The impact of water saturation on the elastic anisotropy dispersion in the Wellington shale at seismic frequencies

Vassily Mikhaltsevitch
GPO Box U 1987
Perth, WA 6845
V.Mikhaltsevitch@curtin.edu.au

Maxim Lebedev*
GPO Box U 1987
Perth, WA 6845
M.Lebedev@curtin.edu.au

Boris Gurevich
GPO Box U 1987
Perth, WA 6845
B.Gurevich@curtin.edu.au

SUMMARY

The anisotropic behaviour of shales is commonly associated with the properties of a transversely isotropic medium, which are determined by five elastic constants such as five independent components of the compliance or stiffness matrix. In this study, we utilize the laboratory low-frequency technique based on stress-strain relationship to measure the dispersion of five independent stiffness tensor components and Thomsen's anisotropy parameters of shale samples saturated with water at four different values of humidity in the range from 12% to 97.5% (12, 44, 72 and 97.5%). We have investigated three shale samples from the Wellington formation cored along the horizontal, vertical and 45°-inclination directions with respect to the bedding plane at seismic frequencies between 0.1 Hz and 100 Hz.

The obtained experimental data show an increased softening of the samples, which manifests itself in reduction of the transversely isotropic Young's moduli and Thomsen's parameters of elastic anisotropy ε and γ, no noticeable changes in parameter δ were found. We also observed large reductions in normal and shear stiffness tensor components with saturation. When the samples were saturated at a relative humidity of 97.5 %, the softening at the higher frequencies was partly compensated by the modulus dispersion.

We presume that the weakening of the elastic moduli and components of the stiffness tensor is caused by the significant percentage of water-swellable smectite in the Wellington shale.

Key words: Anisotropy, shale, elastic parameters, dispersion

INTRODUCTION

At present, ultrasonic methods are the most popular laboratory practices used for the measurements of the elastic anisotropy of shales (see, e. g., Jones and Wang, 1981, Hornby, 1998; Dewhurst and Siggins, 2006; Wong *et al.*, 2008; Sarout and Gueguen, 2008; Kuila *et al.*, 2011). However, the results of ultrasonic measurements on fluid-saturated shales can be influenced by the fluid-rock interaction mechanisms very different from those dominating in the seismic frequency range. Therefore, a number of important observations made in the ultrasonic studies require additional verification at seismic frequencies. In particular, Liu *et al.* (1994) demonstrated that the behaviours of smectite-free shales and shales containing smectite have a significant difference. It was shown that the components of the elastic stiffness tensor c_{11} and c_{33} obtained for smectite-free samples increase with brine or oil saturation, the components c_{66} and c_{44} c_{33} were not much affected , whereas the samples with smectite content showed significant reductions in c_{11}, c_{44} and c_{66}, and smaller reduction in c_{33} with saturation. This result for the components of the elastic stiffness tensor c_{11} and c_{33} was confirmed at seismic frequencies by Mikhaltsevitch *et al.* (2016 a) where the elastic properties and P-wave anisotropy of the smectite-free Mancos shale was investigated as a function of water saturation.

In this study, we investigate the dependence of the elastic anisotropy characterised by Thomsen's parameters on water saturation using three samples cored at 0°, 45° and 90° angles with respect to the bedding plane. The measurements are conducted on three samples acquired from the Wellington formation. The minerology and physical properties of the samples are similar to the samples investigated earlier in Mikhaltsevitch *et al.* (2016 b). Here we present the results obtained with the shale samples saturated at humidities of 12, 44, 72 and 97.5%. The laboratory tests were carried out at a relatively low confining pressure to avoid a laceration of strain gauges due to the high compressibility of the shale.

ELASTIC ANISOTROPY IN SHALES

It is well established that sedimentary shales are transversely isotropic (TI) materials whose elastic properties can be described by five independent components of the elastic compliance matrix $\boldsymbol{S}$ (Mavko *et al.*, 2009). As was shown in Mikhaltsevitch *et al.* (2016) using three plugs sampled in directions of 0°, 45° and 90° with respect to the bedding, these independent components can be found as

$$s_{11} = \frac{1}{E_{11}} = \frac{\varepsilon_3}{\sigma_3},\ s_{12} = -\frac{\nu_{12}}{E_{11}} = \frac{\varepsilon_1}{\sigma_3}, \text{ - horizontal sample;}$$

