Anisotropic Parameter Prediction in Clastic Rocks

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Summary

A method to predict anisotropic well logs in clastic rocks rock was developed. It is based on an assumption that anisotropic properties of rocks in the principal anisotropic directions are related, and the horizontal velocity is a function of vertical velocity and volume of clay in rock. The predicted anisotropic logs are compared with VSP measurements. The application of the predicted anisotropic well logs in lithology discrimination and synthetic anisotropic seismogram generation is explored.

Introduction

Anisotropic properties of rocks are important for seismic imaging, seismic interpretation, and reservoir characterization. They also affect the quality of pre-stack seismic analysis, amplitude analysis, velocity analysis, and rock property inversion. The determination of rock anisotropic properties encounters numerous difficulties in association with cost, accuracy, and applicabilities of the existing methodologies. Measurements of rock anisotropic properties have been conducted mainly in laboratory (e.g., Johnston and Christensen, 1995; Vernik and Liu, 1995, Wang, 2002), in situ through crosshole seismic or VSP (e.g., Winterstein and Paulsson, 1989) and seimic refraction (Leslie and Lawton, 1999). The link between rock physical properties, such as mineral orientation and porosity, and rock anisotropy properties in clastic rocks has been recognized (e.g, Liu, 1994, Johnston and Christensen, 1995, Wang, 2002). In studying anisotropic properties of the Monterey shales, Liu (1994) described one of the origins of anisotropy is due to the preferred clay particle orientation. A SEM image from Hornby et al.(1994) illustrates that alignment of clay minerals in a shale sample is affected by silts. Johnston and Christensen (1995) took a quantitative approach in describing direction dependent properties of shale, by using orientation index determined from X ray diffraction patterns of minerals. They found that a linear relationship between orientation index and velocity anisotropy exists. In this paper, these relationships are examined for the purpose to link conventional well logging measurements, which are measured mainly in the vertical, to rock anisotropic properties. The output is predicted anisotropic well logs.

Anisotropy Prediction Method

Clay and quartz are two principal mineral compositions in clastic rocks. Their elastic properties, volume fraction, and orientations control the effective properties of clastic rocks. Clay minerals often are flat and platy. The volume of clay is often considered equivalent to the volume of shale in well log analysis. The orientations of clay minerals are affected by clay volume and compaction. For instance, ocean bottom deposits and low velocity weathering layers may display little or no anisotropy even they have high clay content. With compassion increasing, clay minerals tend to align in the direction perpendicular to overburden. High velocity in the bedding direction is thus formed. Figure 1 illustrates this effect.

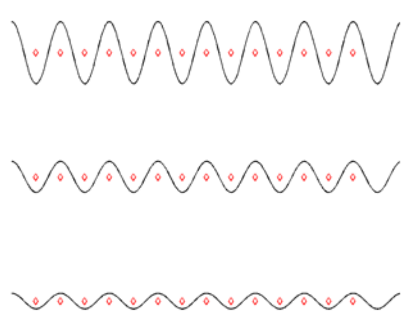

Fig 1. Degree of alignment of clay is affected by the amount of quartz grains, clay volume, and compaction.

For weak anisotropy, Thomsen (1986) defines the simplified anisotropic parameters as $\varepsilon = (Vp_{||} - Vp_{\perp})/ Vp_{\perp}$, $\gamma = (Vs_{||} - Vs_{\perp})/ Vs_{\perp}$, and $\delta = (Vp_{45^o} - Vp_{\perp})/ Vp_{\perp} - \varepsilon$, where "||" and "$\perp$" represent the directions parallel and perpendicular to the fast velocity direction. Here, a statistical approach was taken by using published anisotropic measurements (Thomsen, 1986; Vernik and Nur, 1991; Johnston and Christensen, 1995, Vernik and Liu, 1996) to examine the relationships between anisotropic parameters (Figure 2). Figure 2 reveals the following relationships: 1) ε and γ are approximately equivalent; and 2) best fitting to δ yields a relationship of $\delta = 0.32\ \varepsilon$.

