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Susceptibility and Remanent Magnetization Estimates from Orientation Tools in Borehole Imaging Logs

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Abstract Title

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Abstract

Orientation tools in borehole imaging logs acquire magnetic field data that is used for spatial orientation of the images. We propose to use this information to estimate both magnetic susceptibility and remanent magnetization of rocks inside wells, since measurements of these magnetic parameters are not often available in hydrocarbon exploration to support forward modeling of magnetic data. Using a set of simple equations and reasonable assumptions we were able to estimate the magnetic susceptibility of carbonates and basalts, as well as the remanent magnetization of the basalts, from a Pre-Salt well in Campos Basin, Brazil. When compared to susceptibility values measured in laboratory for the same rock interval, our results show a significant match, which gives confidence to method. Besides its use in hydrocarbon exploration, our methodology can be applied to mineral exploration where magnetic susceptibility is an important property for rock identification.

Introduction

Borehole imaging tools carry triaxial magnetometers in an auxiliary orientation tool (inclinometers) that acquire magnetic information used for spatial orientation of the images. Until recently, its use was restricted to support the inclinometry data. According to Laier et al. (2018), the perception that changes in the measured magnetic field were caused by the presence of magnetic rocks in the borehole has extended its use to the identification of igneous rock intervals in imaging tools data. This fact roses the question if it would be also possible to estimate their magnetic susceptibility, whose measurements in wells are rare in oil industry.

The importance of magnetic forward modeling to Pre-Salt exploration, specially where seismic interpretation shows ambiguity in the differentiation between carbonates and igneous rocks, contrasts with the lack of susceptibility measurements in boreholes. The incorporation of reliable magnetic susceptibility estimates into these models contributes for risks reduction. Despite the applicability of magnetic susceptibility for exploration studies, little use of borehole magnetic logging have emerged in oil industry. As a consequence, borehole logging tools are not available for commercial use in oil industry as far as we know. In this paper we propose to overcome this lack of direct measurements by estimating the magnetic susceptibility of the rocks along the borehole using the magnetic data acquired by the magnetometer included in the orientation tools of imaging logs.

Methods

The total field F measured inside a borehole can be related to the Earth's magnetic field H and to the total magnetization M_T of a rock as:

$$F = (H + M_T) = H + (M_H + M_R) = H + (\chi H + M_R)\,, \tag{1}$$

where M_H is the component of magnetization produced in response to the Earth's magnetic field, M_R is the natural remanent magnetization and χ is the rock's magnetic susceptibility.

Estimates for the magnetic susceptibility χ can be made using two different approaches. The first and more simplistic case is that of sedimentary rocks for which we assume that remanent magnetization is not preserved ($M_R = 0$) since sedimentary rocks has very low content of ferromagnetic minerals, which are responsible for retaining magnetization. In these cases, Equation (1) simplifies to:

$$F_\alpha = H_\alpha + \chi_\alpha H_\alpha \quad \text{or} \quad \chi_\alpha = \frac{F_\alpha}{H_\alpha} - 1, \tag{2}$$

where α may represent any of the x, y and z directions.

The second approach assumes the presence of a natural remanent magnetization M_R caused by the existing magnetic field at the time that rocks with high content of ferromagnetic minerals were formed. This case leads to a situation where there is only one equation and two unknowns χ and M_R as:

$$F_\alpha = H_\alpha + \chi_\alpha H_\alpha + M_{R_\alpha}. \tag{3}$$

However, if we assume χ and M_R as constant along some measured interval, we will have n measurements of F_α and can also get n values for H_α in the same interval. This assumption sounds reasonable as you can make your measured interval n as small as two samples. This allows us to construct a system of n equations and two unknowns χ and M_R, which in matrix form becomes:

$$\begin{bmatrix} H_{\alpha_1} & & 1 \\ & \vdots & \\ H_{\alpha_n} & & 1 \end{bmatrix} \begin{bmatrix} \chi_\alpha \\ M_{R_\alpha} \end{bmatrix} = \begin{bmatrix} F_{\alpha_1} - H_{\alpha_1} \\ \vdots \\ F_{\alpha_n} - H_{\alpha_n} \end{bmatrix}. \tag{4}$$

