ANISOTROPIES OF ELECTRICAL CONDUCTIVITY AND MAGNETIC SUSCEPTIBILITY IN HORN RIVER GROUP SHALES: INSIGHTS INTO ROCK AND PORE FABRICS

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ABSTRACT

Combined anisotropy of electrical conductivity (AEC) and anisotropy of magnetic susceptibility (AMS) measurements provide valuable insights into the rock fabric and 3D orientation of pore spaces in shales. We describe a novel method of determining the 3D anisotropy of electrical conductivity derived from 18 directional resistance measurements (which are then converted to conductivity) made on each shale core sample. Thirty-three initially cubic shale samples were each trimmed and polished into 18 sided samples to facilitate the directional measurements. The samples were from the Horn River Group, British Columbia, Canada. The multifaceted samples were saturated with potassium chloride (KCl) prior to the resistance measurements. The results indicated that these Horn River Group samples were not well described by the usually assumed transversely isotropic model that is often applied to shales. Instead we found that a full 3D anisotropic characterization provided a much better description of their anisotropic properties. Moreover, we found that conductivity varied by up to 17% in the bedding plane, which would not have been expected from the conventional transverse isotropic model. Good correlations were found between the directional resistivities (derived from the resistance measurements) and illite clay content derived from low temperature magnetic susceptibility measurements. Significantly, we also found a good correlation between the percent AEC from our full 3D results and porosity in clay rich samples. This correlation with porosity was not apparent when the same samples were treated as being transversely isotropic. The AEC principal axes suggested that the pores are mainly oblate with that oblateness being closely parallel to the bedding plane. The AEC results were compared with low field anisotropy of magnetic susceptibility (AMS). The AMS was determined by making directional magnetic susceptibility measurements in exactly the same 18 orientations as the directional resistance measurements used to derive the AEC principal anisotropy axes. This allowed a direct comparison between the AMS and AEC principal anisotropy axes. The results indicated that the orientations of the principal AMS and AEC axes were quite similar (although the magnitudes were somewhat different). Since the AMS reflects the anisotropy of the rock matrix minerals, the results indicated that the rock matrix fabric (from the AMS results) tended to be in a similar orientation to the pore fabric (from the AEC results).

INTRODUCTION

Shales have long been known to be electrically anisotropic [1,2]. Recently, however, interest in the accurate interpretation of resistivity data for fluid saturation computations and subsurface structure mapping have led to renewed interest in the study of their electrical anisotropy [3-6]. Since shales typically consist of alternating organic-clay rich and silty intervals, most studies have traditionally treated them as being transversely isotropic with a vertical axis of symmetry [7,8]. In such a model each layer in the laminated sequence is treated like an isotropic medium and an independent resistor. A given sample or section of shale thus consists of a set of resistors, each with resistivity ρ_i. The bulk electrical resistivity is assumed not to vary in the horizontal plane and the degree of electrical anisotropy, λ, is calculated as:

$$\lambda = \rho_v / \rho_h = \sigma_h / \sigma_v \quad (1)$$

where ρ_v is the transverse resistivity (resistivity normal to the lamination plane), ρ_h is the longitudinal (lamination parallel) resistivity, σ_v is the transverse conductivity, and σ_h is the longitudinal conductivity.

The majority of the few available studies on electrical anisotropy in mudrocks determine the degree of electrical anisotropy from wireline log derived resistivities. The vertical resolution of standard induction logging tools is between 2ft and 6ft [4]. At such macroscopic scales electrical anisotropy due to microstructural fabric elements like grain alignment, microfractures or pore distribution are difficult to resolve. Higher resolution laboratory techniques traditionally measure horizontal and vertical resistivities in cubic samples or core plugs. Resistivities are either measured in one cubic sample or on two cylindrical core plugs taken perpendicular and parallel to the bedding plane. Since at least nine directional resistivities are needed to determine the six coefficients of the 3D resistivity (and hence also conductivity) tensor, the petrofabric implications of electrical anisotropy cannot be fully understood with only two directional resistivities (or conductivities). In the present paper, a novel method of determining the anisotropy of electrical conductivity (AEC) from 18 directional resistance measurements (which are then converted to resistivity and conductivity) on each sample is presented. The primary goals were to: (i) identify the petrofabric elements that control electrical anisotropy in shales of the Horn River Basin, (ii) define the 3D orientations and magnitudes of the AEC principal axes, and compare with low field anisotropy of magnetic susceptibility (AMS), and (iii) to test the suitability of the traditional transverse isotropic model of electrical conductivity anisotropy in shales on a core plug scale.