$$s_{33} = \frac{1}{E_{33}} = \frac{\varepsilon_3}{\sigma_3},\ s_{13} = -\frac{\nu_{31}}{E_{33}} = \frac{\varepsilon_1}{\sigma_3}, \text{ - vertical sample;} \quad (1)$$

$$s_{44}=s_{55}=\frac{4\varepsilon_3}{\sigma_3}-s_{11}-s_{33}-2s_{13}=\frac{4\varepsilon_3}{\sigma_3}-\frac{1}{E_{11}}-\frac{1}{E_{33}}+2\frac{\nu_{31}}{E_{33}}.\quad \text{- 45°-sample,}$$

where E_{ii} and ε_i are, respectively, the TI Young's modulus and strain in the x_i - direction, ν_{ij} is the Poisson's ratio corresponding to the compression in the x_i -direction and expansion in the x_j -direction,

The non-zero components of the elastic stiffness matrix $\boldsymbol{C}$ (inverse to $\boldsymbol{S}$) are given by

$$c_{11}=c_{22}=\frac{s_{11}s_{33}-s_{13}^2}{\Delta}=\frac{1}{\Delta}\cdot\frac{E_{11}E_{33}-\nu_{31}^2E_{11}^2}{E_{11}^2E_{33}^2},\ c_{12}=c_{21}=\frac{s_{13}^2-s_{12}s_{33}}{\Delta}=\frac{1}{\Delta}\cdot\frac{E_{11}\nu_{31}^2+E_{33}\nu_{12}}{E_{11}E_{33}^2},$$

$$c_{13}=c_{23}=c_{31}=c_{32}=\frac{(s_{12}-s_{11})s_{13}}{\Delta}=\frac{1}{\Delta}\cdot\frac{\nu_{31}(\nu_{12}+1)}{E_{11}E_{33}},\ c_{33}=\frac{s_{11}^2-s_{12}^2}{\Delta}=\frac{1}{\Delta}\cdot\frac{1-\nu_{12}^2}{E_{11}^2},\ c_{44}=c_{55}=1/s_{44},$$

$$c_{66}\equiv\frac{c_{11}-c_{12}}{2}=\frac{E_{11}}{2(1+\nu_{12})}. \tag{2}$$

where $\Delta=(s_{11}-s_{12})(s_{11}s_{33}+s_{12}s_{33}-2s_{13}^2)=\frac{1}{E_{11}^2E_{33}^2}(1+\nu_{12})(E_{33}-\nu_{12}E_{33}-2\nu_{31}^2E_{11})$.

The P-wave anisotropy of shale can be assessed using Thomsen's parameters ε and δ (Thomsen, 1986)

$$\varepsilon=(c_{11}-c_{33})/2c_{33},\ \delta=\frac{(c_{13}+c_{44})^2-(c_{33}-c_{44})^2}{2c_{33}(c_{33}-c_{44})}. \tag{3}$$

The relative difference between the *SH*-wave velocities in the horizontal and vertical directions can be estimated with Thomsen's parameter γ (Thomsen, 1986):

$$\gamma=\frac{c_{66}-c_{44}}{2c_{44}}. \tag{4}$$

DESCRIPTION OF SAMPLES AND EXPERIMENT

The experiments were carried out on a set of three Wellington shale samples similar to the set described previously in Mikhaltsevitch *et al* (2016). The samples were cut in directions of 0°, 45° and 90° with respect to the bedding plane. The size and density of the samples are presented in Table 1. The helium gas permeability and porosity of the shale were estimated at < 1 μD and ~9 %, correspondingly.

Table 1: The physical parameters of the Wellington shale samples saturated at 44 % humidity.

Sample	**Length, mm**	**Diameter, mm**	**Density, kg/m^3**
vertical	71	38	2520
horizontal	65	38	2500
45°-sample	70	38	2495

The laboratory tests were carried out in the frequency range from 0.1 Hz to 100 Hz using an apparatus based on the based on the forced-oscillation approach which is described in Mikhaltsevitch *et al.* (2014). The elastic characteristics of a specimen are evaluated by comparing the strains in the specimen and in a standard with well-known elastic parameters. The strains generated in the samples during the experiments were under 10^{-7}.

RESULTS AND DISCUSSION

The laboratory measurements were conducted in the range of frequencies from 0.1 Hz to 100 Hz at a confining pressure of 6 MPa. The results of the measurements are presented in Figures 1 – 7. The dependences of the TI Young's moduli and Poisson's ratios on the frequency of stress oscillations are shown in Figures 1 and 2, correspondingly. Six components c_{11}, c_{12}, c_{13}, c_{33}, c_{44} and c_{66} of the elastic stiffness tensor and Thomsen's anisotropy parameters are given in Figures 3-7.