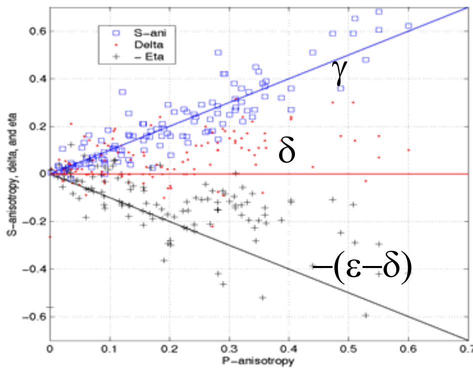

Fig. 2. Relationship between □□□, □ and □.

Except the above relationships, we are interested in whether a relationship between vertical and horizontal velocity exists. Intuitively, an increase in vertical velocity should result in a proportional increase in the horizontal velocity. This is because for giving rock composition higher vertical velocity implies that clay minerals have better alignment. We are also interested in how volume of clay affects the orientation of clay minerals. For clean sand, compaction may influence on rock physical properties similarly in all directions. It is apparent that this is different for a rock with high volume of clay. A quantitative relationship to describe these physical understandings must be found in order to predict anisotropic properties in clastic rocks.

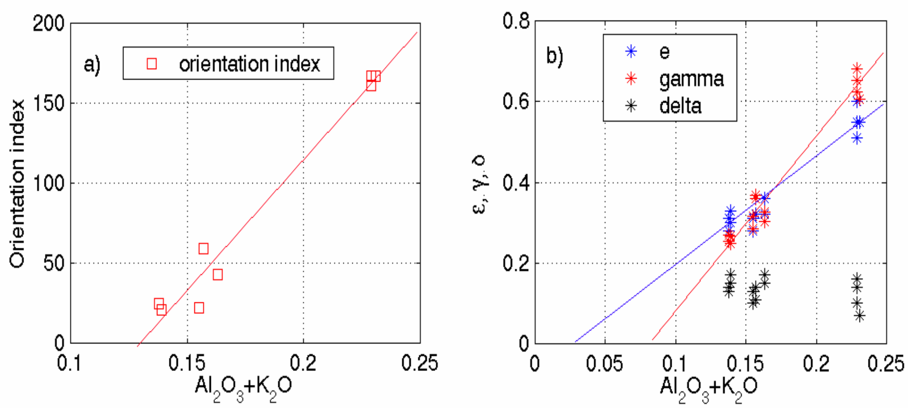

Fig. 3. Relationship between clay volume, clay mineral orientation index and anisotropic parameters.

Here, we use laborotary result from Johnston and Christensen (1995) to explore the relationships we are interested. Figures 3a and 3b show the relationships between volume fraction of major clay minerals (Al_2O_3 and K_2O), mineral orientation index and rock anisotropic parameters (two times of Thomsen's anisotropic parameters). First, we see that the orientation index is linearly correlated with clay volume. Second, we see that a linear relationship exists between anisotropic parameters and clay volume.

To predict anisotropic parameters, we ploted all P-wave and S-wave anisotropic parameters from Figure 2 against P-wave velocity and S-wave velocity, respectively (Figure 4). We notice that there are three control points: 1) rock at critical porosity with an approximated velocity of 1.5 km/s; 2) quartz represnting clean sand with zero porosity; and 3) caly with zero porosity. We have the following observations: 1) clean sands is isotropis (see the horizontal line); 2) rock with 100% clay has fast anisotropy increasing with velocity or compaction (see line with 100% clay); and 3) for a rock with given clay content the anisotropic parameter increasing linearly with velocity or sonic velocity.

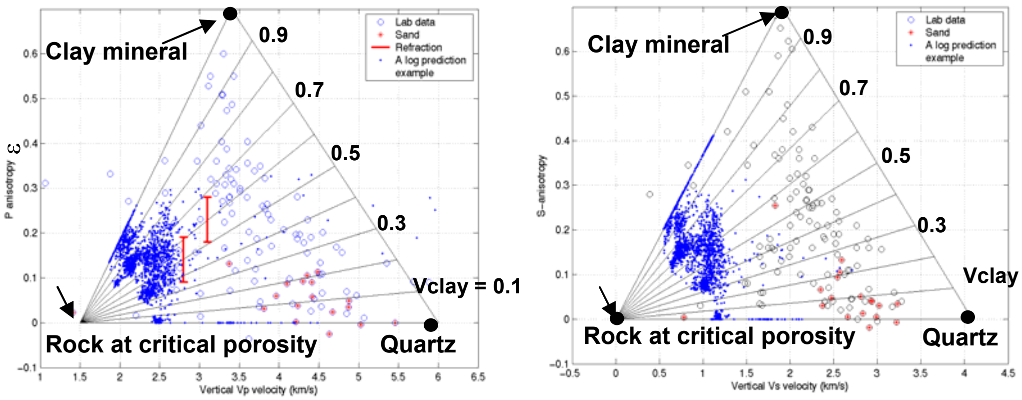

Fig. 4 The relationship between vertical velocities, clay volume, and anisotropic parameters.

