Recognition of drilling-induced remanent magnetization by $Q$-factor analysis: a case study from the KTB-drillholes

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Abstract

Drilling-induced magnetizations (DIRM) have been detected in the rocks of the KTB (German Continental Deep Drilling Program) by determining the Königsberger factor ($Q$-factor), the ratio of remanent to induced magnetization. Specimens from the outer part of the drillcores show significantly enhanced $Q$-factors up to 10 times compared to those from the internal part. Contamination by coating with abrasive material, for example from the drill bit, and grain size variations due to cutting action of the diamond coring system, can be excluded. The DIRM is interpreted to be caused by the magnetization of the core barrel and drill string, which produce higher fields close to rim than in the interior of the drill core. After removing the DIRM contaminated samples from the database, the $Q$-factors for the main KTB rock units have mean values of 4.8 for the gneiss units and 1.6 for the metabasite units. The uncontaminated data set fits in the appropriated field of the susceptibility–$Q$ plot of Henkel J. Appl. Geophys. 32 (1994) 43–53 for metamorphic continental rocks. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Measurements of remanent magnetization on cores from drillholes often reveal a secondary component of magnetization, which is acquired during the drilling process and referred to as the drilling-induced remanent magnetization (DIRM). A large number of studies have been undertaken in order to obtain information about the origin of such DIRM effects. Possible sources that have been discussed are the effects of stress due to cutting (Burmester, 1977; Jackson and Van der Voo, 1985) or of shock associated with the drilling process (Lauer, 1978). In a detailed study by Audunsson and Levi (1989) on titanomagnetite-bearing drill cores from the Columbia River Basalt, DIRM was identified and attributed to a magnetic field induced by the core barrel. These effects were found to be highest at the core rim and decreased toward the internal part of the core. These authors excluded contamination of the drill core on its surface caused by metal abrasion of the drilling equipment as a secondary source of magnetization. The magnetic field acting at the tip of the core barrel during drilling have been modelled by Pinto and
McWilliams (1990) and they found good agreement between the modelled field and the measured field of the drilling equipment. The strongest magnetic field is always measured at the tip of the core barrel and it decreases towards the center of the aperture. Significant variations in the magnetic field strength produced by the core barrel have been recorded from different drilling projects. For example, fields were only 0.15 mT on the core barrel used for the pilot hole of the Continental Deep Drilling Program (KTB) of Germany (Pohl et al., 1991), but up to 5 mT near the joints of the drill string (Worm, unpublished results), 2.5 mT for the Cajon Pass drilling (Pinto and McWilliams, 1990), 1 to > 10 mT for the Ocean Drilling Program (Fuller and Hasted, 1997), and up to 20 mT for the Columbia River Basalt drilling (Audunsson and Levi, 1989). Such variations are likely to depend on the material properties of the core barrel itself. In addition, Pohl et al. (1991) considered the effect of the drilling rig, after core recovery, where fields on the order of 1 mT were measured for the KTB.

Characterization and quantification of DIRM components is of importance in the earth sciences, if the remanent magnetization of drill cores is to be used for paleomagnetic and magnetostratigraphic analyses or the modelling of source layers of magnetic field anomalies. Recognition of these secondary effects is also critical in drilling projects where the direction of the viscous remanent magnetization is used for the reorientation of drill cores. Separation of the secondary DIRM component from the primary natural remanent magnetization (NRM) can be achieved, for example, by stepwise demagnetization with an alternating field or by a thermal demagnetization routine. However, this procedure is generally time-consuming and requires special analytical facilities. For the interpretation of data from drillholes where dense sampling is applied, a quick and routine procedure for recognizing DIRM components is desired.

In this paper, results are presented from investigations of the remanent magnetization in the Continental Deep Drilling Program of Germany (KTB). Although former studies considered DIRM effects in the KTB (Pohl et al., 1991; Worm and Rolf, 1994), no systematic characterization of these secondary influences were made. This study attempts to recognize and characterize DIRM by determining the Königsberger-ratio ($Q$-factor) of magnetization. The $Q$-factor is defined as the ratio between remanent magnetization and the magnetization induced in the geomagnetic field, $Q = \frac{\text{NRM}}{k \times H}$, where $k$ is the magnetic susceptibility. Technical magnetic fields that induce a DIRM can reach magnitudes several times that of the geomagnetic field and therefore, if a significant DIRM is acquired, the measured remanent magnetization can be considerably higher than the undisturbed NRM, thus resulting in elevated $Q$-factors. It will be demonstrated that the $Q$-factor can provide quick information concerning the enhanced magnetic field acting during the acquisition of remanence and therefore can be used to detect drilling-induced magnetization in core material.

