The Meteoritical Society

Meteoritics & Planetary Science 42, Nr 4/5, 829–838 (2007)
Abstract available online at http://meteoritics.org

Petrophysical and paleomagnetic data of drill cores from the Bosumtwi impact structure, Ghana

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(Received 14 August 2006; revision accepted 01 January 2007)

Abstract–Physical properties from rocks of the Bosumtwi impact structure, Ghana, Central Africa, are essential to understand the formation of the relatively young (1.07 Ma) and small (10.5 km) impact crater and to improve its geophysical modeling. Results of our petrophysical studies of deep drill cores LB-07A and LB-08A reveal distinct lithological patterns but no depth dependence. The most conspicuous difference between impactites and target lithologies are the lower bulk densities and significantly higher porosities of the suevite and lithic breccia units compared to meta-graywacke and metapelites of target lithologies. Magnetic susceptibility shows mostly paramagnetic values ($200–500 \times 10^{-6}$ SI) throughout the core, with an exception of a few metasediment samples, and correlates positively with natural remanent magnetization (NRM) and Q values. These data indicate that magnetic parameters are related to inhomogeneously distributed ferrimagnetic pyrrhotite. The paleomagnetic data reveals that the characteristic direction of NRM has shallow normal (in a few cases shallow reversed) polarity, which is in agreement with the Lower Jaramillo N-polarity chron direction, and is carried by ferrimagnetic pyrrhotite. However, our study has not revealed the expected high magnetization body required from previous magnetic modeling. Furthermore, the LB-07A and LB08-A drill cores did not show the predicted high content of melt in the rocks, requiring a new interpretation model for magnetic data.

INTRODUCTION

The Bosumtwi impact structure, Ghana, Central Africa, was formed by a meteorite impact 1.07 Ma ago and is considered the largest (rim-to-rim diameter about 10.5 km) young impact structure known on Earth (Pesonen et al. 2003). The Bosumtwi area is dominated by Proterozoic Tarkwaian-Birimian (~2.2–1.9 Ga) age meta-graywackes, meta-sandstones, and impact-related lithic breccias and suevites. The Bosumtwi crater itself is almost completely filled by Lake Bosumtwi, which has preserved the crater's structure and therefore provides a unique opportunity for carrying out detailed studies to understand its formation process. Bosumtwi is also a likely source crater for the Ivory Coast tektites (Koeberl et al. 1997, 1998), which makes it one of only four impact structures associated with a tektite strewn field.

A wide range of studies (e.g., geophysical: Jones et al. 1981; Plado et al. 2000; Pesonen et al. 2003; geochemical: Koeberl et al. 1997, 1998; geological: Reimold et al. 1998; Koeberl et al. 2005) have been conducted over the past decades, complemented by a shallow drilling program undertaken by the University of Vienna in early 1999. In spite of previous studies, the structural aspects of Bosumtwi are still poorly known. To gain more information, the Bosumtwi Crater Drilling Project (BCDP) was carried out during September and October 2004 as part of the International Continental Scientific Drilling Program (ICDP).

This study focuses on the petrophysical and paleomagnetic investigations of drill cores LB-07A and LB-08A, which contain both impactites and target rocks. Additionally, a comparison with whole core scanning data (Morris et al. 2007) and previous laboratory measurements of the outcropping rocks (Plado et al. 2000) will be given.

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DESCRIPTION OF THE ROCK COLLECTION AND SAMPLING

Within the BCDP two hard rock cores with impactites and target lithologies, named LB-07A and LB-08A, were drilled in the central-western part of the lake (see Fig. 1 in Deutsch et al. 2007). A total of about 400 m of impactite cores was recovered.

