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An Estimation of Sonic Velocities in Shale Using Clay and Silt Fractions from the Elemental Capture Spectroscopy Log

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SUMMARY

Anisotropic differential effective medium approach is used to simulate elastic properties of shales from elastic properties and volume fractions of clay and silt constituents. Anisotropic elastic coefficients of the wet clay pack are assumed to be independent of mineralogy and to be linearly dependent on clay packing density (CPD), a fraction of clay in an individual wet clay pack. Simulated compressional and shear velocities normal to the bedding plane and are shown to be in a good agreement with measured sonic velocities.

Further, elastic coefficients of shales, and , calculated from the log sonic velocities, calibrated porosity and clay fraction obtained from the mineralogy tool are used to invert for elastic constants of clays, C33 and C44. The obtained elastic coefficients of clays show lower scatter than the original elastic coefficients of shales. The noticeable increase of the clay elastic coefficients with the depth increase is shown to result from the positive trend of the CPD with depth. Being interpolated to the same CPD = 0.8, elastic coefficients of clays show no depth dependency. Our findings show that the CPD and silt fraction are the key parameters that can be used for successful modelling of elastic properties of shales.

Introduction

Knowledge of elastic properties of shales and the parameters controlling those properties are important for the quantitative seismic data interpretation, pore pressure prediction and seismic anisotropy. Shales are complex composite materials with nanoscale intrinsically anisotropic clay platelets of different mineralogy interacting with nanoscale pores and silt inclusions of different shape, size and composition. Thus many factors might critically affect elastic properties of these complex shale composites. Considerable effort has been made to predict elastic properties of shales using detailed knowledge of clay and silt mineralogy provided by XRD analysis, silt and pores aspect ratios and orientation distribution functions of clay platelets obtained from SEM images (e.g., Hornby et al., 1994; Peltonen et al. 2008; Peltonen et al., 2009; Bayuk et al., 2007; Jensen et al., 2011). However, such detailed information can be only obtained in laboratories for a limited number of samples and cannot directly be used for upscaling of the shale elastic properties to the well log or reservoir scale.

Here we attempt to model elastic properties of shales from only two key parameters, namely, clay packing density (CPD) and silt fraction. Clay packing density is defined as a clay fraction in an individual wet clay pack. It was shown by Ortega et al. (2007) that clay packing density is a key parameter that controls elastic properties of the clay constituent. A strong effect of silt fraction on elastic moduli and anisotropy of shales was demonstrated by Pervukhina et al. (2007). Our approach is somewhat similar to GeoGenome model suggested by Abousleiman et al. (2010), although we use an anisotropic differential effective medium (DEM) approach (Nishizawa, 1982) to incorporate the effect of silt on the overall elastic properties of shales. We also assume a linear relation of elastic coefficients with CPD (Pervukhina et al., 2008a; Pervukhina et al. 2008b).

Data and Method

Well log data used in this study are obtained from a well with the maximum deviation of 12° from vertical. Compressional, V_P, and shear, V_S, sonic velocities normal to the bedding plane are used for calculating elastic coefficients of shales as follows

$$C_{33}=\rho V_P^2 \tag{1}$$

and

$$C_{44}=\rho V_S^2, \tag{2}$$

where ρ is a high resolution formation density and V_P and V_S are calculated from slownesses obtained by the Schlumberger DSI tool.

Mineralogy data used are the dry weight fractions of the clay, carbonate, pyrite, siderite and quartz+feldspar+mica combination obtained from the Elemental Capture Spectroscopy (ECS) log. In this particular well, the fractions of carbonate, pyrite and siderite are very small and are neglected in further analysis. As the specific clay mineralogy is not known for this well and the perturbations in the clay density due to the mineralogy cannot be taken into account, the volume fractions of silt, f_s, and clay, f_c, are calculated as follows

$$f_s = (1 - m_c)(1-\phi) \tag{3}$$

and

$$f_c = m_c(1-\phi). \tag{4}$$

Here m_c is the dry weight fraction of clay and ϕ is porosity. In this study we used both (1) neutron porosity calibrated with laboratory measurements and (2) porosity calculated from the high resolution formation density as follows

$$\phi = (\rho_g - \rho)/(\rho_g - \rho_w), \tag{5}$$

where ρ_g is the matrix density obtained from dry weight fractions of the composite minerals estimated with ECS log and ρ_w is the saturating liquid density (brine for this particular well).

All the depths in this study are relative and show the distance from one level; for instance, -940 means the depth 940 m below this level. We assume that the rock is shale when the volume fraction of silt is less than 40% and further analysis is done for the depths where $f_s < 0.4$.