SAMPLES AND METHODS

Sample Preparation

33 cubic shale samples from the Imperial Komie well in British Columbia, Canada, were trimmed and polished into 18 sided samples (**Figure 1, top**). 9 samples were from the Muskwa, 17 from the Otter Park and 7 from the Evie formations. The samples were oven dried at 40ºC for 48 hours to remove water held in pore spaces prior to saturating with 20

weight % potassium chloride (KCl) solution. To ensure full saturation, the samples were fully immersed in the electrolyte for one week before taking resistance measurements.

Anisotropy of Electrical Conductivity (AEC) and Comparison with Anisotropy of Magnetic Susceptibility (AMS) in Multifaceted Shale Samples

Determination of the anisotropy of electrical conductivity (AEC) first involved electrical resistance being measured in at least 9 axes for each sample. For each of the Horn River Group samples saturated in the KCl solution, electrical resistance was measured in the 9 axes shown in **Figure 1 (middle)**. In each axis, two determinations of resistance were measured in opposite directions of current flow and were averaged to determine the electrical resistance in that axis. Therefore 9 directional resistances were produced from 18 measured electrical resistances. **Figure 1 (bottom)** shows a schematic of the set-up used to measure electrical resistance. A potential drop of 10V was applied across a circuit consisting of a resistor of known resistance in series with a Horn River Group sample whose resistance was unknown. The voltage was applied by an AFG320 function generator connected to the sample via Ag-AgCl disc electrodes attached to opposite faces of the sample in the direction of current flow. The voltage drop across the sample and test resistors were measured using a Tektronix TD3054B digital oscilloscope. Electrical resistance in each sample direction was calculated as follows:

$$R_{sample} = \{R_{test}\ (V_1\text{-}V_2)\} \ / \ V_2 \qquad (2)$$

where R_{sample} is the resistance of the sample, R_{test} is the resistance of the test resistor, V_1 is the voltage drop across the sample and V_2 is the voltage drop across the test resistor. The 9 directional resistances were converted to electrical resistivities using the method described in Ebufegha [9] and then converted to conductivity (by taking the reciprocal of each resistivity value), and the 9 conductivity values were then used to calculate the anisotropy of electrical conductivity (AEC). The same 9 measurement axes that were used for determining electrical resistance were also used here for determining anisotropy of magnetic susceptibility (AMS) using a Bartington MS2B low field magnetic susceptibility sensor and the method described by Ebufegha and Potter [10]. Having identical measurement axes meant that the magnetic anisotropy could be directly compared with the electrical anisotropy.

RESULTS AND DISCUSSION

The full 3D anisotropy of electrical conductivity (AEC) results indicated that the Horn River Group samples studied were not transversely isotropic. The results showed conductivity variations in the bedding plane of 0.1% to 17%. The percent AEC (defined as $100(\sigma_1 - \sigma_2) / \sigma_3$ where σ_1, σ_2 and σ_3 are the max, int and min conductivities) is shown in **Figure 2 (left hand profile),** and varies between 65% and 107% in the Evie formation and between 73% and 180% in the Muskwa and Otter Park formations. In all three formations, maximum and intermediate electrical conductivities were closely parallel to the bedding plane and minimum electrical conductivity closely perpendicular to it. Using the traditional (transversely isotropic) model, however, the % σ_h/σ_v overestimated the anisotropy by a

factor of 1.4 to 12.9 in the different formations (**Figure 2, right hand profile**) compared to our full 3D AEC results. The variation in % σ_h/σ_v ranged from 140% to 390% in the Evie, and between 157% and 1557% in the Muskwa and Otter Park.
Current flow in the Horn River Group shales is mainly by surface conductance through the electrical double layer of clay minerals. A moderate to strong correlation (R^2 ranging from 0.5 to 0.76) between the concentration of illite (which we determined from low temperature magnetic susceptibility measurements [11]) and electrical resistivity (and therefore conductivity) was observed in all nine measurement axes [9]. Although clay content was the primary control on conductivity of Horn River Group shales, its correlation with the anisotropy of electrical conductivity was poor (R^2 was only 0.073 for the samples studied). A good correlation was instead observed between anisotropy of electrical conductivity and porosity. **Figure 3 (top)** shows porosities cross-plotted against % anisotropy of electrical conductivity (AEC) values obtained from our full 3D electrical anisotropy approach (derived from the 18 directional resistance measurements) in the clay rich Lower Muskwa and Otter Park formations. A clear correlation is observed with $R^2 = 0.70$. (Note that the porosities were derived from density log measurements, with a correction for organic matter, and only samples with total organic carbon, TOC, data were used for this purpose). In contrast **Figure 3 (bottom)** shows that the % σ_h/σ_v values (assuming the samples are transversely isotropic) for the same samples did not show any strong correlation with porosity ($R^2 = 0.15$).

