Ultrasonic measurement of anisotropy on the Kimmeridge Shale:

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Summary

Shales are the most ubiquitous lithology in a sedimentary basin and simultaneously the least characterized. We report on the measurement of the anisotropic elastic properties of some 72 suites of plugs from Kimmeridge shale. This represents a total of 216 plug measurements. The anisotropy displays a strong correlation with total organic content even over the limited range of organics sampled. Furthermore the P-wave anisotropy expressed as ε is strongly correlated with the S-wave anisotropy expressed as γ. Measurements of δ while not correlate with either ε or γ appear to be bounded and display both positive and negative values. If the measurements are taken literally, anisotropy appears to be variable within a formation.

Introduction

Anisotropy factors in a first order way into seismic imaging and attribute analyses. The consequences of ignoring anisotropy has lead to the drilling of a good number of dry holes where anomalies are caused by shale on shale or anisotropic shale over or under sands (Margesson and Sondergeld, 1998). The magnitude of anisotropy in shales varies considerable and has been measured to be as much as 42% in shear velocity (Sondergeld and Rai, 1992) and 38% in P-wave (Hornby, et al., 1999). These magnitudes are pathological for many seismic problems. Incomplete estimates of these parameters can be obtained from surface seismic directly. Walkaway VSPs provide a better means to determine the anisotropic elastic constants (Miller et al., 1994) but are often prohibitively expensive. Single borehole logs can not measure the intrinsic elastic anisotropy of the formation. A sufficient number of different angle penetration through a homogeneous shale might provide a surrogate approach in charterizing anisotropy (Hornby, et al., 1999). Measurements on core while expensive remain one of the best means of quantifying the anisotropic elastic constants of a formation, especially when the shale can be captured in the same penetration for reservoir properties and further when the core can be analyzed in real time.

We have extensively sampled a rather stable Kimmeridge shale from two separate wells. The Kimmeridge was sampled soon after recovery and efforts were taken to preserve the original fluids in place. The depth ranges for the core along with the TOC (total organic carbon) variations are shown in Figure 1.

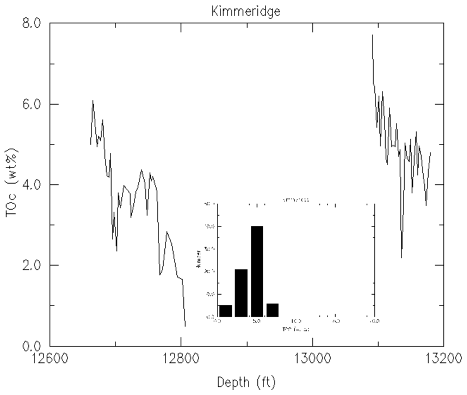

Figure 1 The distribution of TOC in Kimmeridge shale sampled in two wells.

The TOC variation while limited to a maximum of 8% is quite significant in controlling the properties of these samples. The bulk density shows very little dependence on total clay content but does appear to be strongly dependent on TOC (see Figure 2)

We measured the compressional and polarized shear velocities on a suite of 3 plugs taken from a small volume of whole core. The plugs were extracted assuming the shale possessed hexagonal symmetry. Vertical, horizontal and a 45^{o} core plugs were extracted with respect to bedding. These plugs were then sleeved and subjected to effective pressure while the velocities were measured. We present only the parameters measured at 3000 psi in this work. Assuming hexagonal symmetry three plugs are sufficient to calculate the required 5 elastic constants and the Thomsen (1986) parameters (ε, γ, δ). Investigations of anisotropic dependencies upon total clay content proved futile so only those upon TOC will be discussed below.

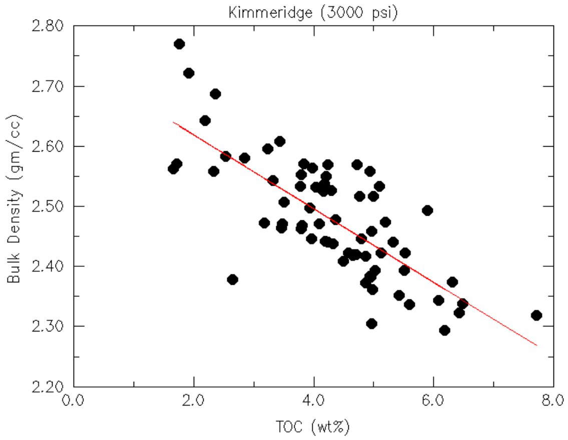

Figure 2: Shale density for all samples plotted against TOC. Bulk density decreases as TOC increases.