In our seismic-frequency measurements, we observed a softening of the samples with increasing the level of saturation accompanied by reduction of the Young's modulus, Poisson ratio (Figures 1 and 2) and two Thomsen's parameters of elastic anisotropy ε and γ (Figure 6), no noticeable changes in parameter δ were found (Figure 7).

For an anisotropic rock with a laminated structure, Brown – Korringa equations (Brown and Korringa, 1975) predict that normal stiffness components c_{11} and c_{33} grow with liquid saturation when shear stiffness components c_{44} and c_{66} do not change (Liu *et al.*, 1994). The Wellington shale has a high percentage of smectite minerals associated with a strong swelling effect in presence of water

(Salles *et al.*, 2010). We found large reductions not only in normal (c_{11} and c_{33}) but also in shear (c_{44} and c_{66}) stiffness components with increasing saturation (Figures 3 and 5).

In our measurements at the lower frequencies, we observe a gradual softening of the samples with increasing saturation presented by the monotonic reduction of the Young's modulus (Figure 1) and decrease of the anisotropy parameters (Figures 6 and 7). At the higher frequencies, the softening effect in the samples saturated at 97.5% humidity is partly counterbalanced by the dispersion of the TI Young's moduli, which also leads to the decrease of anisotropy.

Qualitatively, the results of this study are close to the results published by Liu *et al.* (1994). They investigated the effects of brine and oil saturation on anisotropy in shale samples at ultrasonic frequencies. They found that all stiffness tensor components obtained for the samples with smectite content (2% - 6%) experienced significant reductions with brine saturation.

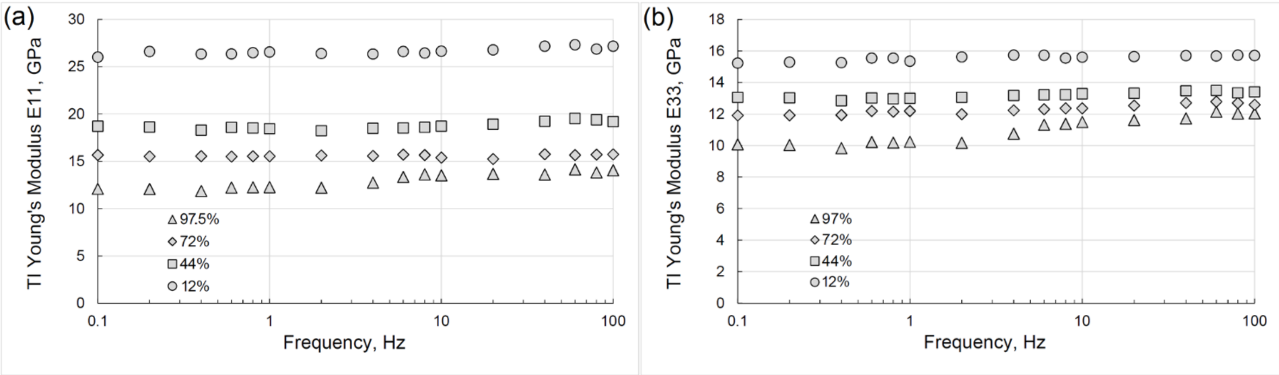

Figure 1: The TI Young's moduli measured on the horizontal (a) and vertical (b) shale samples saturated at relative humidities of 9, 44, 72 and 97 %; the confining pressure is 6 MPa.