The Horn River Group shales are significantly more electrically anisotropic than they are magnetically anisotropic. Their AEC values are between 65% and 180% while their AMS values range from 0% to 35%. No direct correlation is observed between percent AEC and percent AMS. A relationship was, however, observed between the AEC and AMS principal axes orientations. Samples with normal magnetic fabric [10] at room temperature (maximum AMS axis parallel to the bedding plane and minimum AMS axis normal to it) have minimum AMS axis orientations that show a similar profile with depth as their minimum AEC axes (**Figure 4 A**). Both the AMS and AEC minimum axes are steeply inclined and normal to the bedding plane. The steep inclinations mean that the declinations are less well defined and show more scatter (as would be expected)**.** Samples with inverse magnetic fabric [10] at room temperature (minimum AMS axis parallel to the bedding plane and maximum AMS axis normal to it, due to the presence of stable single domain ferrimagnetic particles) have maximum AMS axis orientations that show a similar profile with depth as their minimum AEC axes (**Figure 4 B**). The results suggest that preferred mineral or matrix alignments (from the AMS orientations) and the pore space alignments (from the AEC orientations) are essentially in the same orientations.

CONCLUSIONS

1. The Horn River Group shales from the Imperial Komie well are not transversely isotropic with respect to electrical conductivity, contrary to the traditional model. When transverse isotropy is assumed, the relationship between porosity and percent anisotropy of electrical conductivity is not obvious. Including the full 3D variation of electrical conductivity in anisotropy determination yields a clear correlation with porosity.

2. Clays are the primary control on electrical conductivity in the shale samples studied, while porosity is the primary control on the anisotropy of electrical conductivity. In clay rich rocks the concentration and spatial arrangement of clay minerals significantly affects the electrical conductivity. Since the pore saturating fluid is not the only control on electrical conductivity, saturation calculations that do not account for clay conductivity and its anisotropy may be erroneous.
3. The orientations of the principal AMS and AEC axes are quite similar, and indicate that both the mineral and pore space alignments are closely parallel to the bedding plane.

ACKNOWLEDGEMENTS

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REFERENCES

1. Mousseau, R. J. and Trump, R. P., 1967. Measurement of electrical anisotropy of clay-like materials. *Journal of Applied Physics*, **38** (11), 4375 - 4379.
2. Chemali, R., Gianzero, S. and Su, S. M., 1987. The effect of shale anisotropy on focused resistivity devices. SPWLA 28th Annual Logging Symposium.
3. Klein, J. D., Martin, P. R. and Allen, D. F., 1997. The petrophysics of electrically anisotropic reservoirs. *The Log Analyst*, **38**, 25-36.
4. Clavaud, J. B., 2008. Electrical anisotropy of shale: the effect of compaction. *Petrophysics*, **49** (3), 243-260.
5. Bachrach, R., 2011. Elastic and resistivity anisotropy of shale during compaction and diagenesis: Joint effective medium modeling and field observations. *Geophysics*, **76** (6), E175- 186.
6. Ellis, M., Ruiz, F., Nanduri, S., Keirstead, R., Azizov, I., Frenkel, M. and MacGregor, L., 2011. Importance of anisotropic rock physics modelling in integrated seismic CSEM interpretation. *First Break*, **29**, 87-95.
7. Tsvankin, I., 1997. Anisotropy parameters and P-wave velocities for orthorhombic media. *Geophysics*, **62** (4), 1292-1309.
8. Saeidi, O., Rasouli, V., Vaneghi, R. G., Gholami, R. and Torabi, S. R., 2014. A modified failure criterion for transversely isotropic rocks. *Geoscience Frontiers*, **5**, 215-225.
9. Ebufegha, V. T., 2016. Anisotropy of mudrocks: Quantifying controls and fabric implications in the Horn River Basin. PhD Thesis, University of Alberta, pp.185.
10. Ebufegha, V. T. and Potter, D. K., 2014. A comparison of quantitative techniques for determining the 3D anisotropy of shale samples: application to Horn River Basin shales, British Columbia, Canada. In *Proceedings of the 2014 International Symposium of the Society of Core Analysts, 8-11 September 2014*, Avignon, France. Paper SCA2014-011 (12 pages).
11. Ebufegha, V. T. and Potter, D. K., 2016. Quantifying shale mineralogy and anisotropy from low temperature magnetic susceptibility measurements. In *Proceedings of the 2016 International Symposium of the Society of Core Analysts, 21-26 August 2016*, Snowmass, Colorado, USA. Paper SCA2016-033 (12 pages).

