MODEL TEMPLATES FOR QUANTIFYING PERMEABILITY CONTROLLING PARAMAGNETIC CLAY MINERALS AT IN SITU RESERVOIR TEMPERATURES

*Arfan Ali and †David K. Potter

*Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, UK

†Department of Physics and Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Austin, Texas, USA 18-21 September, 2011

ABSTRACT

Recent work has shown strong correlations between magnetic measurements and key petrophysical parameters such as clay content and permeability in clastics (Potter, 2007; Potter and Ivakhnenko, 2008) and carbonates (Potter et al, 2011). The magnetic measurements in this previous work were mainly undertaken at ambient (room temperature) conditions. One of the main aims of the present paper is to show how these types of measurements depend upon temperature, and therefore depth downhole. Pure diamagnetic minerals such as quartz, calcite or the clay kaolinite should theoretically show no dependence of magnetic susceptibility with temperature, and therefore will show no variation in magnetic susceptibility with depth. In contrast, paramagnetic minerals (for example, important permeability controlling clays such as illite or chlorite), should theoretically show a decrease in magnetic susceptibility, according to the Curie Law for low applied fields. A series of theoretical model templates using the Curie Law were developed to model the temperature dependence of mixtures of diamagnetic and paramagnetic minerals. The model curves were compared with laboratory measurements on shoreface and turbidite reservoir samples. The experimental data showed a good match to the expected trend of the model curves. Moreover, the illite content derived from the model template curves agreed well with the illite content independently derived from magnetic hysteresis measurements at high field and X-ray diffraction (XRD) measurements. These model templates, in conjunction with downhole magnetic susceptibility and temperature data (or a known or assumed geothermal gradient), allow one to quantify the diamagnetic versus paramagnetic mineral content in situ downhole. This information is potentially useful for planning a coring and core analysis program, by allowing more quantitative mineral content data to be acquired for early in the development of a field at the appraisal well stage. Furthermore, knowing the temperature dependence of permeability controlling clay minerals may help one to make predictions of permeability in situ downhole.

INTRODUCTION

Magnetic susceptibility measurements on reservoir rock samples have recently been shown to correlate with key petrophysical parameters like clay content and permeability. These correlations were initially seen for low field measurements (Potter, 2007), and later for high field measurements (Ivakhnenko and Potter, 2008; Potter and Ivakhnenko, 2008; Potter et al, 2011). The measurements were performed mainly at ambient (room temperature) conditions and were not representative of the downhole in-situ conditions (Ali and Potter, 2010). To predict petrophysical properties (clay content, permeability) in situ from downhole magnetic susceptibility measurements we need to know the temperature dependence of the magnetic susceptibility of reservoir samples. The magnetic susceptibility of diamagnetic minerals (such as quartz, calcite, kaolinite) does not theoretically vary with temperature. In contrast, the magnetic susceptibility of paramagnetic minerals (such as the permeability controlling clay mineral illite) should decrease with increasing temperature according to the Curie Law (at least for low applied fields). In this paper we have derived theoretical model template curves for the variation of magnetic susceptibility with temperature for various illite plus quartz and chlorite plus quartz mixtures using the Curie Law. We then compared these model curves with experimental data for some shoreface and turbidite reservoir samples containing illite. We found that a very good fit between model curves and the experimental data, and that the illite content derived in this way agreed well with independent measurements from room temperature magnetic hysteresis curves and XRD measurements. The template curves allow us to quantify permeability controlling paramagnetic clays (in this case illite) in situ from downhole magnetic susceptibility measurements.

MODEL TEMPLATE CURVES OF MAGNETIC SUSCEPTIBILITY WITH TEMPERATURE FOR IMPROVED CLAY CONTENT ESTIMATES IN SITU AND COMPARISON WITH EXPERIMENTAL DATA

Figure 1 shows theoretical model template curves of magnetic susceptibility with temperature for mixtures of illite and quartz using the Curie Law as follows:

$$M/B = C/T \tag{1}$$

where M is the magnetization, B is the applied field, M/B is the magnetic susceptibility, C is a mineral specific Curie constant, and T is the absolute temperature in Kelvin. Figure 1 also shows experimental data for three turbidite reservoir rock samples (a shale UTS1, a uniform shaly sand UT17a and a graded shaly sand UT17b) acquired using a Variable Field Translation Balance (VFTB) for an applied field of 20 mT. Note that we found that results for an applied field of 800 mT are very similar to those at 20 mT. All these samples contain illite as the main clay mineral (see Table 1). The experimental data for the turbidite samples follows the trend of the theoretical template curves (Figure 1). Likewise the experimental data for the shoreface samples follows the trend of the template curves (Figure 2).