Based on Figure 4, the equation for P wave-anisotropic prediction is

$$\varepsilon = \frac{0.7 * Vclay * (Vp - Vp\_water)}{(Vp\_quartz - Vp\_water - 2.29 * Vclay)} \tag{1}$$

and for S-wave anisotropy prediction is

$$\gamma = \frac{0.70 * Vclay * Vs}{(Vs\_quartz - 2.1 * Vclay)} \ . \tag{2}$$

Where the constant Vp_quartz = 6.05 km/s, Vs_quartz = 4.09 km/s, and Vp_water = 1.5 km/s.

VSP Verification and anisotropic well logs

Armstrong et al (1995) conducted a vertical seismic profile (VSP) measurement at a well in the area of North Sea. The target zone is the shale above the reservoir (Figure 5). The shale formation has an average clay volume of 73% and average Vp of 2.3 km/s. The VSP measurement yields P-wave anisotropic parameter ε as 0.l4. Using the well logs as shown in Figure 5 and Equations 1 and 2, we generated P-wave and S-wave anisotropic well logs. Figure 6 illustrates the anisotropy prediction procedure. The arrows demonstrate using clay volume and sonic log to predict anisotropic log. In Figure 6, blue dots represent the data points of entire logs and the red dots are the log segment corresponding to the shale formation. Using the method developed in this study, the value of the predicted P-wave anisotropic parameter for the shale formation is 0.133. It is 5 % lower than the VSP measurement. The predicted S-wave anisotropic parameter has a value of 0.145 that is close to predicted P-wave anisotropic parameter. This is consistent with Figure 2 and the relationship γ = -0.01049 + 0.9560ε that was derived from lab measurements by Wang (2002).