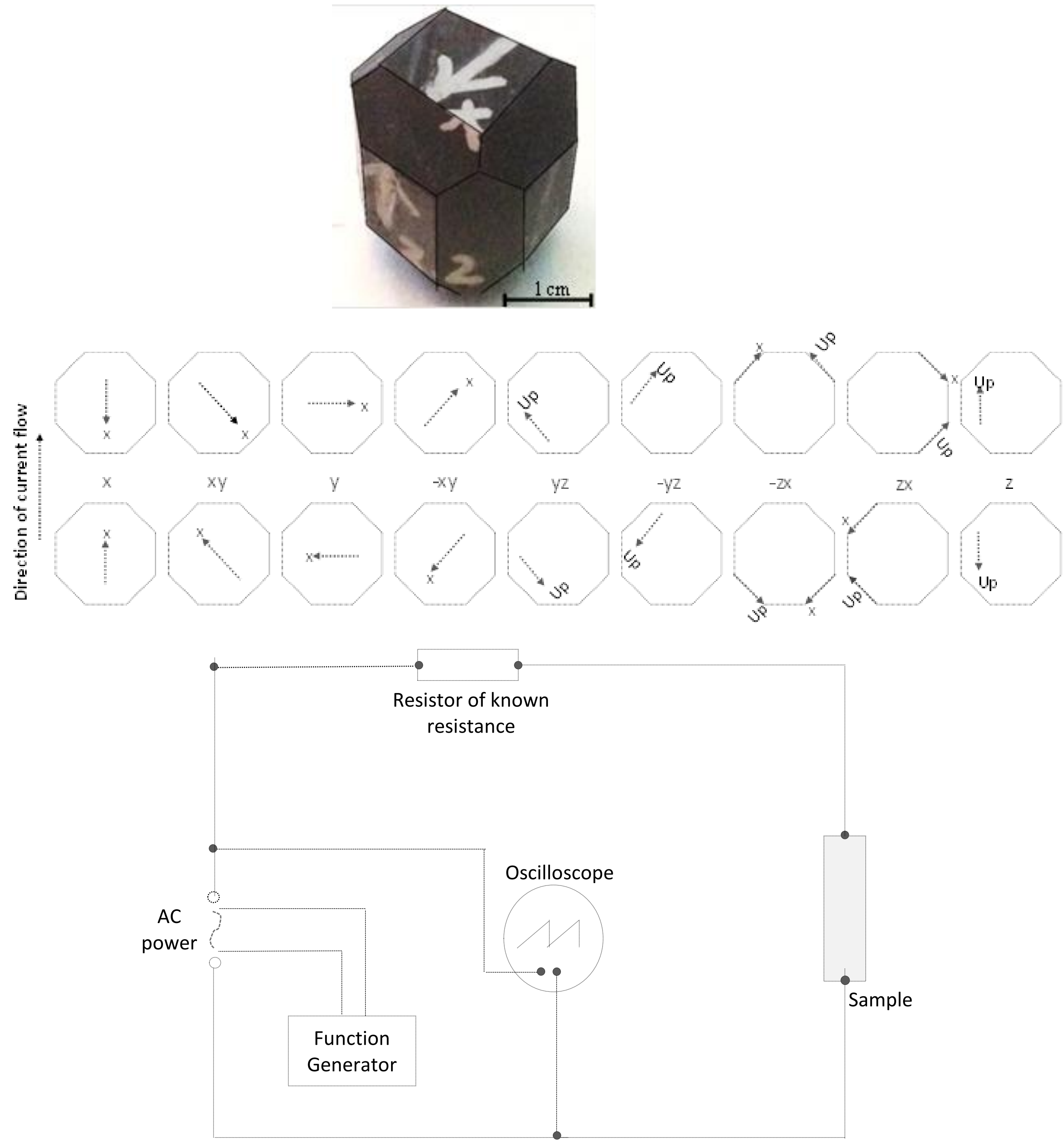


Figure 1. Top: One of the 18 sided samples that allow resistance measurements to be made in 9 different sample axes. **Middle:** Schematic of the 18 measurement