High-Precision Orientation of Three-Component Magnetic Downhole Logs

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Introduction

The possible benefits of measuring the magnetic flux density in three components continuously along a borehole have been recognized a long time ago by researchers who developed models and interpretation schemes for 3-component magnetic borehole data (Parker and Daniell, 1979; Gallet and Courtillot, 1989).

Common borehole methods provide data not allowing for an orientation with respect to a global reference, since this requires a highly accurate orientation system independent of the magnetic measurements. A first attempt to obtain the orientation of the sonde was made by Bosum et al. (1988) using a mechanical gyro and accelerometers. However, at that time the data quality of the gyro did not allow for a continuous 3-component measurement. Steveling et al. (2003) provide an example from the Hawaii Scientific Drilling Project (HSDP) drill hole, where directional information of magnetization was used to separate massive lavas from hyaloclastites. However, their directional analysis was limited to the inclination because information on the tool rotation around the vertical axis was not available.

Here, we describe the successful development of an orientation procedure with very high resolution independent of magnetic data. Test data were acquired in the 2.5-km-deep ICDP Outokumpu Research Hole in eastern Finland (Kukkonen, 2007) with the so-called Göttinger Borehole Magnetometer (GBM). The sonde uses three fiber optic gyros (FOGs) exhibiting a small drift of 1.5°h^{-1} and a high resolution of 9x10^{-5} degrees. In combination with a built-in Förster magnetometer triplet, the GBM can record the magnetic field in three components as well as the tool orientation continuously. In the Outokumpu drill hole, errors (root mean square) were 0.14° for the inclination and 1.4° for the declination of the magnetic flux density.

Technical Details and Data Preparation

The GBM sonde (3.25 m long, 68 kg) has a diameter of ~86 mm and approximately 140 mm including the centralizer (Fig. 1). The magnetic sensor group of the GBM consists of three Förster magnetometers with a maximum amplitude range of ±50,000 nT for the horizontal components (B_x, B_y) and ±70,000 nT for the vertical component (B_z). The resolution is 6.1 nT for B_x and B_y and 8.5 nT for B_z. The fiber optic gyros have a temperature-dependent drift which is minimal for temperatures above 32°C. Furthermore, the Gaussian noise of the FOG data decreases with increasing temperature to an average of 2x10^{-3} degrees in all components. In order to provide optimal operating conditions, the FOGs are mounted in an aluminum cylinder which is thermally isolated against the housing and actively heated by heater elements. To determine the temperature dependent characteristics for posterior recalibration, we conducted several calibration measurements. Due to the delicate electronics inside the FOGs, the maximum ambient operating temperature is 71°C.

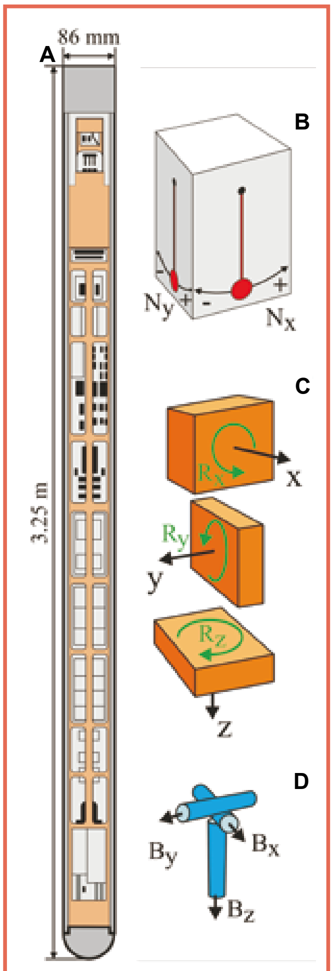

Figure 1. [A] Schematic sketch of the GBM [B] inclinometer, [C] fiber-optic gyros, [D] Förster-magnetometer triplet.

High demands on accuracy require extensive data processing. The first step is the calibration of the Förster probe triplet. The calibration measurements have been done in a magnetic laboratory equipped with a Braunbek coil system with active field compensation (Glassmeier et al., 2007). The quasi-zero-field region inside the Braunbek sys-tem has a residual field of <1 nT. With this system it is possible to determine the sensor offsets, the misalignment between the three sensor axes, and the scaling factors between measured data and genuine field. An alternative method is based on measurements in at least twelve positions while the external field has to be constant (Auster et al., 2002). By minimizing the differ-ence between the external and the measured field, the calibration factors can be computed. Another important step is the drift correction of the FOG data, using the temperature-dependent calibration factors previously determined in the laboratory. Finally, the actual reorientation procedure is carried out, which transforms the magnetic data from tool to geographical coordinates using the orientation information provided by the FOGs.

