The Elastic Anisotropy of Whitby Mudstone under Saturated and Partially-Saturated Conditions

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Introduction

Mudstones are unique since they can act as a source, reservoir, seal and/or flow barrier. This makes them of interest in various industries, including for petroleum exploration and underground repository evaluation. These clay-rich rocks are often highly anisotropic (e.g., Vernik and Liu 1997), which complicates predictions in their elastic properties. This results in significant issues in geophysical interpretations, such as depth conversion and imaging of geological structures.

Understanding the elastic anisotropy of mudstones is crucial for successful hydrocarbon exploration and production. Velocity measurements and anisotropy data are reported in the literature (e.g., Jones and Wang 1981; Vernik and Nur 1992), but experiments are often performed on poorly-preserved mudstone samples without any pore pressure control. This does not represent the *in situ* conditions of mudstones, resulting in ambiguities in their elastic properties.

This study examines the impact of water saturation on the elastic anisotropy of the Whitby Mudstone. Undrained compression tests are performed at 25 MPa effective confining pressure on mudstone core plugs with different water saturations. *P*-wave and *S*-wave velocities are measured along multiple ray paths during consolidation and axial loading to obtain Thomsen's anisotropy parameters (ε, γ, and δ) under isotropic stress conditions.

Materials and Methods

The mudstone samples originate from a wave-cut platform in the Whitby Mudstone Formation (WMF). This formation is used as an analogue for the Dutch Posidonia Shale Formation, which is considered as the main shale-gas target of the Netherlands. Mudstone blocks were collected from the same horizon in the outcrop and were stored in seawater to prevent them from drying. Four cylindrical cores were drilled from these blocks. One preserved core was stored in seawater and has an initial saturation of 92% ±10%, whereas three other core plugs were equilibrated in desiccators with different relative humidity atmospheres, corresponding to saturations of 70% ±10%, 58% ±10%, and 28% ±10%.

Undrained compression tests were performed at 25 MPa effective confining pressure on preserved and partially-saturated mudstone samples. The pore pressure was controlled at 2 MPa for the preserved core plug, whereas this was not controlled/monitored for the partially-saturated ones. The core plugs were consolidated until low consolidation rates were reached, and axially loaded with a constant axial displacement rate of 10^{-7} s^{-1}. Four *S*-wave transducers and sixteen *P*-wave transducers were attached directly to the core plug to measure *P*-wave and *S*-wave velocities horizontally (V_{ph}, V_{sh}) and vertically (V_{pv}, V_{s1}), and the quasi-P wave velocity (qV_{p49}). A velocity survey was performed every six hours during consolidation and every hour during axial loading. One survey consists of 18 consecutive shots fired by each transducer acting as a source. During each shot, the remaining transducers act as receivers. The average values of the measured velocities were used to obtain Thomsen's anisotropy parameters ε, γ, and δ (Thomsen 1986).

Elastic anisotropy

The *P*-wave (ε) and *S*-wave (γ) anisotropy of the Whitby Mudstone are high (~0.3, ~0.4, respectively), which is consistent with previous studies (Zhubayev et al. 2016) (Figure 1a, b). The high initial anisotropy is caused by, for example, the alignment of anisotropic clay minerals, and the presence of fractures and laminations.

The degree of water saturation has a significant impact on the elastic anisotropy parameters. Both ε and γ increase with decreasing water saturation. The change in elastic anisotropy with dehydration may be caused by the formation of desiccation fractures. Fractures are known to enhance the elastic anisotropy (Hudson 1981; Vernik and Nur 1992). The value for the wave front geometry (δ) remains ~0 at water saturations ranging from 100% - 58% (Figure 1c), but increases up to ~0.2 at a water saturation of 28%. Note that the uncertainty for δ is extremely large.

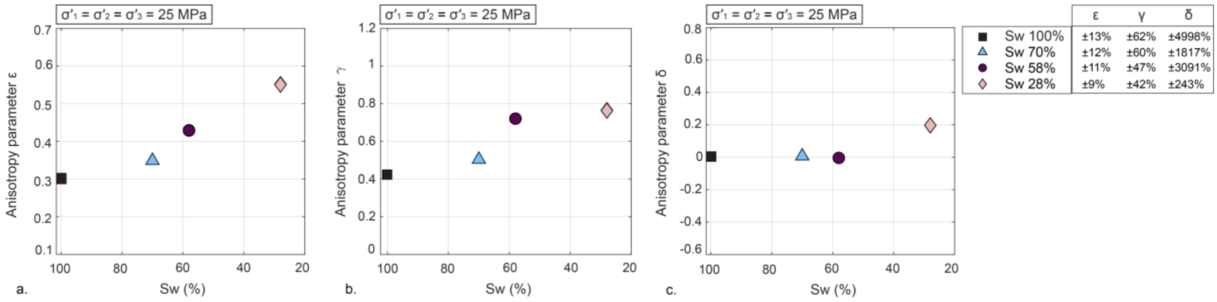

Figure 1: Impact of water saturation (Sw) on the elastic anisotropy parameters (a) ε, (b) γ, and (c) δ of the Whitby Mudstone during isotropic consolidation.

Conclusions

The Whitby Mudstone has a high intrinsic anisotropy. Loss of pore water leads to a significant increase in the *P*-wave and *S*-wave anisotropy. The degree of water saturation should always be reported when performing experiments on clay-rich rocks. In addition, care should be taken when extrapolating the elastic properties obtained from partially-saturated samples to *in situ* conditions.

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