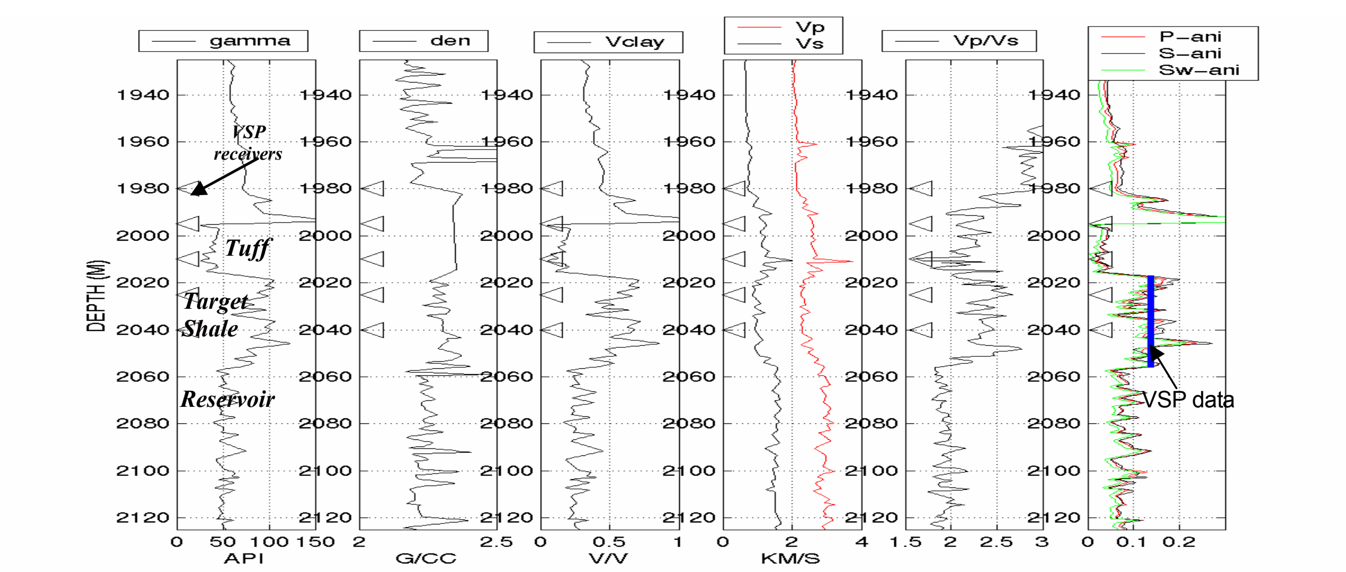

Fig. 5. Dipole sonic logs and predicted anisotropic logs for a well in the North Sea.

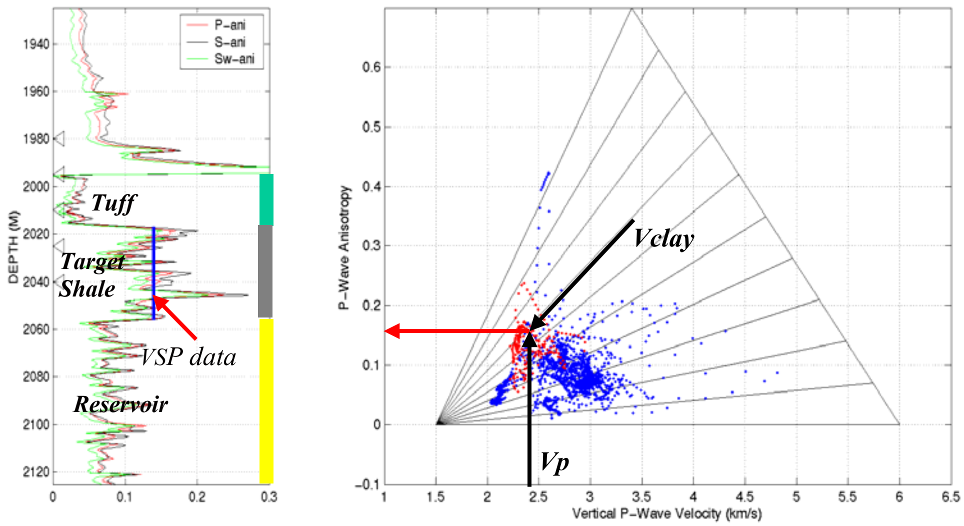

Fig. 6. Anisotropic log prediction and anisotropic well logs.

For a second example, anisotropic well log prediction was performed on a well with dipole sonic logs in West Canadian Sedimentary Basin (Figure 7). We can see that 1) the predicted anisotropic parameters are less than 0.3; 2) the P-wave anisotropic parameters in general are smaller than S-wave anisotropic parameters; and 3) the values of anisotropic parameters for sand are approximately equal to zero.