Case Study from the Outokumpu Deep Drillhole

The GBM sonde was utilized in a logging campaign in the Outokumpu research borehole in eastern Finland (Fig. 2) in September 2008. This 2516-m-deep well was drilled from 2004 to 2005 and is maintained by the Geological Survey of Finland as a deep geolaboratory. It offers ideal conditions for magnetic measurements as it cuts through a highly magnetized 200-m-thick Cu-Co-Zn bearing ophiolitic layer (1300–1500 m) at moderate temperatures below 40°C (Kukkonen, 2007).

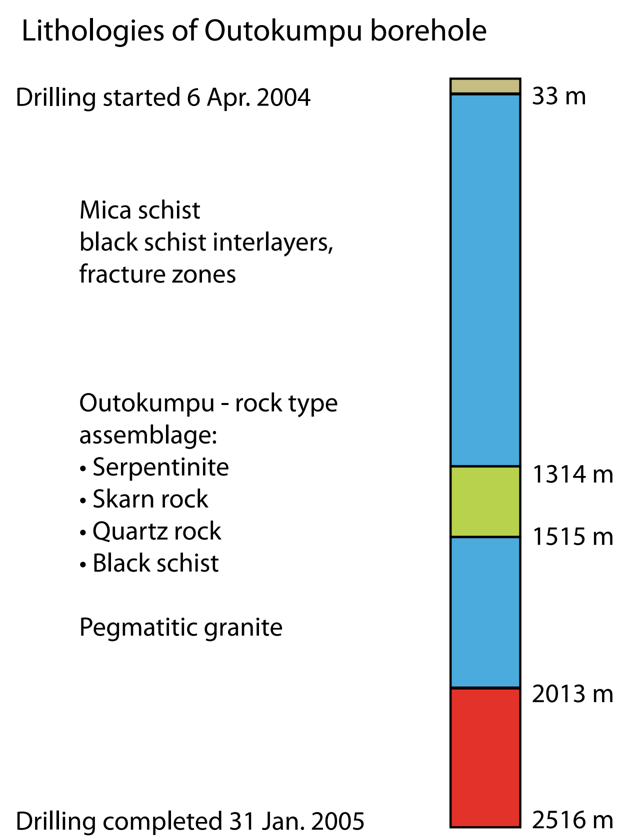

Figure 2. Borehole scheme of the Outokumpu well with simplified lithological units (Kukkonen, 2007).

Figure 3 shows a comparison of downlog and uplog data of sample measurements before and after reorientation. The mean difference between downlog and uplog in the total field (Fig. 3A) is on the order of 30 nT. The horizontal components after recalibration, but before reorientation, are depicted in Figs.3B and 3C. The large variations of ±11,200 nT are due to the rotation around the vertical axis. Depth regions with rapid changes (e.g., at 800 m), which are produced by sudden rotations, can be observed. A possible explanation is that they are caused by borehole wall outbreaks. The cable tension built up by the use of non-rotating centralizers may be released in such breakout sections. This hypothesis is supported by an observed co-occurrence between sections of rapid tool rotation and increasing caliper.

For the reorientation procedure, the magnetic data from the internal tool coordinate system xyz are projected onto the geographical system North, East, and Vertical (downwards). Each magnetic data triplet is multiplied by a rotation matrix computed from the FOG's data. Furthermore, other effects have to be considered, one of which is the Earth's rotation. The fiber optic gyros measure rotation depending on their orientation with respect to Earth's rotational axis, in addition to the tool rotation. Therefore, the Earth's rotational vector has to be projected into the tool system and subtracted from the FOG data in all three components for each depth.

The next processing corrects the misalignment of the FOG system. If the three axes of this system are not exactly perpendicular to each other, rotation around the z-axis will cause a spurious signal in the x- and y-gyros, which would be mistaken for a real rotation. Due to the torque in the cable, the rotation around the z-axis dominates. Thus, we consider only the misalignment between the x- and z-axis, as well as y- and z-axis, which were determined by calibration measurements to be 0.19° and 0.02°, respectively.

Another challenge is the computation of the rotation matrix itself. During the sampling period of 0.5 seconds, rotation occurs continuously around all three axes. However, when computing the rotation matrix, one has to assume rotation in a specific order—for instance, in roll-yaw-pitch convention. Instead of using only one rotation matrix per step, the movement is smoothed by dividing the period into fifty steps. Each matrix corresponds to a rotation by only 1/50 of the measured rotation angles. This reduces the error particularly in regions where fast rotations in all three axes exist.

