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Low- temperature magnetic anisotropy in shales and mudstones: Application in modelling mineralogy and fabric in the Horn River Basin, British Columbia

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Summary

An intrinsic property of rock forming minerals is their magnetic susceptibility (ratio of induced magnetization and applied field strength). For any given rock sample, the bulk magnetic susceptibility is therefore a contribution from the diamagnetic, paramagnetic, ferrimagnetic and antiferromagnetic phases, one or more of which may dominate the measured rock susceptibility. Separating the contributions of different magnetic phases can yield useful qualitative and quantitative information about mineralogy and mineral fabrics. In this contribution, the temperature dependence of magnetic susceptibility and anisotropy of magnetic susceptibility (AMS) are used to model clay content and distribution as well as quartz and calcite (diamagnetic) content in the Devonian Horn River Group of British Columbia. Given the significant impact of clays on petrophysical parameters, results from this non-destructive method are used to understand the relationship between clay content and porosity.

A comparison of room temperature and low temperature susceptibility results show that the magnetic fabric of the Horn River Group is dominated by paramagnetic minerals. Based on the observed distribution of paramagnetic versus diamagnetic mineral content and thin section analyses, three distinct lithofacies are identified; siliceous and clay rich mudstones, argillaceous shale and calcareous, clay rich mudstones. A strong correlation between porosity and percentage anisotropy of magnetic susceptibility (AMS) indicates that clay content and distribution is a major control on porosity.

Introduction

Clay minerals make up about 30% to 60% of shales and mudstones and because of their sheet-like morphology, they are strongly anisotropic, tending to be preferentially aligned with increasing overburden pressure such that they significantly affect petrophysical parameters like permeability and porosity. An understanding of clay content and distribution within pore spaces is therefore an important component of reservoir models for controls on porosity and permeability. Studies have shown strong correlation between not only magnetic properties like susceptibility and elements of petrofabric including mineralogy, but also between magnetic properties and petrophysical properties (Ali and Potter, 2012). Diamagnetic minerals like quartz and calcite have very low, negative magnetic susceptibilities that may be overshadowed by the low but positive susceptibilities of paramagnetic minerals like illite, chlorite and smectite. Small amounts of ferrimagnetic minerals with high and positive magnetic susceptibilities can dominate room temperature low field magnetic susceptibility measurements, so it is necessary to separate the contributions from different magnetic phases before interpretations are made. The low temperature method used in this study is non-destructive, inducing no chemical changes in samples but rather enhancing the contribution and fabric of paramagnetic phases in samples.

Method

The temperature dependence of magnetic susceptibility as described by the Curie-Weiss law is used to separate the contributions to susceptibility of different minerals or magnetic phases. The magnetic susceptibility of paramagnetic minerals like illite and chlorite varies inversely with temperature. At low temperatures, the reduction of thermal agitation of atoms causes a decrease in randomization of paramagnetic moments. The resulting increase in allignment of moments increases net magnetization and magnetic susceptibility at low temperatures (Bierderman et al. 2014). The Curie-Weiss equation is as follows;

$$\chi_{measured} = C / (T - \theta_{para}) + \chi_o$$

C is the Curie constant, θ_{para} is the paramagnetic Curie temperature and χ_o is the temperature independent diamagnetic contribution or Van Vleck susceptibility. The closer a sample is to purely paramagnetic, the smaller and closer to zero the value of χ_o will be (Vogt et al. 2003). Diamagnetic susceptibility is independent of temperature and ferrimagnetic susceptibility is independent of temperature between 120K and room temperature.

In this study, cubic samples from the Muskwa, Otter Park and Evie formations are cooled down to at least 173K by full immersion in a liquid nitrogen bath and their low field magnetic susceptibilities as a function of temperature measured during heating to room temperature. Samples are not cooled below 120K in order to exclude deviations from the Curie Law that occur as a result of the Verwey transition.

In order to compute 3D ellipsoids, magnetic susceptibility is measured in nine different directions as samples heat up to room temperature from 173K.

Results

Preliminary low temperature results show that samples from all three formations in the Horn River Group obey the Curie-Weiss law. The observed AMS is therefore controlled by paramagnetic minerals of which clays, particularly illite, are most relevant. Based on the observed distribution of paramagnetic versus diamagnetic mineral content and thin section analyses, three distinct lithofacies are identified; siliceous and clay rich mudstones, argillaceous shale and calcareous, clay rich mudstones. The upper 13m to 15m of the Muskwa formation is dominated by siliceous, clay rich mudstones with higher AMS than the more argillaceous lower 20m. The Otter Park is primarily made up argillaceous shale and the Evie is predominately calcareous, clay rich mudstones. The orientation of 3D ellipsoids was used to characterize grain alignments in all three formations. Argillaceous intervals are characterized primarily by normal magnetic fabrics (χ_{max} is parallel to bedding and χ_{min} is perpendicular to bedding) whereas more siliceous and calcareous intervals have randomly oriented maximum (χ_{max}) and minimum (χ_{min}) susceptibility directions. There is thus, better alignment of clay particles in the argillaceous intervals despite the higher concentration of clays in the siliceous and calcareous intervals. Better alignment of clays with increasing overburden pressure results in a decrease in inter-aggregate porosity and lower average pore sizes.

A strong positive correlation between the anisotropy of magnetic susceptibility at room temperature and porosity has also been observed. Since the anisotropy of magnetic susceptibility (AMS) is controlled primarily by clays, the correlation between AMS and porosity indicates a positive correlation between clay content and porosity. At certain intervals in the Otter Park, a negative correlation between porosity AMS is observed. High porosities in these intervals speak to other controls on porosity.

We also observed a positive correlation between diamagnetic mineral content and porosity. More siliceous and calcareous intervals have the highest clay content and porosities.

Conclusions

This study demonstrates that magnetic properties, specifically susceptibility, can be used to effectively characterize mineralogy and mineral fabrics in shales and mudstones.Since bulk magnetic susceptibility and the anisotropy of magnetic susceptibility are significantly impacted by elements of petrofabric including petrophysical parameters, they can be used in the quantitative modelling of controls on porosity. The ability to enhance select mineral fabrics by simply altering temperature also makes it possible to isolate the effects of particular minerals and fabrics on petrophysical properties.

References

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