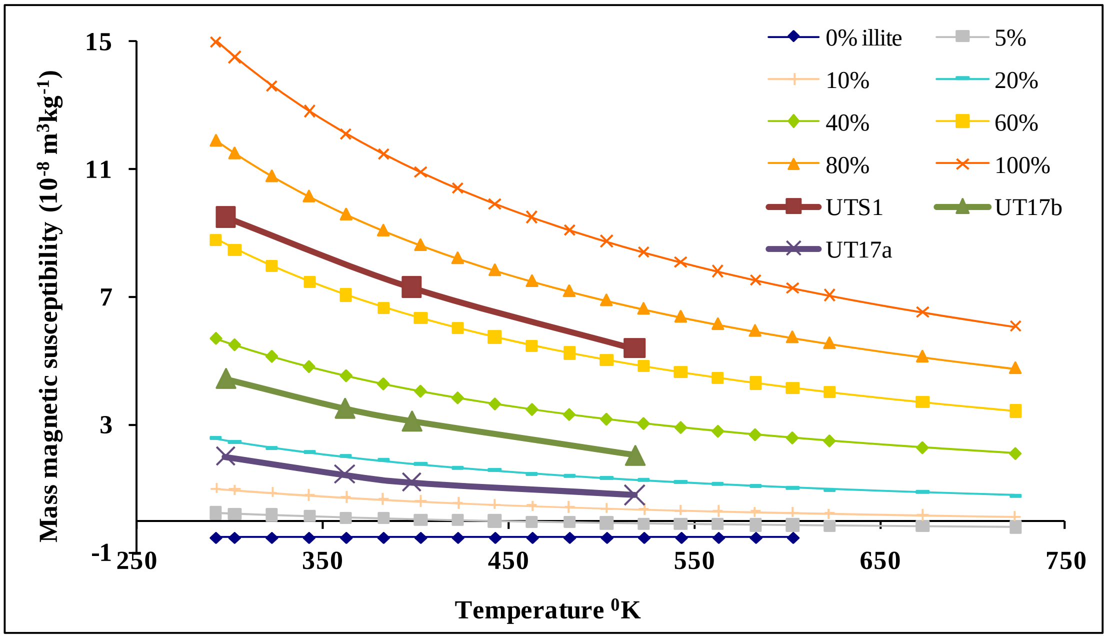

Figure 1. Theoretical model template curves of mass magnetic susceptibility with temperature for various mixtures of illite (illite percent is shown) and quartz using the Curie Law. The experimental curves for three turbidite samples (shale UTS1, uniform shaly sand UT17a and graded shaly sand UT17b) measured in a field of 20 mT are also shown. The experimental data nicely follow the template curves.