1.1. Drilling / coring equipment

Two deep boreholes were drilled during the KTB research program (1987–1994). A pilot hole reached a depth of 4000 m, with in situ temperatures of up to 180°C (KTB-Vorbohrung, KTB-VB), and the ultra-deep main hole was drilled down to 9100 m, with temperatures of 260°C reached at the base (KTB-Hauptbohrung, KTB-HB). This study is focussed on samples from the KTB-VB from which a nearly complete core (diameter of 94 mm) is available, extracted by wireline recovery technique with diamond coring systems. A spin of 250–350 U/min was used for cutting the cores (Engeser, 1995).

1.2. Magneto-minerology of the KTB rocks

The KTB drill holes passed through a sequence of metamorphic rocks constituting the Variscan basement of the Bohemian Massif in East Bavaria, Germany (Hirschmann et al., 1997). Three main types of rock units have been defined: gneiss units that mainly consist of paragneisses and minor intercalations of amphibolites; metabasite units that are composed of amphibolites, metagabros and metaultramafic rocks; and a subordinate varied unit of alternating metavolcanics, paragneisses and amphibolites (Harms et al., 1993). Due to the steep inclination of the metamorphic foliation and through intense reverse faulting, a repetition of rock units is encountered in the drilled
profile (Duyster et al., 1995). In this study, we investigate samples from the gneiss and metabasite units, which cover the major part of the drilled profile in the KTB-VB (Fig. 1). The average susceptibilities are around $400 \times 10^{-6}$ (SI-Units) in the gneiss units and $1000 \times 10^{-6}$ in the metabasite units (Berckhemer et al., 1997) which are mainly due to paramagnetic minerals such as biotite in the gneisses and hornblende in the metabasite lithologies. However, locally the susceptibilities are increased up to $> 10^{-2}$, due to ferrimagnetic minerals.

Pyrrhotite was found to be the main carrier of remanence in both the gneiss and metabasite units of the KTB-VB and KTB-HB. But whereas pyrrhotite is the only ferrimagnetic mineral present in the gneiss units, the rocks of the metabasite units may locally also contain some magnetite (Berckhemer et al., 1997; Kontny et al., 1997). Especially in ultramafic intercalations high magnetic susceptibilities up to 0.15 SI-units are related to the presence of magnetite. In the gneiss units of the KTB-VB ferrimagnetic and antiferromagnetic pyrrhotites are intergrown while in

Fig. 1. Schematic profile of the KTB-VB and susceptibility and remanence log (whole core measurements) from quasi-continuous measurements performed in the KTB-field laboratory (after Bücke et al., 1990). (A) Variegated units, (B) paragneiss units, (C) metabasite units.
1.3. Sampling routine

This study uses the database that has been obtained during routine magnetic measurements on the KTB drill cores in the magnetic laboratory of Grubenhausen (Geol. Survey of Lower Saxony). Results presenting these measurements were previously published by Worm and Rolf (1994). The sample sites for this database have been selected on the basis of the continuously measured susceptibility on the drill cores, performed at the KTB field laboratory (Bücker et al., 1990). Samples are taken from sections with high susceptibilities and remanence values, which reflected the occurrence of ferrimagnetic minerals within the paragneiss and metabasite units (Fig. 1). These sections are of interest because they contribute to the magnetic anomaly found in the area of the KTB location (Pucher, 1986, 1994).

At each sampling site, two plugs were drilled, in order to obtain a total of eight specimens, each with a diameter of 1" and a height of 2.1 cm (Fig. 3). For the metabasites the ferrimagnetic type predominates (Kontny et al., 2000). The grain size for the ferrimagnetic pyrrhotite ranges mainly from 10 to 100 μm in both rock units and the grains show multidomain characteristics (Kontny et al., 1997). In Fig. 2, thermomagnetic curves are presented that reflect the typical magneto-minerology of the investigated rock units with two-phase pyrrhotite (ferrimagnetic + antiferromagnetic) predominating in the gneisses and a single pyrrhotite phase (ferrimagnetic) in the metabasites.
each specimen, the susceptibility and the remanent magnetization were measured and the $Q$-factor has been calculated. The database contains measurements on 523 gneiss and 636 metabasite specimens, however, for this study we considered only those specimens with remanence values higher than 50 mA/m (245 gneisses, 198 metabasites) as the NRM measurements were performed with a relatively low-resolution spinner magnetometer.