LB-07A was drilled into the deep crater moat, about 0.5 km northwest of the central uplift. The drill hole is about 545 m deep and impact rocks (polymict lithic breccia, monomict lithic breccia, and suevite) were recovered from 333.38 to 545.08 m. Lithologically the LB-07A consists of alternating sequence of impact breccias with relatively low amount of melt, and meta-graywacke and metapelite intercalations, which are interpreted as mega-clasts (Reimold et al. 2006). The upper part of the breccias is clast-rich meta-graywacke, however, various metapelite, quartzite, and carbonate target clasts are significant as well (Coney et al. 2006; Reimold et al. 2006). Clast size of breccias varies from a few millimeters up to several tens of meters, but no systematic clast-size pattern, as a function of depth, has been observed so far.

Drill core LB-08A is located at the outer flank of the central uplift. This core is about 451 m deep, with impactites occurring between 235.6 m and 262 m. The latter depth marks the bedrock transition. Polymict lithic breccias are followed by thick sequences of meta-graywacke with suevite dikes (Deutsch et al. 2006; Ferrière et al. 2006).

The sampling interval of the cores was sufficient (one sample per 1–5 m, where the condition of the core allowed) to allow high-resolution petrophysical core logs. The prism-like specimens, or occasionally cylinders, were cut out of the drill cores.

Petrophysical properties of more than 130 specimens (representing about 100 samples) were measured at the Solid Earth Geophysics Laboratory at the Division of Geophysics, University of Helsinki. Seventy-eight specimens (from 61 samples) were used for paleomagnetic study. Due to a very fragile nature of the drill cores, the specimens from the lower part of LB-07A are not included in this analysis.

METHODS

Magnetic susceptibility, the intensity of natural remanent magnetization (NRM), Koenigsberger ratio (Q ratio; representing the ratio of remanent to induced magnetization), bulk and grain density, and porosity were measured in collaboration with two other laboratories: the Geological-Paleontological Institute of Ruprecht-Karls University, Heidelberg (50 samples; see also Kontny et al. 2007), and the Laboratory of Petrophysics at the Department of Applied Geosciences and Geophysics, University of Leoben (16 specimens; see Schell et al. 2007), in order to better understand the formation of Bosumtwi impact structure and to provide constrains for geophysical modeling. Petrophysical parameters were determined using standard methods (e.g., Plado et al. 2000). For density and porosity measurements the Archimedean method, based on weighting water saturated (saturated bulk density—hereafter called simply "bulk density") and owen dried samples in air and in water, was used. In a few cases, the dry bulk density measurements were carried out using tiny glass beads (20–50 μm) (Consolmagno et al. 1998) as replacement of water. The bulk susceptibility measurements were performed using a RISTO-5 kappabridge (operating frequency of 1025 Hz, and DC field intensity 48 A/m), or KLY-2 (see also Schell et al. 2007) and KLY-4S kappabridges (870 Hz, 300 A/m; see Kontny et al. 2007).

Paleomagnetic studies were carried out at laboratories in Helsinki and Heidelberg. The measurements were carried out with the 2G Superconducting Rock Magnetometer (SQUID) (Helsinki), and MI AFD 1.1 demagnetizer (Magnon International) combined with JR-5A spinner magnetometer (AGICO) (Heidelberg). The samples were demagnetized in alternating field up to 160 mT (in some cases 100 mT) using 2.5–10 mT steps (Helsinki; for method description of paleomagnetic studies in Heidelberg, see Kontny et al. [2007]) to identify primary and secondary magnetization components.

For thermal demagnetization (from ambient temperature to 650 °C) the Schoenstedt TDS-1 (Helsinki) and MMTD1 (Heidelberg) furnaces were used.

RESULTS

Petrophysical Properties of Lithological Units and Their Depth Dependence

Petrophysical results are plotted as a function of depth for both drill cores (Fig. 1) to illustrate possible depth dependence of physical properties (Pohl et al. 1977). The petrophysical parameters of different lithologies of the LB-07A and LB-08A drill cores are summarized in Table 1 in comparison with petrophysical data of exposed Bosumtwi surface rocks (Plado et al. 2000). Note that all values in Table 1 are given as sample means.

