilon$; and 3) as observed by others, elliptical anisotropy should not be considered as commonly encountered cases.

Anisotropic Parameter Mapping Method

The first key question to answer is whether there exists a relationship between vertical and horizontal velocity.

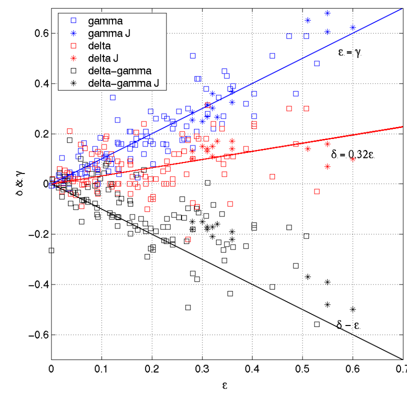

Fig. 3 Relationship between ε, γ, and δ.

Intuitively, an increase in vertical velocity should result in a proportional increase in the horizontal velocity. This is because giving rock composition higher vertical velocity implies that the rock is more compacted and at the same time implies clay minerals have better alignment in horizontal direction. The second question is associated with fraction of clay minerals and its relationship with orientation of clay minerals. For clean sand, compaction may have the same influence on rock physical properties in all directions. This is different for a rock with high volume of clay. Using vertical velocity to represent rock compaction and clay volume to represent clay mineral alignment becomes apparent. However, a quantitative relationship to describe these facts must be found in order to predict anisotropic properties of clastic rocks.

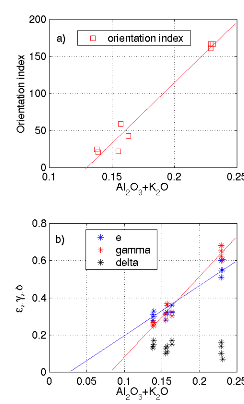

Fig. 4 The relationship between clay volume, clay mineral orientation index and anisotropic parameters (data from Johnston and Christensen, 1995)

Figure 4a and 4b show the relationship between volume fraction of major clay minerals (Al_2O_3 and K_2O), mineral orientation index and rock anisotropic parameters, which were calculated using laboratory measurements fromJohnston and Christensen (1995). It is apparent that the orentation index is linearly correlated to clay volume. A linear relationship exists between anisotropic parameters and clay volume as well. Combining these facts and the correlations for both vertical and horizontal velocities to compaction of rock, a rock physical mapping technique was developed. Figure 5 illustrates this. Notice that the data in Figure 5 is the same as used in Figure 3. In Figure 5a, the anisotropic parameter ε is a function of P-wave vertical velocity and clay volume. Each line represents the rock with given clay volume. It can be seen that with increasing velocity, ε increases and then decreases. This may illustrate that early stage compaction results in alignment of clay minerals but this effect decreases when the majority of alignments have been accomplished. Consequently, if the vertical velocity and clay volume are given, ε can thus be calculated. This could be used to obtain anisotropic parameter γ by using vertical S-wave velocity (Figure 5b). In Figure 5, the ε data points from Johnston and Christensen (1995) have been separated accordingly with respect to the clay volume.

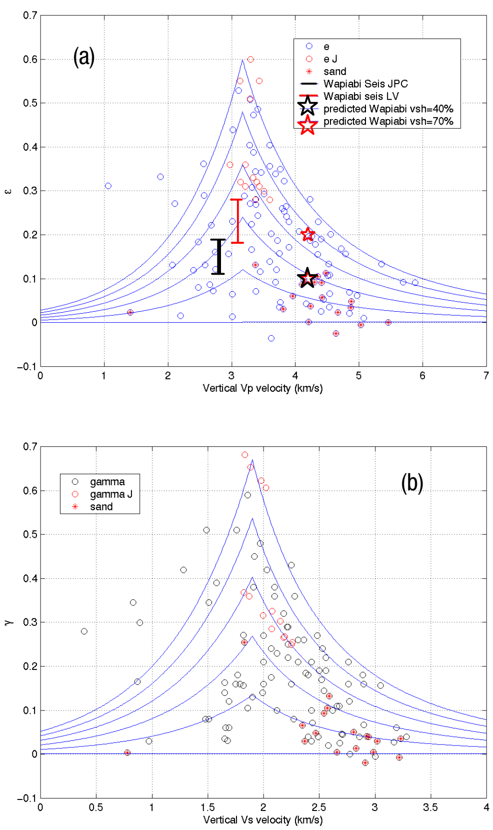

Fig. 5 The relationship between vertical P-wave velocity (a) , S-wave velocity (b), clay volume, and anisotropic parameters. Red thick lines represent the measurements of Wapiabi formation by seismic refraction (Leslie and Lawton, 1999). The stars are the predictions using conventional well logs.

Prediction Example

Figure 6 shows an example of the prediction using well logs from well 06-19-19-03w5 in the Foothills area of Southern Alberta. The target formation of the prediction is Wapiabi clastic rocks. The top Wapiabi formation has shale volume equal to about 40% and the lower potion has a value of about 75%, both are calculated from gamma ray. Using the sonic velocity and the volume of shale, ε values are predicted for the entire log curve. The average value for ε in the upper part of Wapiabi formation is about 0.1 and about 0.2 for the lower part where higher volume of shale is present. These predictions together with the measurements from refraction seismic (Leslie and Lawton, 1999) for this formation are projected in Figure 4a. The prediction here for the upper part of formation is consistent with Leslie and Lawton's (1999) results. In addition, δ was predicted as 0.032 and 0.064, respectively, by using the empirical relation of $\delta = 0.32\varepsilon$. In this study, γ has not been predicted due to the lack of shear sonic at the well used.

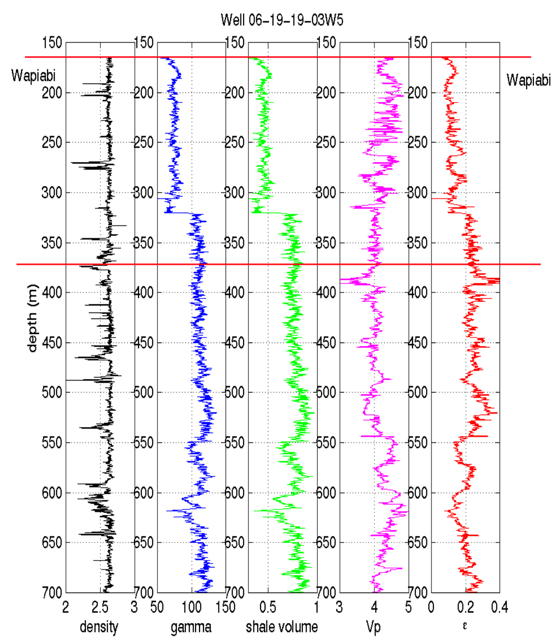

Fig. 6 The prediction of ε at well 06-19-19-03W5 in the LongView, Foothills area of Southern Alberta.

Conclusions

Utilizing conventional well logs to predict anisotropic properties of clastic rocks has been shown to be consistent with seismic measurements. It indicates that rock anisotropy could be predicted from conventional well logs. Further validation is required to achieve more accurate predictions.

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