2. Results

In general, specimens from the gneiss and metabasite units show strong variations in $Q$-values with a wide range of scattering between 1.3–45.4 and 0.1–18.6, respectively (Fig. 4). The mean value for the gneiss units is $8.6 \pm 6.7$, which is significantly higher than the mean $Q$-factor for the metabasites at $2.2 \pm 2.0$. This difference in the mean values of the $Q$-factor may reflect the differences in the magnetominerology between the rock types.

Fig. 4. Histogram of $Q$-factors for all specimens (marked in dark grey) from the gneiss ($N = 245$) and metabasite ($N = 198$) units considered in this study. The data set marked in light grey colour shows the $Q$-factor distribution after removing the outermost specimens, effected by DIRM.

Fig. 5. $Q$-factors in relation to the plug position (see Fig. 3) shown for 12 samples from a gneiss section. The $Q$-factors are significantly enhanced in the outermost specimens of the two plugs (positions 1, 4 and 5, 8, respectively).
One reason for the scatter of $Q$-factors becomes obvious when the data are compared with the position of the measured specimen within the drilled plugs. Specimen nos. 1 and 4, as well as nos. 5 and 8, from the outermost parts of the drill core, reveal significantly higher $Q$-factors than specimen nos. 2, 3, 6, and 7, which are located around the center of the drill core. For example, this pattern is evident in the presentation of $Q$-factors for 12 samples from a paragneiss section taken from the interval 2250–2350 m, where the $Q$-values are shown in relation to their position in the drilled plugs (Fig. 5). In the outer parts, the $Q$-factors are significantly enhanced and reach maximum values of up to 42.8, while in the internal parts, values do not exceed a $Q$-factor of 10. The highest value for the $Q$-factor measured in the whole KTB-VB profile reached 45.4 in hornblende-bearing gneisses at 2574.33 m.

Fig. 6. The diagrams (a) to (c) give evidence that there is no correlation between the magnitude of susceptibility and the $Q$-factor. Examples are given from the gneiss (a) and metabasite (b) units that show the $Q$-factor and susceptibility for different plug positions (susceptibility given in $10^{-6}$ SI units). In (c), the $Q$-factor is plotted vs. the susceptibility for samples from the gneiss sections (a total of 210 specimens). Specimens from the outermost positions (1, 4 and 5, 8) presented in filled squares as well as the specimens from the inner positions (2, 3 and 6, 7) presented in unfilled squares show a wide range of susceptibility without any correlation to the $Q$-factor.
In order to exclude that this distribution is related to the magnitude of susceptibility that might be enhanced in the outer samples by coating of metal abrasive materials from the core barrel, we compared the $Q$-factors with the susceptibility values. In Fig. 6a, the $Q$-factor is plotted against the magnitude of susceptibility for paragneisses with a significant ferrimagnetic contribution ($k > 500 \times 10^{-6}$). Evidently, there is no correlation between these two magnetic parameters. This holds for the samples from the internal as well as from the outer part of the drill cores. That susceptibility and $Q$-factors are not related is also documented in Fig. 6b,c. Here, examples are shown from both gneiss and metabasite units, where the susceptibility values and $Q$-factors are compared for eight specimens from different plug positions of a sampling site (as shown in Fig. 3). From these results, a contamination of the drill core by drilling artifacts can be excluded.

Furthermore, we performed acquisition curves for the isothermal remanent magnetization (IRM) which provides information concerning the differences in grain sizes and domain structure. In Fig. 7, the IRM curves for specimens from the different plug positions are compared for both gneiss and metabasite lithologies. There is no variation observed between the specimens with relatively high $Q$-factors from the outermost parts of the core and those with lower $Q$-factors, from the internal parts of the core. Samples from the gneiss and metabasite units show an identical course of IRM-acquisition curves, with weak magnetic behavior where more than 90% of magnetization is acquired in a magnetic field $< 100$ mT. This is consistent with a multidomain state of the pyrrhotite that has also been observed in reflected light microscopy (Kontny et al., 2000).