To perform forward modelling of the effect of silt grains, we use the Differential Effective Media (DEM) approach developed for transversely isotropic (TI) medium by Nishizawa (1982). Five elastic coefficients of clay are calculated as follows

$$C_{ij} = C_{ij}^{*}\left(CPD - 0.5\right). \tag{6}$$

Here C_{ij}^{*} are elastic coefficients of hypothetic clay pack with $CPD = 1$, which were shown to be equal to C_{11}^{*} = 46.4 GPa, C_{33}^{*} = 29.9 GPa, C_{13}^{*} = 17.9 GPa, C_{44}^{*} = 6.7 GPa and C_{66}^{*} = 11.2 GPa (Pervukhina et al., 2008a). The clay packing density is calculated as

$$CPD = \frac{f_c}{f_c + \phi}. \tag{7}$$

To invert the elastic properties of shale for elastic properties of the clay pack if a silt fraction and elastic parameters of silt inclusions are known, an algorithm that minimizes modelled and measured elastic coefficients was used. The algorithm is implemented in MATLAB. The developed code is used to invert the measured velocities of shales into elastic properties of clays. To do this we first calculate elastic constants C_{33}^{s} and C_{44}^{s} from the measured sonic V_p and V_s velocities and density using equations (1)-(2). Then the silt fraction is calculated using mineralogy data and calibrated porosity (equation 3). Finally, we use the inversion MATLAB algorithm to compute the elastic properties of the clay pack from the elastic moduli C_{33}^{s} and C_{44}^{s} of shales.

Results and discussion

The velocities estimated using the model described above are shown in Figure 1 in comparison with the measured sonic velocities. Calibrated neutron porosity is used for these simulations. Simulations obtained using porosity calculated from density (equation 5) give similar values of velocities. In both cases the predicted velocities are in a good agreement with the log measurements.

The elastic coefficients C_{33} and C_{44} of clays obtained by inversion from the elastic coefficients of shales vs. shifted *CPD* (*CPD*-0.5) are shown in Figure 2. Calibrated neutron porosity is used for these simulations. For comparison, the elastic coefficients C_{33}^{s} and C_{44}^{s} of shales are shown on the same plots. One can see that the elastic coefficients of clay exhibit observable linear increase with increasing *CPD*, while C_{33}^{s} and C_{44}^{s} exhibit large scatter. Such scatter can be explained with the effect of silt on the elastic coefficients of shale. This effect can be accounted for by the DEM inversion for the clay elastic properties.

When plotted as a function of depth, the elastic coefficients of shales and clays exhibit a small (but clear) increase with depth and strong dispersal caused by the effects of the *CPD* on the clay moduli and of the *CPD* and f_s on the shale elastic coefficients. As the *CPD* parameter also increases with