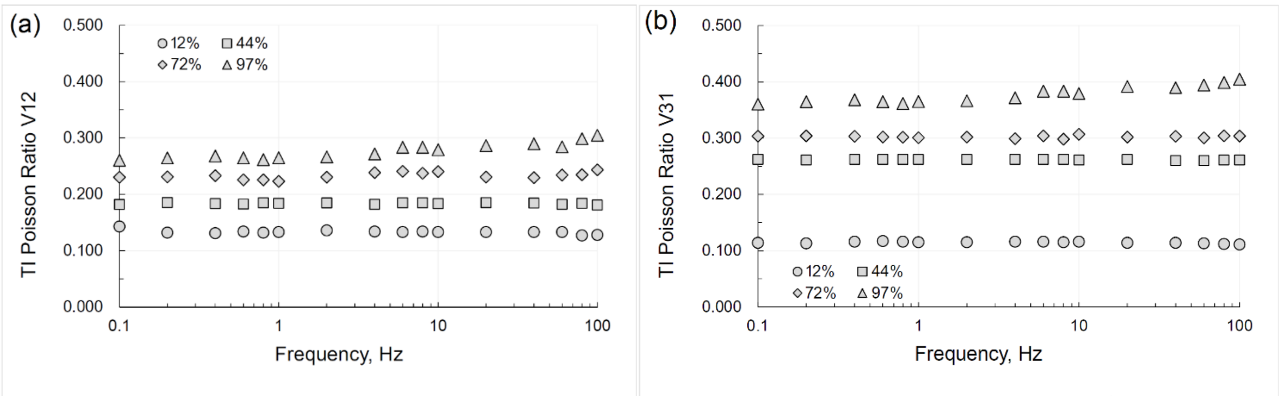

Figure 2: The TI Poisson's ratios ν_{12} (a) and ν_{31} (b) measured on the vertical and horizontal samples at a confining pressure of 6 MPa and relative humidities of 9, 44, 72 and 97 %.

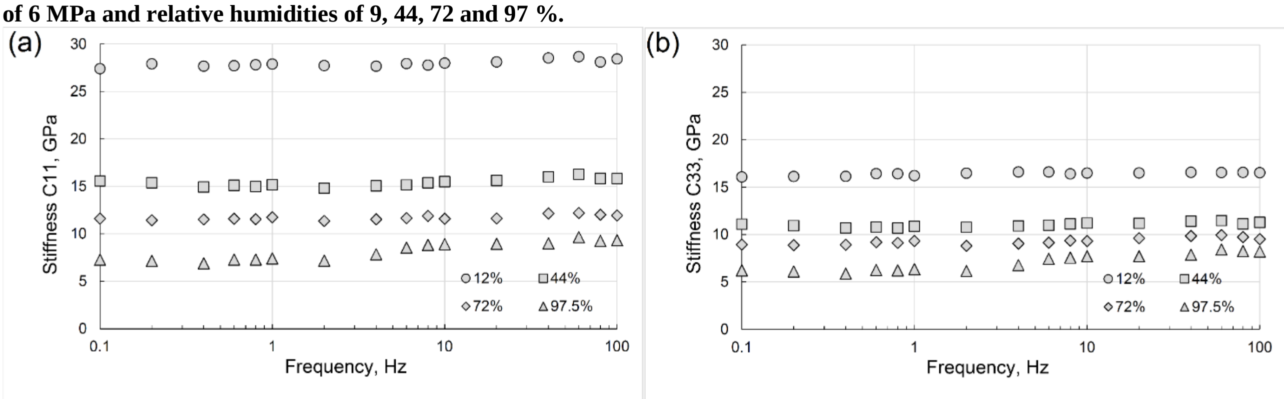

Figure 3: The components c_{11} and c_{33} of the elastic stiffness tensor computed for the Wellington shale samples saturated at relative humidities of 9, 44, 72 and 97 %.

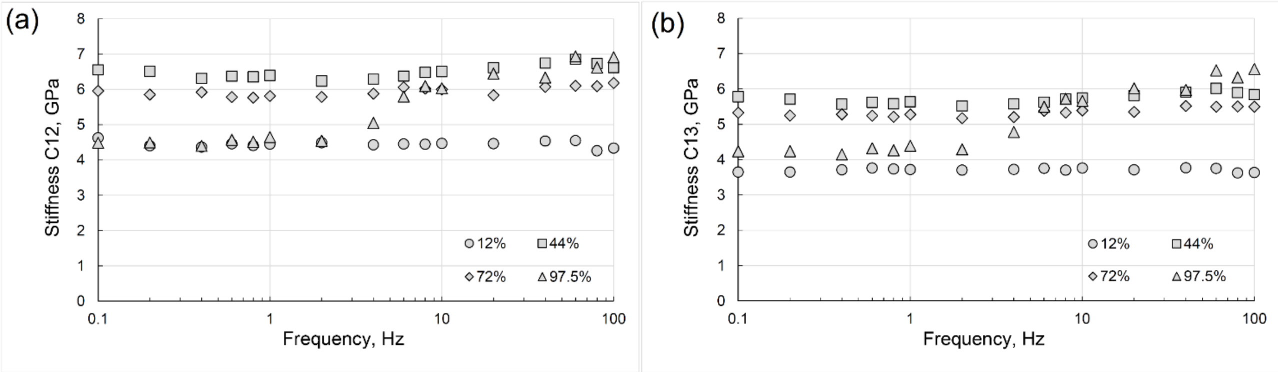

Figure 4: The components c_{12} and c_{13} of the elastic stiffness tensor computed for the Wellington shale samples saturated at relative humidities of 9, 44, 72 and 97 %.