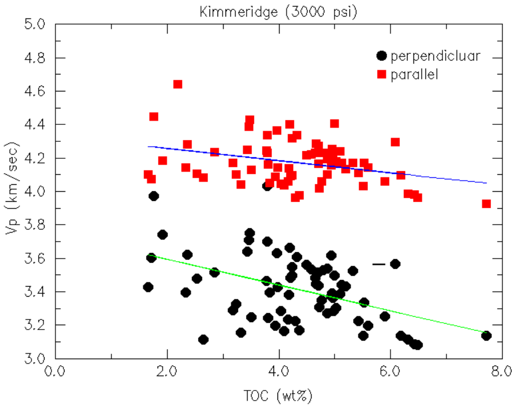

Figure 3: Compressional velocity plotted against TOC for measurements parallel and perpendicular to bedding.

We present the compressional (Figure 3)and shear (Figure 4) velocities measured parallel and perpendicular the bedding planes where the faster shear is polarized parallel to the bedding. These values are plotted against TOC. Vp and Vs appear to have a simple dependence on TOC. The dependencies perpendicular to bedding appear more pronounced for Vp.

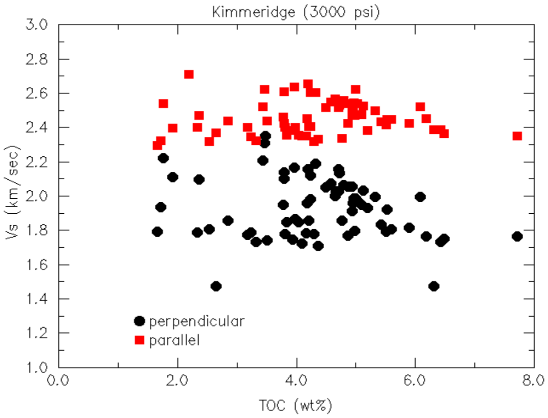

Figure 4: Shear velocities plotted against TOC for measurements perpendicular and parallel to bedding.

A plot of Vp/Vs reveals significant scatter especially for the measurements perpendicular to bedding but an overall trend of decreasing value with increasing TOC (see Figure 5)

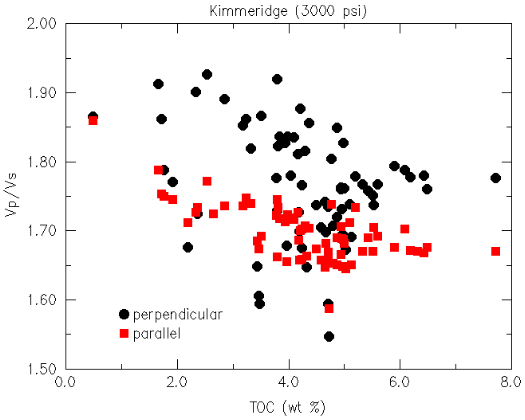

Figure 5: Variation in Vp/Vs ratios perpendicular and parallel to bedding plotted against TOC.

We can combine the measured velocities to compute the parameters ε, γ and δ. The parameters ε and γ are plotted in Figure 6.

Since **ε** represents the P-wave anisotropy and **γ**, the shear, Figure 6 indicates the two are strongly correlated. If either the P-wave or S-wave anisotropy can be measured then one could have confidence in estimating the other.

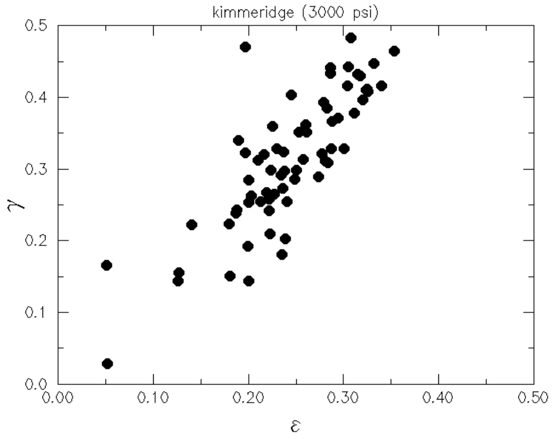

Figure 6: Plot of γ versus ε, the P-wave and S-wave anisotropic parameters. Note the strong correlation.

Our preliminary studies indicate that TOC exerts a control on **ε** and **γ**, however other factors such as clay type and alignment must also contribute. This is displayed in Figure 7 below where **ε** is plotted against TOC. These findings are in accord with those of Rundle and Schuler (1981),Vernik and Liu (1997) and Vernik and Nur (1990) for other kerogen rich shales.