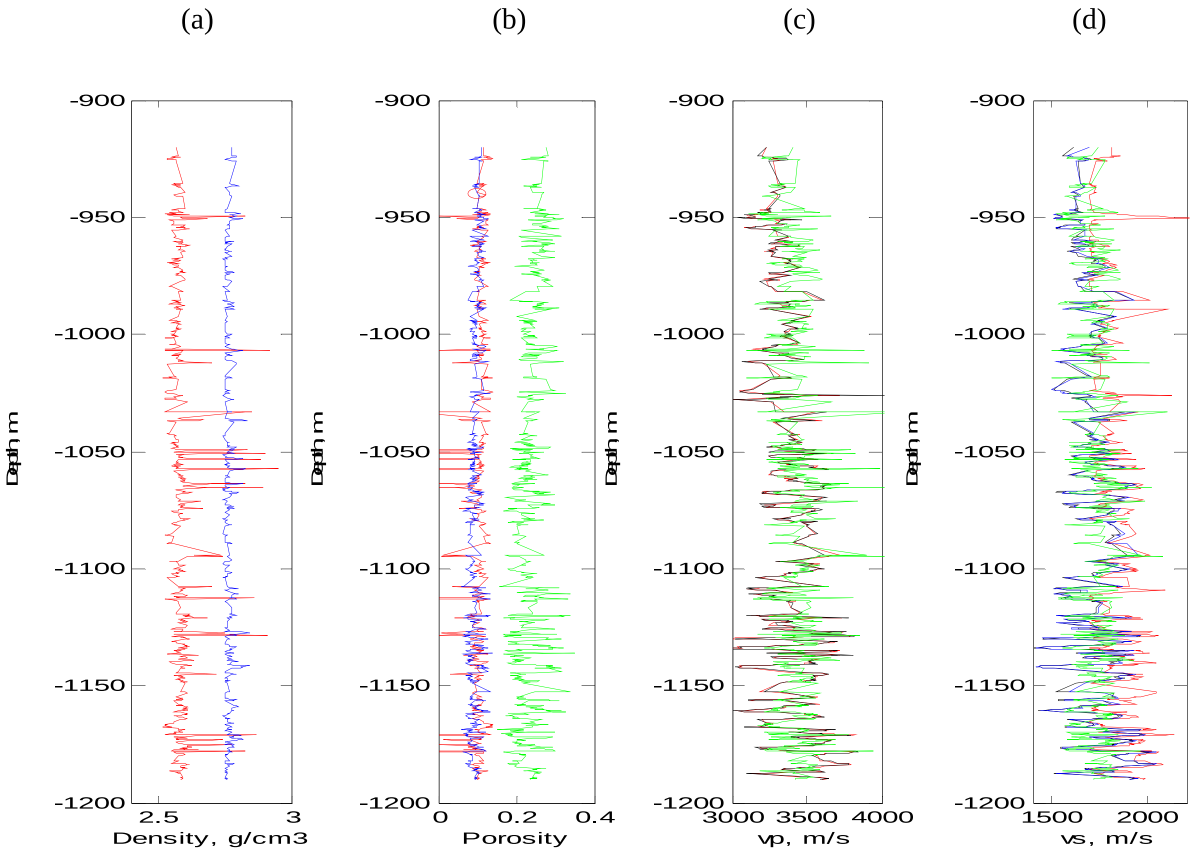

Figure 1 *Log data: (a) Density,, (red) and matrix density, RHGE, (blue); (b) Porosity, (green), calibrated (blue) with laboratory measurement (red circle) and calculated from density (red); (c)* V_P *: measured by monopole P&S transmitter array (red), receiver array (black) and simulated using calibrated neutron porosity (green); (d)* V_S*: measured by monopole P&S (red), by upper dipole (black) and lower dipole (blue) and simulated using calibrated neutron porosity (green).*

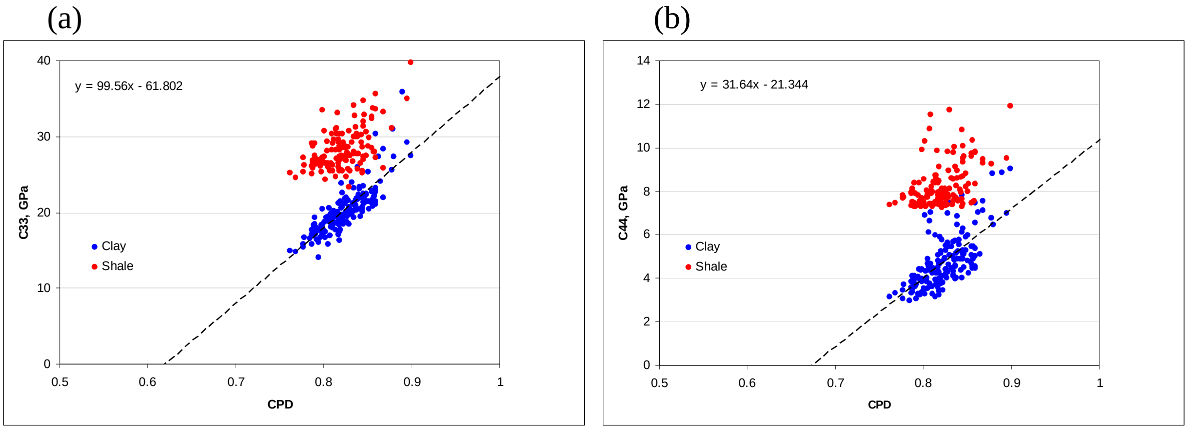

Figure 2 *Elastic moduli of shale (red circles) and clay (blue circles): (a)* C_{33} *and (b)* C_{44}.

depth, the rise in elastic moduli when the depth increases might be caused by either this increase of the *CPD* or the increase of clay moduli. In the latter case for the same value of the *CPD*, elastic moduli would increase when the depth increases. Such a phenomenon can be caused by closure of compliant porosity in clays, which would affect the elastic moduli but would have negligible effect on the *CPD*. To exclude the effect of the *CPD* parameter, we calculated elastic properties of clay for the same *CPD* of 0.8 as follows:

$$C_{ii}^{0.8} = \frac{0.3}{(CPD - 0.5)} C_{ii}^{CPD},\ i=3,4 \tag{8}$$

where C_{ii} and CPD are elastic moduli and clay packing density for a particular depth. The elastic coefficients of clay, $C_{33}^{0.8}$ and $C_{44}^{0.8}$ exhibit no depth dependency.

Conclusions

We demonstrate that clay packing density and silt fraction are key parameters for modelling of elastic properties of shales. Knowledge of these parameters allows accurate prediction of elastic properties of shales without detailed mineralogical analysis. CPD and f_s parameters can be obtained from log measurements if the ECS or similar mineralogy log is available or clay fraction can reliably be estimated from other measurements. The use of porosity calculated from density gives good results. However, neutron porosity cannot be used without having calibration, for example with laboratory measurements.

The clay packing density parameter is shown to be a proxy of effects of compaction processes on elastic properties of clay matrix of shales. The elastic coefficients of clay with the same CPD show no depth dependency.

Acknowledgements

This work was funded through the CSIRO SHARC consortium sponsored by Total, Sinopec, Exxon-Mobil, BG Group, Statoil, Chevron and ConocoPhillips. The sponsors are thanked for permission to publish the work.

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