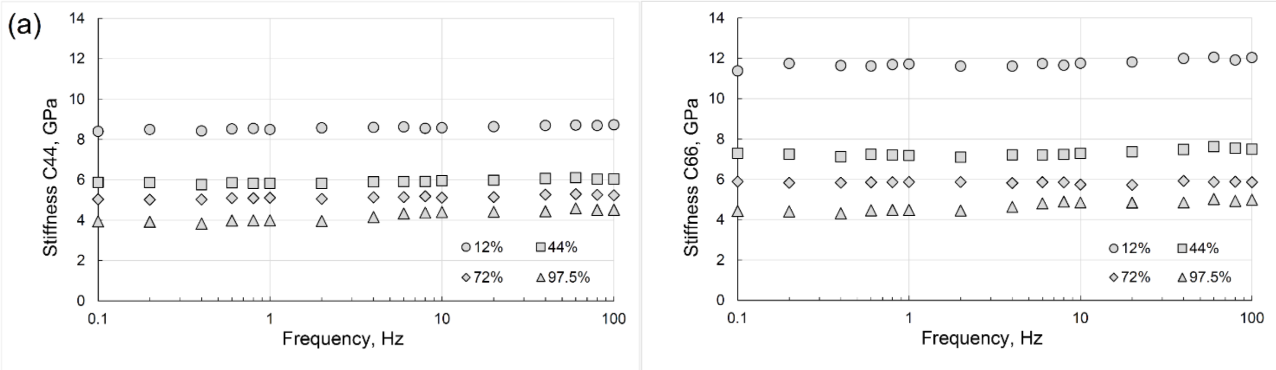

Figure 5: The components c_{44} and c_{66} of the elastic stiffness tensor computed for the Wellington shale samples saturated at relative humidities of 9, 44, 72 and 97 %.

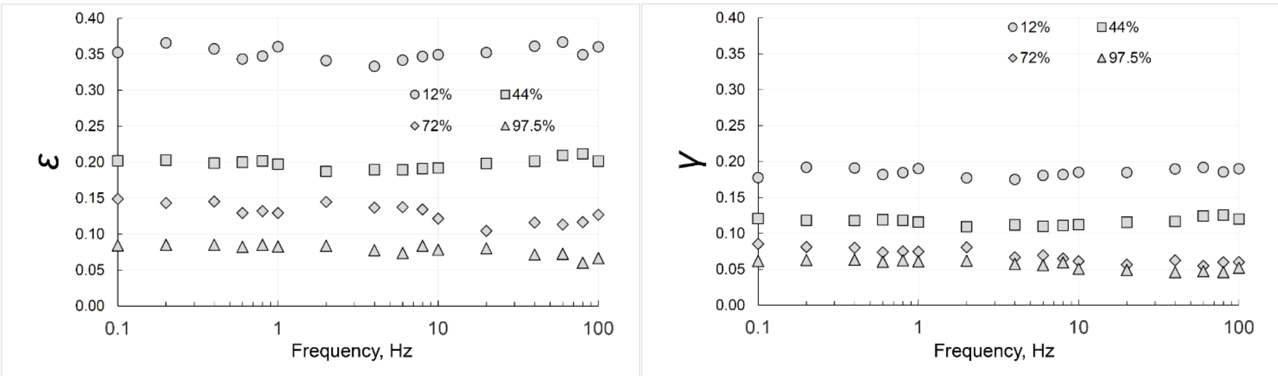

Figure 6: Thomsen's anisotropic parameters ε and γ calculated for the Wellington shale samples saturated at relative humidities of 9, 44, 72 and 97 %.