directions along 9 different sample axes. **Bottom:** Schematic of the experimental set-up for resistance measurements.

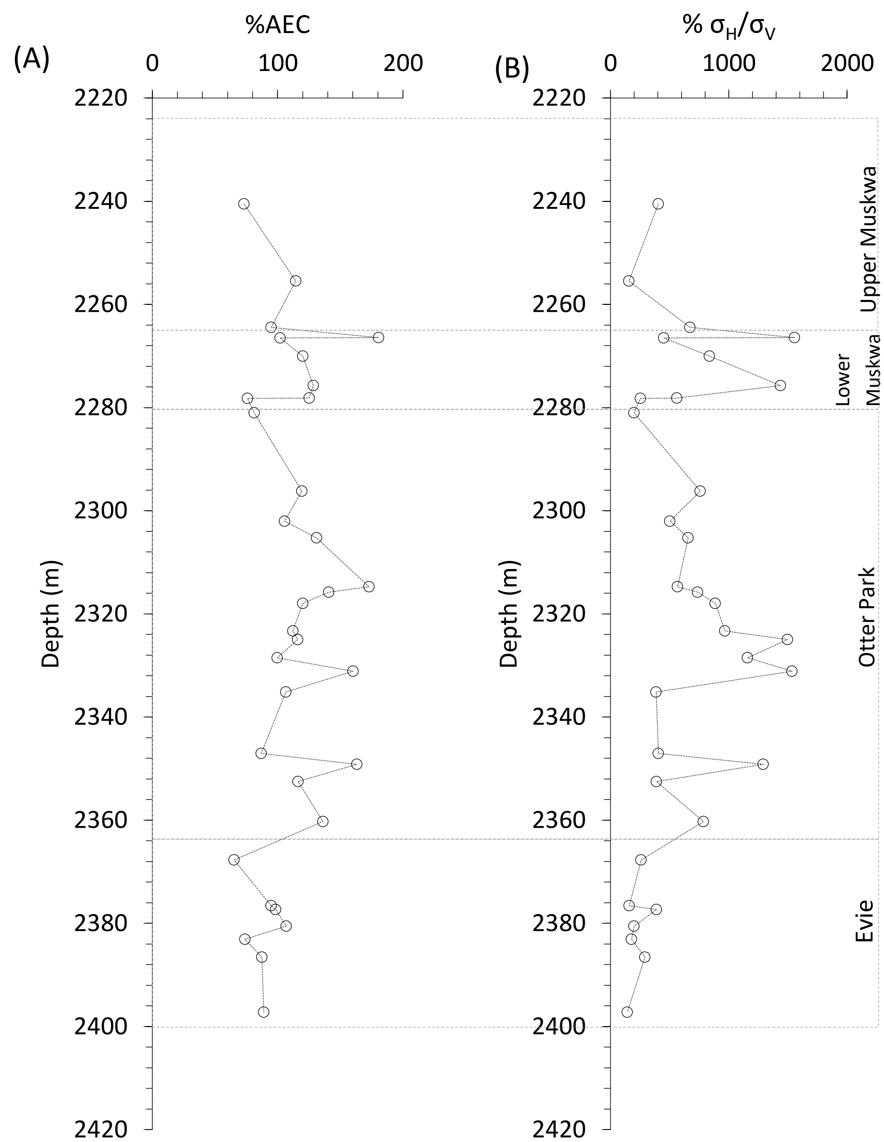
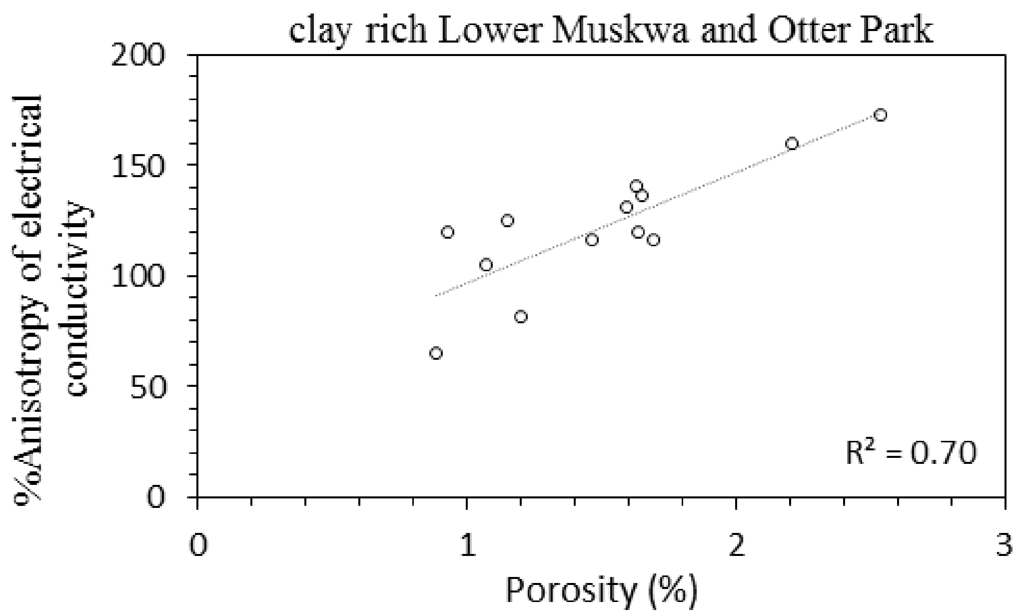