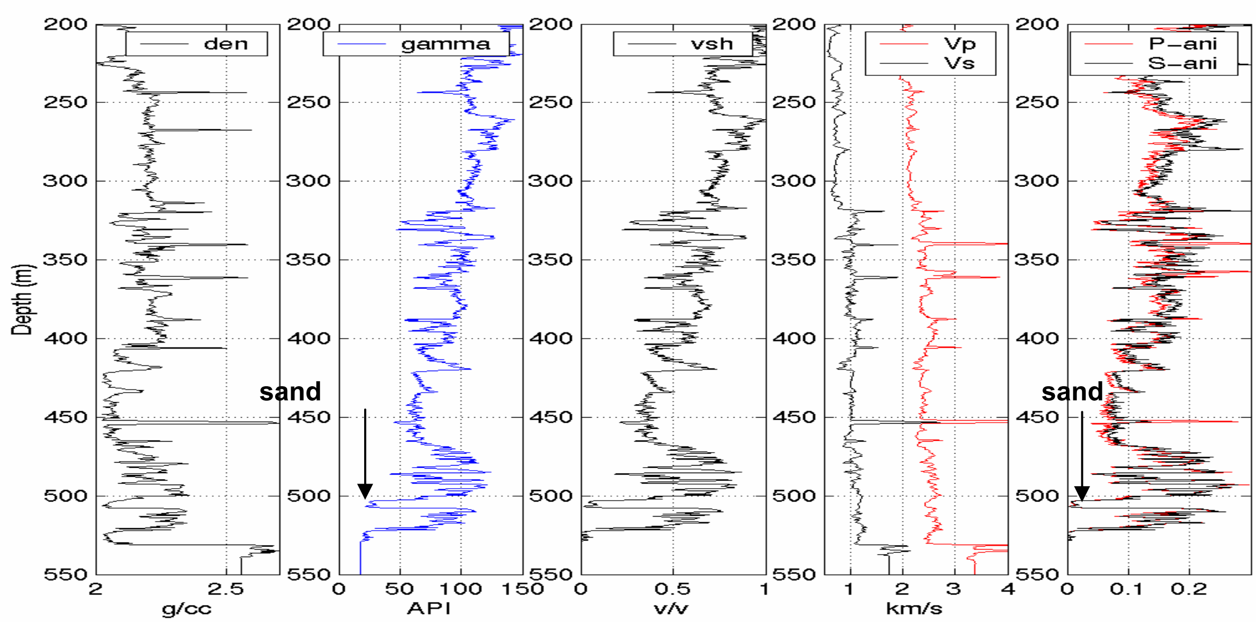

Fig. 7. Anisotropic parameter prediction using well logs from West Canadian Sedimentary Basin.

Anisotropic synthetic seismogram

As most rocks are weakly anisotropy, the contrasts of anisotropic parameters between two layers, $\Delta\varepsilon = \varepsilon 2 - \varepsilon 1$ and $\Delta\gamma = \gamma 2 - \gamma 1$, have a magnitude similar to P- or S-reflectivities. Here we call these contrasts anisotropic reflectivities. We thus generated the anisotropic synthetic seismograms (Figure 8). This synthetic seismogram provides anisotropic contrasts in a band limited seismic fashion. It may be useful for lithology discrimination. In Figure 8, we see that the anisotropic synthetic yields the simple and best contrasts between sands and shales.

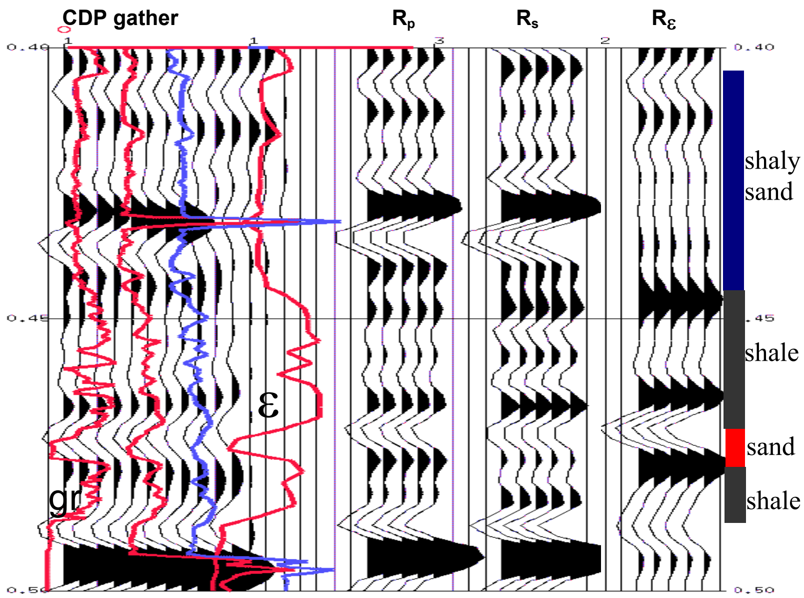

Fig. 8. A synthetic CDP gather with anisotropic synthetic accompanied by P and S-reflectivity synthetics

Conclusions

1. We predicted anisotropic logs using sonic logs and clay volume. The prediction shows consistency with VSP measurements. This newly produced anisotropic information has potential to be used in lithology discrimination, anisotropic synthetic generating, AVO modeling, AVO extraction and inversion, and in seismic imaging.

2. The empirical relationship is established mainly based on physical understanding of the relationship between volume clay and orientations of clay minerals, velocities, porosity and compaction. An optimizing empirical relationship may be obtained by using the data with information of clay volume and porosity.

3. This study suggests that laboratory measurements for anisotropy should conduct no only measuring velocities but also clay volume together with porosity.

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