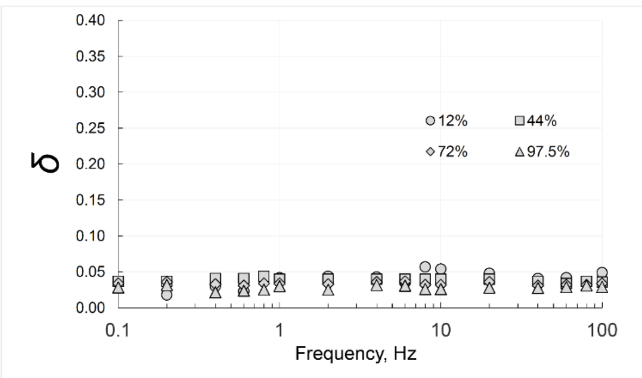

Figure 7: Thomsen's anisotropic parameter δ calculated for the Wellington shale samples saturated at relative humidities of 9, 44, 72 and 97 %.

CONCLUSIONS

We present the results of seismic-frequency laboratory study of the elastic and anelastic properties of three Wellington shale samples cored at 0°, 45° and 90° with respect to the bedding plane of a shale formation, saturated with water at relative humidities of 12, 44, 72 and 97.5 %. The laboratory measurements were conducted in the frequency range of 0.1 Hz to 100 Hz at a confining pressure of 6 MPa.

The laboratory stress-strain measurements of shale anisotropy offers an important advantage over traditional ultrasonic methods. The low-frequency methodology of estimating the anisotropy parameters allows to avoid the difficulty in the interpretation of seismic data using the results obtained at ultrasonic frequencies.

The experimental data show an increased softening of the samples, which manifests itself in reduction of the TI Young's moduli and Thomsen's parameters of elastic anisotropy ε and γ, no noticeable changes in parameter δ were found. When the samples were saturated at a relative humidity of 97.5 %, the softening at the higher frequencies was partly compensated by the modulus dispersion. We associate the chemical and physical-chemical weakening effects with the significant percentage of water-swellable smectite in the Wellington shale.

REFERENCES

Brown, R., and Korringa, J., 1975, On the dependence of the elastic properties of a porous rock on the compressibility of the pore fluid: Geophysics, 40, 608-616.

Dewhurst, D. N., and Siggins, A. F., 2006, Impact of fabric, microcracks and stress field on shale anisotropy: Geophysical Journal International, 165, 135–148.

Hornby, B. E., 1998, Experimental laboratory determination of the dynamic elastic properties of wet, drained shales: Journal of Geophysical Research, 103, 945–964.

Jones, L. E. A., and Wang, H. F., 1981, Ultrasonic velocities in Cretaceous shales from the Williston basin: Geophysics, 46, 288–297.

Kuila, U., Dewhurst, D. N., Siggins, A. F., and Raven, M. D., 2011, Stress anisotropy in low porosity shale: Tectonophysics, 503, 34-44.

Liu, X., Vernik, L., and Nur, A., 1994, Effects of saturating fluids on seismic velocities in shales: 64th Annual International Meeting, SEG, Expanded Abstracts, 1121-1124.

Mavko, G., Mukerji, T., and Dvorkin, J., 2009, The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media: Cambridge University Press.

Mikhaltsevitch, V., Lebedev, M. and Gurevich, B., 2014, Measurements of the elastic and anelastic properties of sandstone flooded with supercritical CO_2: Geophysical Prospecting, 62, 1266-1277.

Mikhaltsevitch, V., Lebedev, M. and Gurevich, B., 2016 a, A laboratory study of the elastic anisotropy in the Mancos shale at seismic frequencies: 86th Annual International Meeting, SEG, Expanded Abstracts, 3174-3178.

Mikhaltsevitch, V., Lebedev, M., Pervukhina, M., Zandi, S., and Gurevich, B., 2016 b, Elastic anisotropy of the Wellington shale at seismic frequencies – Laboratory measurements: 86th Annual International Meeting, SEG, Expanded Abstracts, 392-397.

Salles, F., O. Bildstein, J. M. Douillard, M. Jullien, J. Raynal, H. Van Damme, 2010, On the cation dependence of interlamellar and interparticular water and swelling in smectite clays: Langmuir, 2010, 26, 5028–5037.

Sarout, J., and Gueguen, Y., 2008, Anisotropy of elastic wave velocities in deformed shales: Part 1 — Experimental results: Geophysics, 73, D75-D89.

Thomsen, L., 1986, Weak elastic anisotropy: Geophysics, 51, 1954–1966.

Wong, R.C.K, D.R. Schmitt, D. Collis, and R. Gautam, 2008, Inherent transversely isotropic elastic parameters of over-consolidated shale measured by ultrasonic waves and their comparison with static and acoustic in situ log measurements: Journal of Geophysics and Engineering, 5, 103-117.