Figure 2. (A) Percent 3D anisotropy of electrical conductivity (AEC) derived from the 18 resistance measurements in the directions shown in the middle schematic of **Figure 1**. (B) Percent conductivity parallel to the lamination plane to that perpendicular to the lamination plane (% σ_h / σ_v) using the traditional two conductivity (transversely isotropic) model. Note that this model significantly overestimates anisotropy compared to the full 3D measured anisotropy shown in (A).



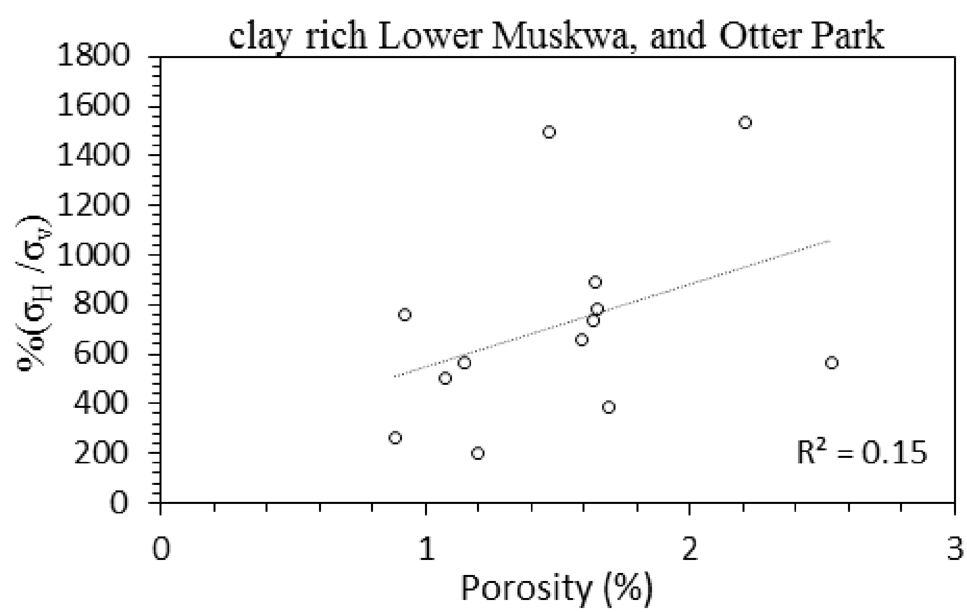


Figure 3. Top: Crossplot of porosity versus percent 3D anisotropy of electrical conductivity (AEC) derived from the 18 resistance measurements. **Bottom:** Crossplot of porosity versus percent conductivity parallel to the lamination plane to that perpendicular to the lamination plane (% σ_h / σ_v) using the traditional two conductivity (transversely isotropic) model.