This system can be solved for χ_α and M_{R_α} using the least squares method, for instance. So, the mean value of χ and the magnitude of vector M_R will be given by:

$$\chi = \frac{\chi_x + \chi_y + \chi_z}{3} \quad \text{and} \quad M_R = \sqrt{M_{R_x}^2 + M_{R_y}^2 + M_{R_z}^2}. \tag{5}$$

Additionally, the inclination I_R and declination D_R of the remanent magnetization may be estimated by rearranging Equation (3) in terms of the remanent magnetization. Therefore, we can define the remanent magnetization components as:

$$\begin{aligned} M_{R_x} &= F_x - H_x - \chi H_x = M_R \cos I_R \cos D_R, \\ M_{R_y} &= F_y - H_y - \chi H_y = M_R \cos I_R \sin D_R, \\ M_{R_z} &= F_z - H_z - \chi H_z = M_R \sin I_R. \end{aligned} \tag{6}$$

The vertical components of remanent magnetization M_{R_z} in Equation (6) allows to estimate the inducing remanent field inclination I_R with the help of previously estimated remanent magnetization magnitude M_R,

$$I_R = \arcsin\left(\frac{F_z - H_z - \chi H_z}{M_R}\right). \tag{7}$$

Similarly, remanent magnetization declination D_R can be estimated from the horizontal components of remanent field (M_{R_x} and M_{R_y}) as:

$$D_R = \arccos\left(\frac{F_x - H_x - \chi H_x}{M_R \cos I_R}\right) \quad \text{or} \quad D_R = \arcsin\left(\frac{F_y - H_y - \chi H_y}{M_R \cos I_R}\right). \tag{8}$$

The estimates of magnitude M_R, inclination I_R and declination D_R completely define the remanent magnetization.

We have shown that estimates of magnetic susceptibility and remanence are possible through simple calculations when magnetic field data from borehole imaging logs are available.

Results

As an example, we have applied our method to estimate both the magnetic susceptibility and the remanent magnetization of a sequence that includes Pre-Salt carbonates and igneous rocks from Campos Basin, Brazil. The magnetic data used was acquired in well 1-RJS-755-RJ, which has identified oil in carbonate reservoirs of the Pre-Salt section. The logged segment was composed by a carbonate section extending from 6125 to 6210 m on top of a large basalt section between 6211 and 6681 m.

Estimates of magnetic susceptibility χ for the carbonate interval show absolute values ranging between 1.0×10^{-2} and 5.6×10^{-2} SI. Such values were about one order of magnitude higher than the average values for carbonates found in the literature (Lowrie, 1997), suggesting they may be influenced by the igneous rocks right below (see Figure 1). The interval extending from 6211 to 6681 m is composed by igneous rocks and was divided into six smaller segments separated by tiny carbonate layers. These intervals extend from 6211 to 6300 m, 6305 to 6495 m, 6500 to 6535 m, 6540 to 6570 m, 6585 to 6605 m and 6620 to 6681 m. Because values can be different in the intervals, estimates were be done separately using equations (4) and (5) for each interval. The estimates for the six igneous intervals are 1.4×10^{-1}, 3.1×10^{-1}, 7.8×10^{-2}, 2.6×10^{-1}, 3.3×10^{-1} and 2.6×10^{-1} SI, respectively. These results are within the expected range for igneous rocks according to the literature (Lowrie, 1997).

In terms of remanence intensity, the estimated values range from about 2.0 to around 6.0 Am^{-1}, which are lower in amplitude when compared to the strength of actual Earth's magnetic field. Although low field values are expected to occur during geomagnetic field reversals (Glatzmaiers and Roberts, 1995), it is also possible that the intensity of the remanent field haven't been fully preserved inside these rocks along the time. However, the fact that both χ and M_R estimates do not show widely disperse values gives confidence to the results. Results for both inclination I_R and declination D_R of the remanent magnetic field were also very consistent, which gives credibility to the estimates. In terms of remanence inclination the results point to angles between $-27°$ and $-30°$ pointing to the same direction of the actual Earth's field. Declination estimates show high values, but with small dispersion, ranging from around $112°$ to $118°$. Unfortunately, there is no remanent inclination and declination measures to compare.