These investigations show clear evidence for the enhancement of the $Q$-values in samples from the outermost parts of the drillcore. After eliminating these specimens from the bulk of the measured samples, a mean $Q$-value of $4.8 \pm 1.9$ is calculated for the gneiss units (considering only specimens from position nos. 2, 3, 6, and 7). For the metabasite units, the mean value is significantly lower with $1.57 \pm 1.04$ as measured from the internally positioned specimens.

![Fig. 7. IRM-acquisition curves for examples from the gneiss (a) and metabasite (b) units. Each diagram comprises data of four specimens from a drilled plug (positions 1 to 4, see Fig. 3). For (a), the $Q$-factors are 14 and 9 for the outer specimens and 5 for both inner specimens, and for (b), 1.2 and 1.5 for the outer specimens and 0.5 for both inner specimens, respectively. There is no significant difference in the acquisition behavior between samples from the different plug positions.](image)
3. Discussion

Based on the analyses of the $Q$-factors of magnetization, the influence of DIRM on the remanent magnetization is recognized for the rocks of the KTB. Contamination of the drill core that may enhance the susceptibility, such as that arising from coatings of abrasive material from the drill bit, can be excluded. Grain size variations due to the cutting action of the diamond coring system that could influence the grain size distribution can also be neglected. Having excluded these possible contributions, we consider that the magnetic field of the core barrel is the principle source for the DIRM.

There are differences in the magnitude of DIRM for the two main rock types recovered from the KTB drillholes. A strong influence of DIRM is found in paragneisses. A mean value for the $Q$-factor of 8.6 was reduced to 4.8 after removing specimens from the outer parts of the drill core, which presents a reduction of 44%. In metabasites, the influence of DIRM is weaker. The mean $Q$-factor decreased from 2.2 to 1.6 (27%) after correction of the data. These $Q$-factors from the inner core area are considered to represent more reliable values for the calculation of magnetization for these KTB rocks. This might have an influence on the modeling of magnetic anomalies in the KTB-area (Bosum et al., 1997).

As the drill site is situated in a crystalline basement complex, we compared the obtained $Q$-factors for the gneisses and metabasites with other magnetic data for basement rocks published by Henkel (1994).

![Fig. 8. Combined susceptibility-$Q$-value diagrams (susceptibility in cgs units). (a) Standard-diagram based on data from the Nordkalott-project (Henkel, 1994). (b) Paragneiss units, all specimens; (c) paragneiss units, specimens from the internal part of the core only; (d) metabasite units, all specimens; (e) metabasite units, specimens from the internal part of the core only.](image-url)
He presented a statistical analysis of 31,183 samples from metamorphic rocks of Scandinavia (Nordkalott project) and introduced a combined susceptibility-Q-value plot where fields for different magnetominerologies were discriminated. Overall, the KTB data matches well with this discrimination diagram for the magnetic parameters of basement rocks (Fig. 8). The data from the gneiss units plot in the field for pyrrhotite-bearing rocks, which are characterized by $Q$-factors of around 10. However, the data for the metabasite units plot between the fields for pyrrhotite and magnetite and show an increase in susceptibility which corresponds to the decrease in $Q$-values. This increase in susceptibility is related to an increasing magnetite content at the expense of pyrrhotite which leads to correspondingly lower $Q$-factors (see Fig. 8a). The lowest $Q$-values (0.1–1) are related to ultramafic rocks that bear magnetite and show the highest susceptibilities.

We have shown in this study that the remanent magnetization may be significantly enhanced by secondary effects induced during the drilling process. Such factors can cause an increase in the $Q$-values up to 10-fold in magnitude. It is therefore critical that these secondary effects are considered before using NRM intensity data for geophysical modelling. The magnetic field of the core barrel and the drill string may also induce a secondary magnetization in the borehole-wall which affect borehole anomalies measured with a downhole magnetometer. The statistical analysis of $Q$-factors obtained from sections perpendicular to the core axis therefore presents a quick and useful method for the recognition of DIRM in magnetic databases of drilling projects, where large quantities of data can easily be checked for this secondary overprint.

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