Bulk density of core samples from LB-08A is, on average, higher than in LB-07A. The average bulk density (2300–2750 kg/m^3) of LB-08A is slightly lower in the upper part of the core and increases with depth. This, however, seems to be related to brecciation (see below). Bulk density of core samples from LB-07A displays a strong scatter from 1900 to 2650 kg/m^3 throughout the core, but does not show any depth dependence. The uppermost part of core LB-08A consists of impact breccias, which progress into target lithologies, such as meta-graywackes and metapelites (e.g., schists, phyllites, etc.; for a detailed lithology see Deutsch

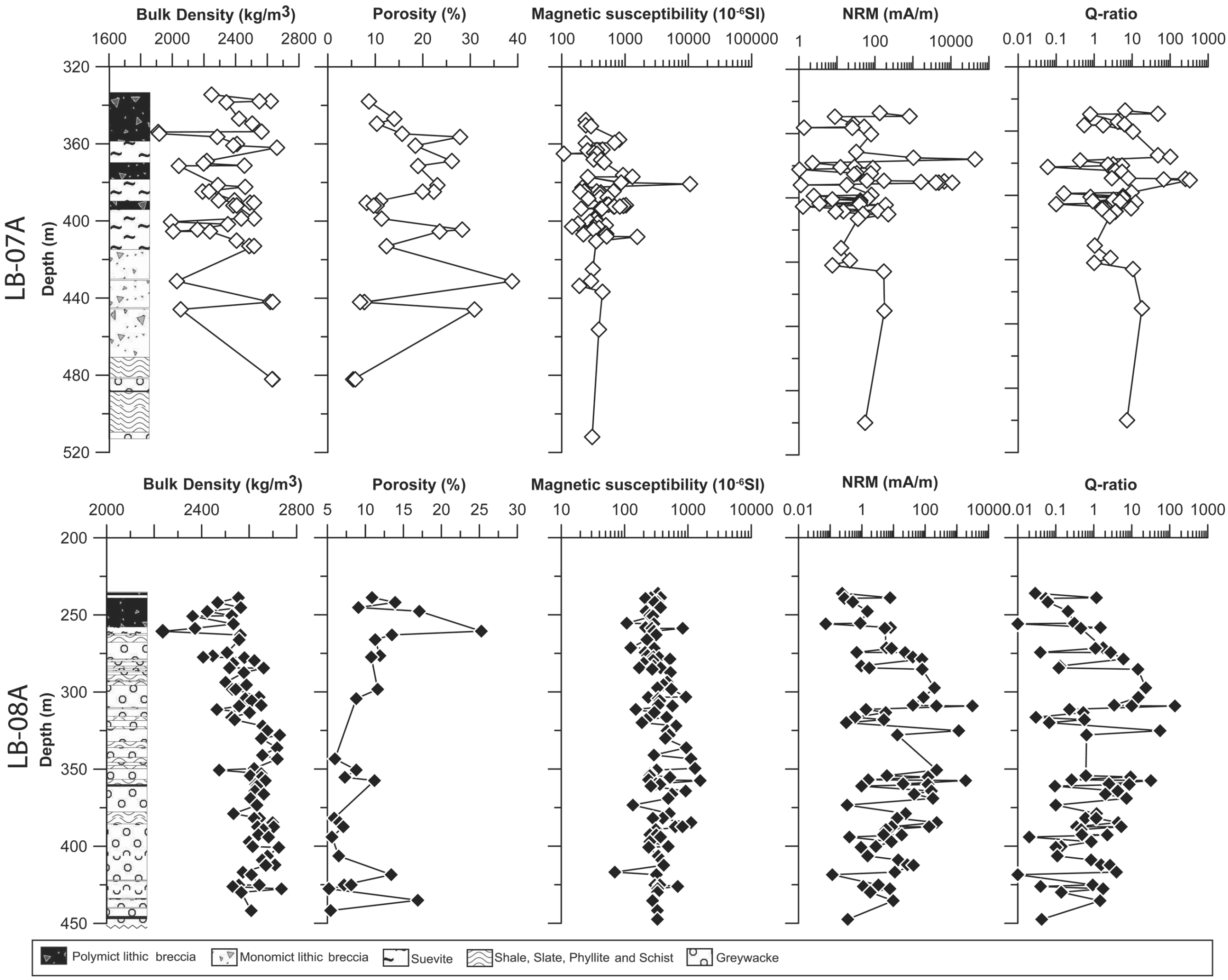

Fig. 1. Variation of petrophysical properties as a function of depth in LB-07A (up) and LB-08A (down) drill cores. Measurement data of all three laboratories are included. Lithology by Koeberl et al. 2007.