Magnetic susceptibility laboratory measurements were made in 58 rock samples distributed along the analyzed interval and plotted together with the susceptibility estimates in Figure 1. For the carbonate interval estimate, results show values one order of magnitude higher than those measured in the lab. Estimates for the igneous rocks presented better results when compared with the lab analysis. The predictions for the majority of the igneous intervals show values just a little higher than the measurements. Among all, the first interval shows the best estimate. Taken into account that only the magnetic field acquired inside the well was used for the estimates, results were considered as satisfactory to provide reliable susceptibility and remanence values for forward magnetic modeling purposes.

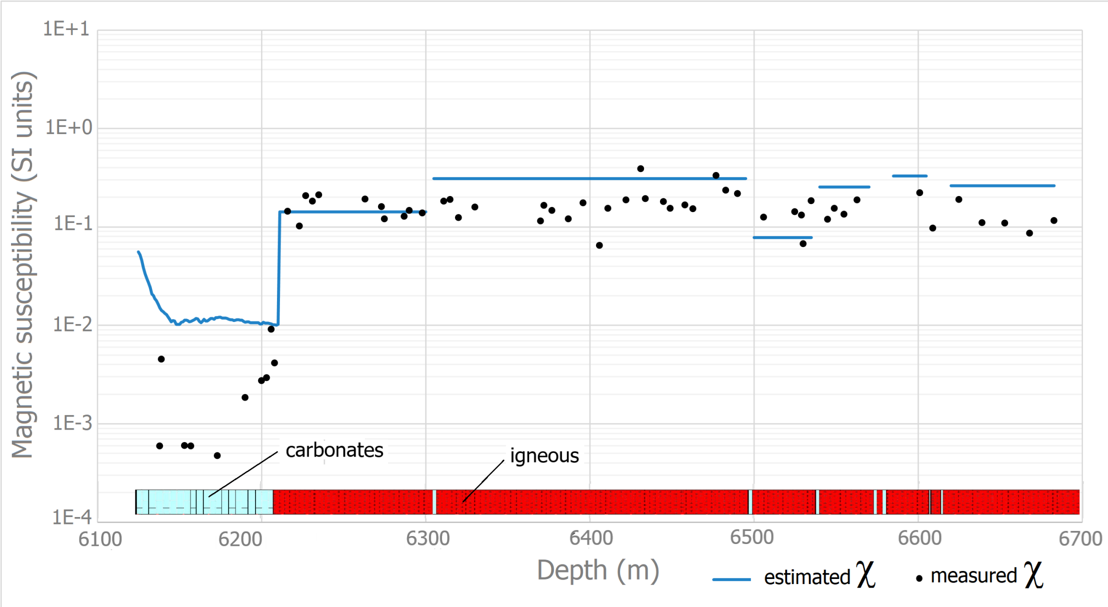

Figure 1: Magnetic susceptibility estimates for well 1-RJS-755-RJ and the result of 58 susceptibility laboratory measurements made in rock samples. The lithologic log along the well is exhibited in the base of the chart for illustration.

Conclusions

The proposed methodology has estimated magnetic susceptibility values inside the range of values published in the literature for igneous rocks, and very close to laboratory measurements taken from rock samples collected in the well. Although measurements of intensity, inclination and declination for magnetic remanence were not available to validate our estimates, the small values dispersion of each variable and the consistence of the results in terms of what we would expect for a magnetic field, gives confidence to the process. The promising results achieved with this research lead to the conclusion that both magnetic susceptibility and remanent magnetic field can be satisfactorily estimated, for forward magnetic modeling and inversion purposes, from the magnetic field acquired by orientation tools in borehole imaging logs. This is of fundamental importance specially in the case of hydrocarbon exploration, where direct measures are rare. The methodology can also be applied in mining boreholes if magnetic field measurements were available.

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