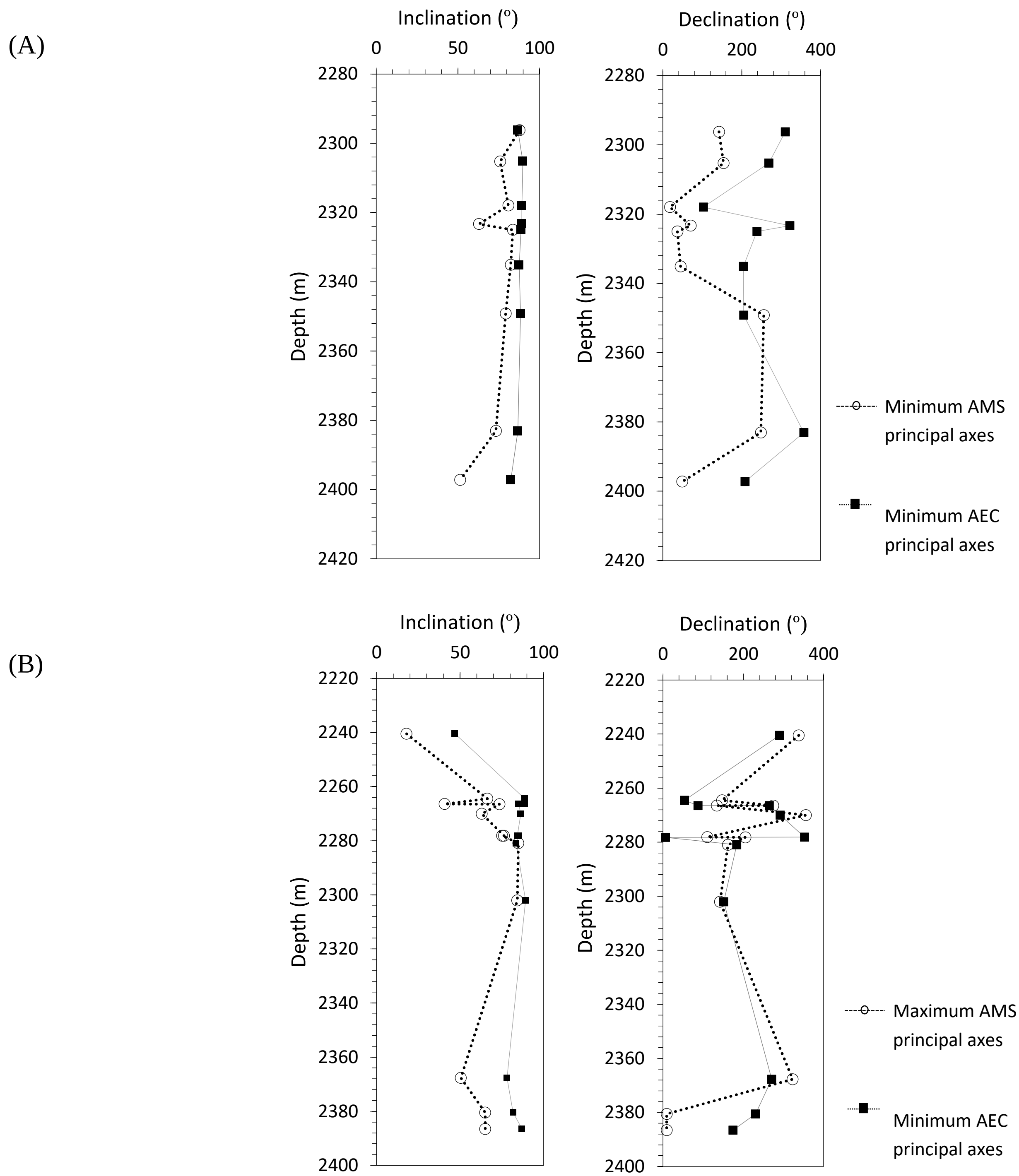


Figure 4. Variation with depth of the orientations (inclination and declination) of the principal anisotropy axes. (A) minimum anisotropy of magnetic susceptibility (AMS) axes and minimum anisotropy of electrical conductivity (AEC) axes for samples with normal magnetic fabrics. (B) maximum AMS axes and minimum AEC axes for samples with inverse magnetic fabrics.