The final correction takes the tool orientation above ground into account. Before actually starting the logging, the tool is set up in a vertical position above the borehole and is aligned to a north marker by a sighting telescope mounted on the housing. This defines the start orientation in the FOG data with an accuracy of 5×10^{-2} degrees. Having finished the uplog this procedure is repeated, so that the orientation at these two time points can be ensured. If the reorientation procedure works perfectly, the two orientations should match exactly after processing. Nevertheless, differences of a few degrees are usually observed in all three components. Based on these deviations, additional drift corrections are computed and applied to the FOG data to minimize the orientation differences. In Figs. 3D–3F, the example logs are shown after the complete reorientation procedure.

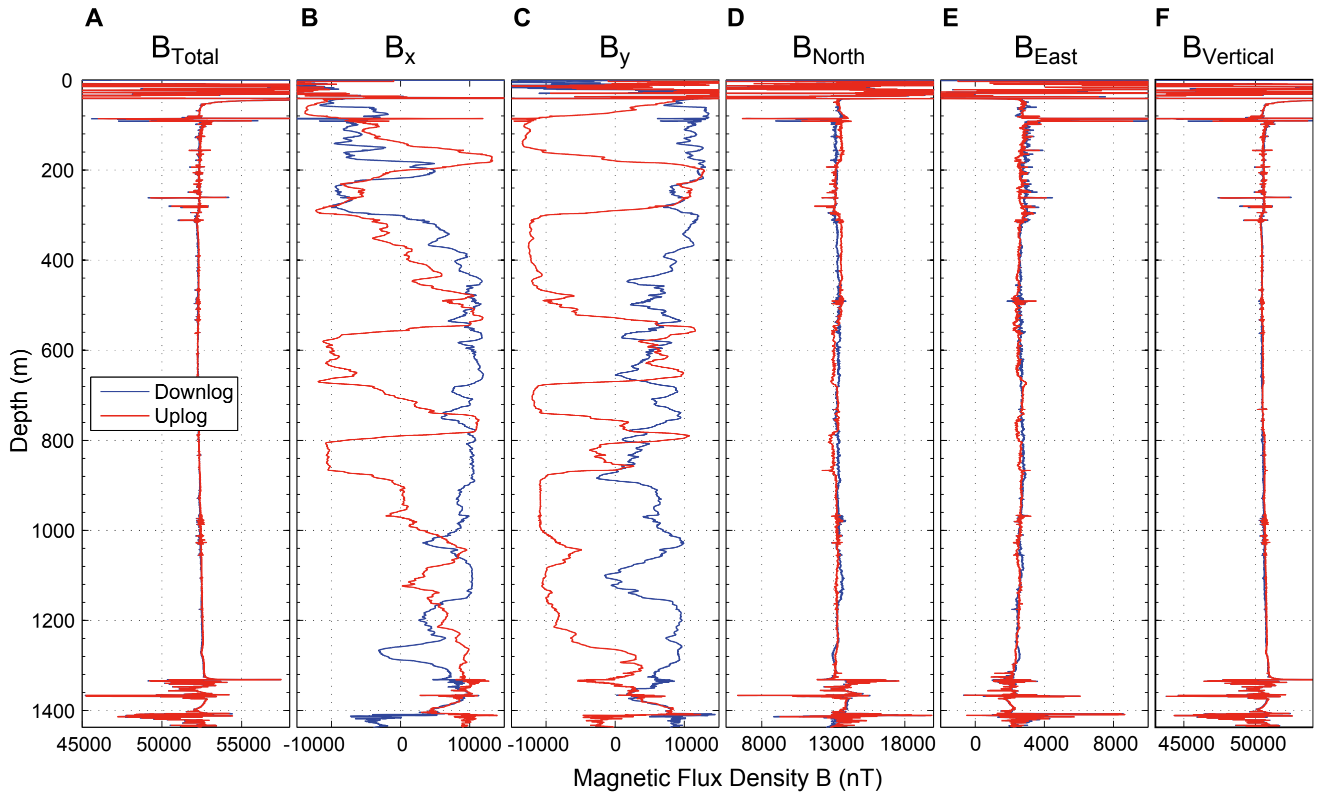

Figure 3. [A] Total magnetic flux density, [B and C] horizontal components before reorientation (internal tool coordinates xyz), [D–F] magnetic flux density after reorientation with geographic coordinates North, East, Vertical.

Quality Assessment

One possibility to assess the quality of the reorientation procedure is the comparison between the uplog and the downlog. For a quantitative evaluation, we use the root mean square (RMS) of the difference. This results in errors of RMS_{Total} = 50 nT, RMS_{North} = 250 nT, RMS_{East} = 180 nT, and $RMS_{Vertical}$ = 75 nT for the total, north, east, and vertical components, respectively. The deviations are not equally distributed. In regions between two fast rotations (e.g., 800–880 m), the discrepancy reaches up to 500 nT. There are also sections where the deviation is much smaller (less than 45 nT) in all three components between 680 m and 750 m. The errors of inclination and declination of the magnetic flux density result are $RMS_{Inclination} = 0.25^{\circ}$ and $RMS_{Declination} = 0.75^{\circ}$, respectively.