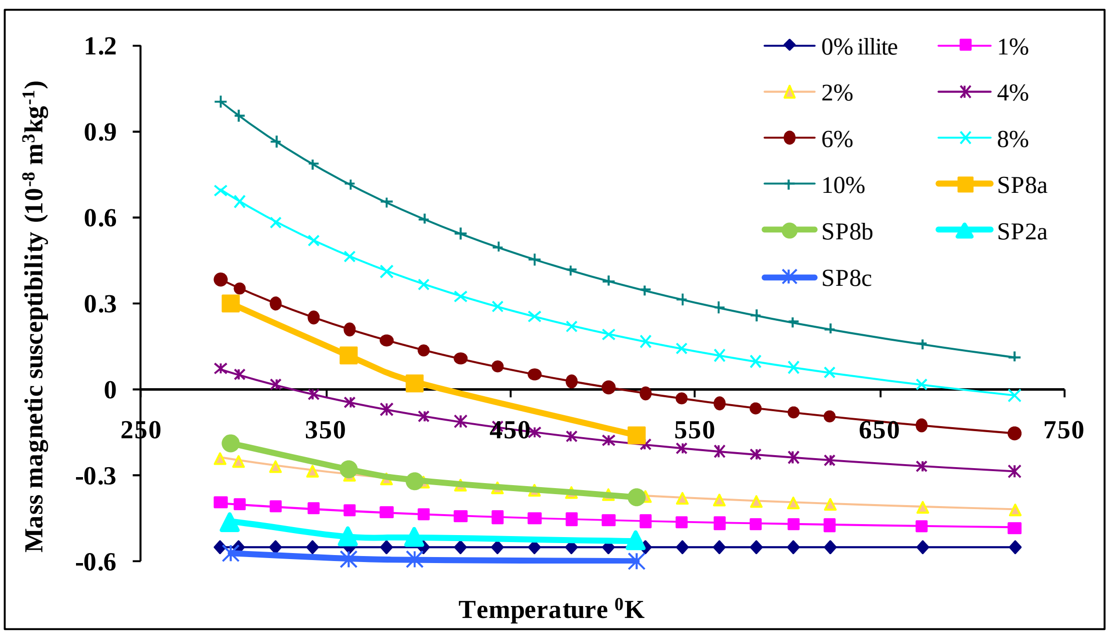

Figure 2. Theoretical model template curves of mass magnetic susceptibility with temperature for various mixtures of illite and quartz using the Curie Law. The experimental curves for four shoreface samples (SP2a and SP8a-c, each containing a different illite content) were measured in a field of 20 mT

To verify whether the model templates of Figures 1 and 2 are giving realistic values of illite content for the reservoir samples, we compared the results with independent estimates based on measuring the high field slope of each sample's magnetic hysteresis curve at room temperature using the methodology of Potter and Ivakhnenko (2008). As a further check we obtained XRD data for each sample. Table 1 summarizes all the results and shows that in most cases the three independent methods give very similar values for a particular sample.

Table 1. Percentage illite content obtained from the model template curves of Figures 1 and 2, and independently from magnetic hysteresis curves and XRD measurements. Note that sample SP8c also contains some kaolinite (diamagnetic) which is why it plots below the 0% illite line in Figure 2. Sample UT17a contains some smectite as well as illite, which may help to explain the difference between the XRD and magnetic results (the magnetic results assumed all the paramagnetic material was illite).

Sample type and number	**Illite content derived from model templates of Figures 1 and 2 (%)**	**Illite content derived from room temperature high field hysteresis curves (%)**	**XRD derived illite content (%)**
Uniform Turbidite			
UTS1 (shale)	63-67	63.4	62.4
UT17a (shaly sand)	14-16	15.6	6.8
Graded Turbidite			
UT17b (shaly sand)	30-32	31.4	29.0
Shoreface			
SP8a (muddy sand)	4.5-5.6	5.6	4.9
SP8b (sand)	2.0-2.3	2.3	1.8
SP2a (sand)	0.3-0.7	0.7	1.0
SP8c (sand)	0	0.1	0.2

TEMPLATE CURVES OF OTHER PERMEABILITIY CONTROLLING PARAMAGNETIC MINERALS

Model templates similar to those in Figures 1 and 2 can be determined for other permeability controlling paramagnetic clays for their quantification in situ from downhole magnetic susceptibility measurements. The information obtained can be used for modeling permeability and other key petrophysical parameters in situ downhole where no core is cut. In Figures 3 and 4, we have shown model template curves for chlorite clay and quartz mixtures, and montmorillonite clay and quartz mixtures respectively. The chlorite curves were modeled for CFS chlorite (where CFS is the locality of the chlorite as given by Borradaile et al, 1990). We have also determined model templates for other non-clay permeability controlling paramagnetic minerals (siderite in particular), and compared them with relevant reservoir samples, but we are unable to show everything here merely due to restrictions of space.