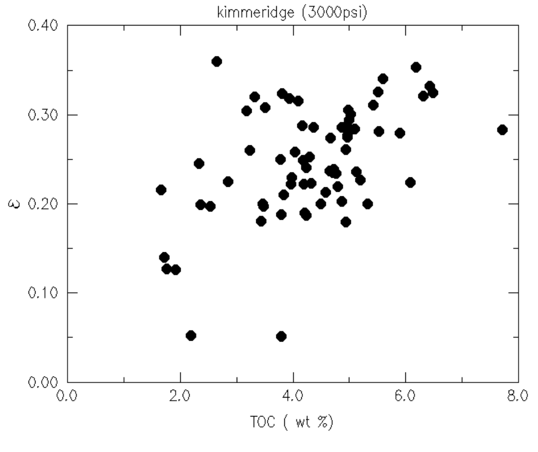

Figure 7: Plot of ε versus TOC. Note the strong linear dependence on TOC.

The anisotropic parameter of most interest to oblique P-wave propagation is of course **δ** (Thomsen, 1986). We plot the values of delta calculated from the required velocity measurements against the parameter **ε** in Figure 8.

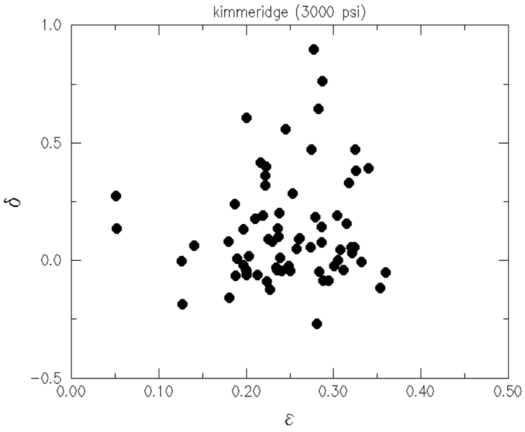

Figure 8:Plot of δ versus ε, the P-wave and oblique anisotropic parameters. δ values are positive and negative and seemingly uncorrelated with ε.

Figure 8 reaffirms some early findings: (1) **δ** can be positive, negative or zero; (2) that there is no apparent correlation between **δ** and either **ε** or **γ**. The independence of **δ** is not surprising in that it involves elastic constant which is not common to either **ε** or **γ**, e.g C_{13}. This constant is derived from measurements on the 45^o plug using either quasi-P or quasi-S waves. It also turns out that C_{13} suffers perhaps most experimental uncertainty in that small alignment errors lead to substantial errors in C_{13} and hence in **δ**.

Heterogeneity

A summary of all the measurements of **ε**, **γ** and **δ** is presented in Figure 9. These histograms show a variation in values of anisotropic parameters which reflect experimental errors and real vertical heterogeneity in the anisotropy of the Kimmeridge shale. While all the values of **ε** and **γ** in these distributions are positive, **δ** has a significant number of negative values. The shear number of negative values would lead us to believe that they are simply not all the result of experimental errors. It is clear however that the measurement of **δ** involves the 45^o core plug and small errors in the angle at which the plug is taken with respect to the anisotropic fabric results in substantial errors in δ.

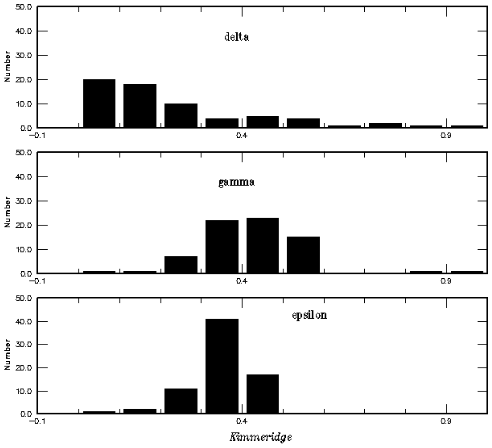

Figure 9: Histograms of the anisotropic parameters ε, γ and δ.

Conclusions

Organic content plays a role in controlling anisotropy in shales. A strong relationship between ε and γ has been documented. δ appears uncorrelated with the other two anisotropic parameters (ε and γ). Measurement of delta are very sensitive to the simple procedures used to take the 45^o core plug. Small errors in the actual orientation of this plug lead to large errors in the ultimate values of δ. Further shales can and do exhibit heterogeneous anisotropy. Upscaling core measurements needs to be considered when comparing to logs or seismic.

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