Besides comparing downlog and uplog in the same measurement, the reproducibility between different logs is also an important criterion. In Fig. 4, two logs measured on

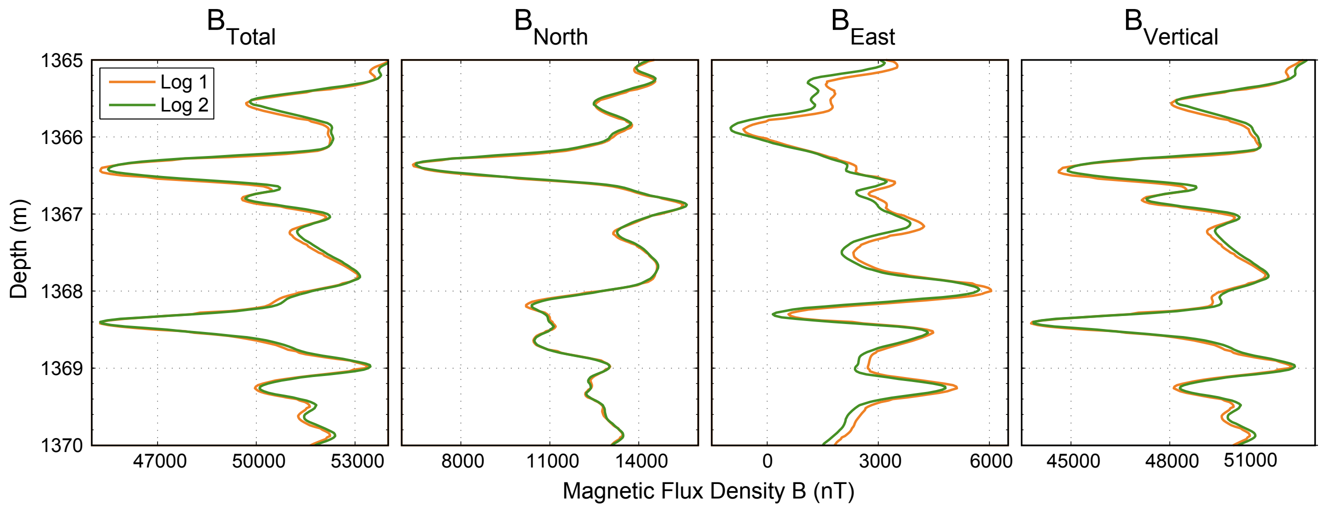

Figure 4. Comparison between two different logs, extract of strongly magnetized region. Each line represents the mean value of downlog and uplog.

two consecutive days under identical conditions are shown. Each log consists of the average value of the corresponding downlog and uplog. To illustrate the spatial resolution, a section of the strongly magnetized Outokumpu rock assemblage is shown in detail (Fig. 4). All features are reproduced very well. The average amplitude deviations between the two logs are 170 nT in the total and vertical components, 10 nT in the east component, and 330 nT in the north component. The deviations in orientation are $RMS_{Inclination} = 0.14^{\circ}$ and $RMS_{Declination} = 1.4^{\circ}$.

Outlook

The logging results from the Outokumpu drill hole are used to calculate the rock magnetization, based on a model developed by Bosum et al. (1988). Existing susceptibility measurements are used to separate remanent from induced magnetization. Preliminary results indicate that the direction of remanent magnetization is inhomogeneous and scattered. From a statistical analysis we were able to identify two preferred directions of remanent magnetization which might be related to the genesis of the Outokumpu rock assemblage in the depth region of 1300–1440 m. The results of the ongoing detailed analysis including magnetic laboratory measurements will be reported elsewhere. Based on the comparison of our *in situ* direction of remanent magnetization with direction measured in the laboratory, we might also be able to carry out a reorientation of core samples from this section.

We will continue to improve the accuracy of the reorientation procedure. Presently, the main source of error is the fast rotation of up to 10° around the z-axis during the sample period of 0.5 seconds. Since the sampling period is limited by the data transfer rate to the base station, an upgrade of the tool hardware is desirable. We plan to implement a flash memory, which will enable us to increase the sampling frequency by twenty-fold. This will also enhance the spatial resolution of the tool using the same logging speed. Furthermore, we intend to carry out extended calibration measurements to obtain the misalignment angles between all three FOG axes and their scaling factors. We will also re-measure the calibration factors of the magnetic sensors, considering possible temperature dependence. We aim for errors less than 0.1° for both inclination and declination of the magnetic flux density.

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