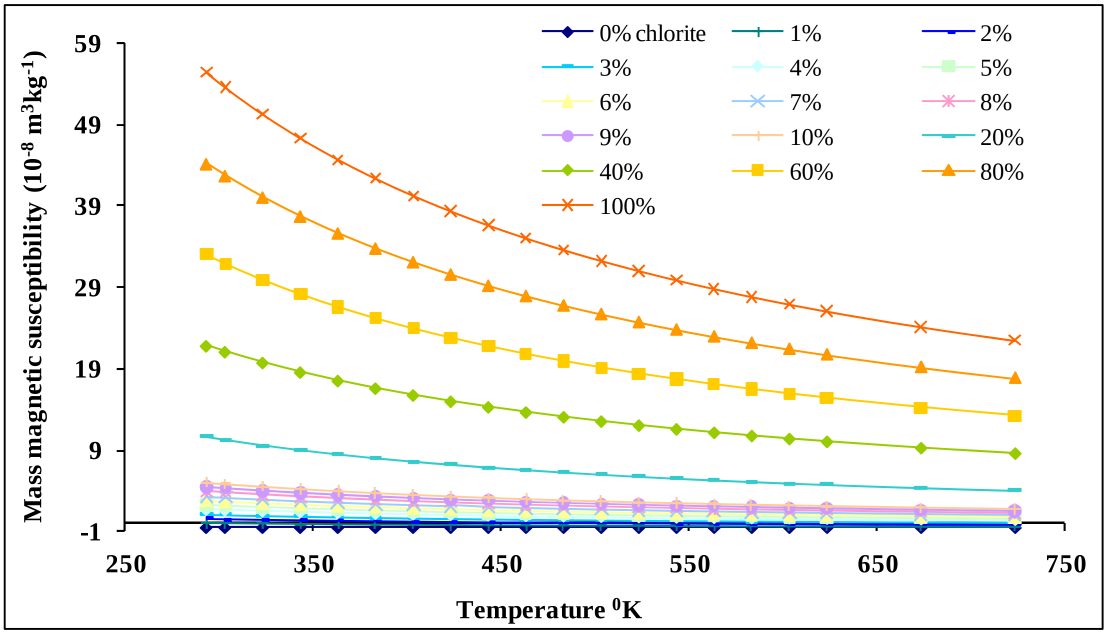

Figure 3. Theoretical model template curves of mass magnetic susceptibility with temperature for various mixtures of chlorite (chlorite percent is shown) and quartz. The curves are modeled for CFS chlorite (where CFS is the locality given by Borradaile et al, 1990).

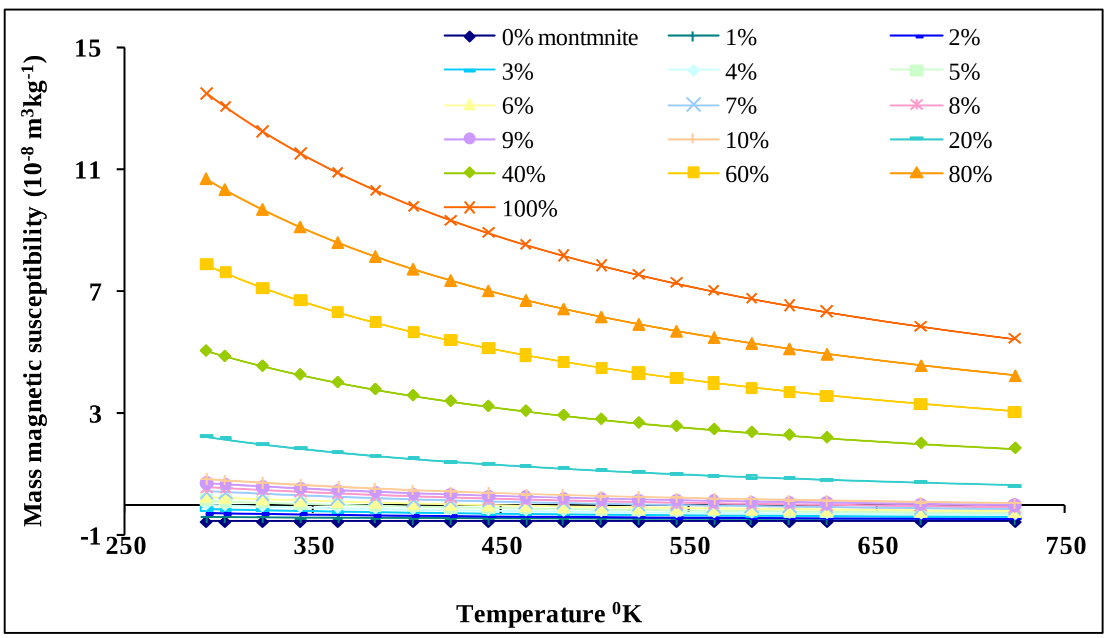

Figure 4. Theoretical model template curves of mass magnetic susceptibility with temperature for various mixtures of montmorillonite (montmorillonite percent is shown) and quartz.

CONCLUSIONS

The main conclusions from this work can be summarised as follows:

- The experimental thermomagnetic data for the turbidite and shoreface reservoir rock samples studied here closely follow the model template curves of magnetic susceptibility with temperature based on the Curie Law.
- The illite content derived from the model template curves agrees well in most cases with the illite content derived independently from magnetic hysteresis loops at room temperature, and XRD measurements.
- Downhole magnetic susceptibility data, in conjunction with temperature data (or the depth with a known or assumed geothermal gradient), can potentially be used with the modified model template curves to quantify the permeability controlling paramagnetic clay content and to model permeability in situ downhole. This information would be potentially useful early on in the appraisal stage of a field.

ACKNOWLEDGEMENTS

The Helmholtz Alberta Initiative (HAI) funded this research, and is supported by funding from the Alberta Government and the Helmholtz Foundation. The authors thank John Chatzis and Roland Lenormand for their valuable comments during the review process.

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