et al. 2007) in the lower part of the core. The most conspicuous difference in petrophysical data between impactites and target lithologies of both drill cores are the lower bulk densities and significantly higher porosities (up to 38%; Fig. 2a; Table 1) of the suevite and lithic breccia units compared to meta-graywackes and metapelites. On average, porosities of lithic breccias are higher in drill core LB-07A (27%) than in LB-08A (15%). This high porosity and the extremely fragile nature of impactite samples from LB-07A can be explained by the strong brecciation down to the micrometer scale and their low consolidation. Porosities of the metasedimentary target rocks remain mostly below 10%. The grain densities (Table 1) display similar values in the breccia and meta-greywacke units. Thus the lower bulk densities are clearly related to the formation mechanism of the impactite units (Figs. 1 and 2a).

No significant differences were found for magnetic susceptibility (χ) of drill core LB-07A and LB-08A. In both drill cores, magnetic susceptibility does not show any trend with depth. However, different units can be characterized easily by magnetic data, such as susceptibility. The magnetic susceptibility range mostly between 200 and 500 × 10^{-6} SI, indicating paramagnetic values. Only a very small, inhomogeneously distributed ferrimagnetic component (see below) with few magnetic susceptibility highs (up to 1600 × 10^{-6} SI) is present. One specimen had a very high magnetic susceptibility (10.630 × 10^{-6} SI; Fig. 1; see Kontny et al. 2007). The NRM and Koenigsberger values vary throughout the investigated depth interval, but slightly lower values are found in the upper part of the LB-08A drill core. The NRM values range between 0.1 mA/m and 300 mA/m and Q values between 0.01 and 328. Magnetic susceptibility correlates positively with NRM (Fig. 2b; correlation coefficient +0.95, including sample with the highest χ and NRM [see above] and +0.4 excluding the above mentioned sample) and Q ratio. Magnetic susceptibility and natural remanent magnetization

Table 1. Petrophysical properties of the selected rocks from deep drill cores (this study) and exposed rocks (Plado et al. 2000). Presented are data measured in Helsinki only.

Lithology	*n*	D_b (kg/m^3)	D_g (kg/m^3)	P (%)	χ (10^{-6} SI)	NRM (mA/m)	Q
Impactites							
Lithic breccia							
LB-07A	16	2200	2660	27.2	368	69.1	4.3
LB-08A	4	2380	2660	15.2	300		
Suevite							
Exposed rocks[a]	2	2040	2370	25.6	330	36.8	4.4
LB-07A	7	2240	2610	21.9	516	59.4	4.7
Mean of impactites	27	2250	2640	24.2	390	67.2	4.4
Target rocks							
Granite							
Exposed rocks[a]	5	2490	2640	7.6	132	0.16	0.08
Meta-graywacke							
Exposed rocks[a]	4	2560	2690	7.7	220	0.25	0.03
LB-07A	14	2520	2670	10.1	303	45.5	2.5
LB-08A	41	2620	2720	9.7	364	73.9	3.9 (1.5)
Metapelite[b]							
Exposed rocks[a]	1	2510	2730	8.3	150	0.6	0.13
LB-07A	2	2630	2730	5.6	670		
LB-08A	27	2650	2800	7.6	685	224.9	4.6
Mean of target rocks	84	2610	2730	8.8	448	103.2	3.9

[a]Exposed Bosumtwi surface rocks (Plado et al. 2000).
[b]Incl. shales, phyllites, schists.
Abbreviations: *n* = number of samples, D_b = bulk density (wet density in Plado et al. [2000]), D_g = grain density, P = porosity; χ = magnetic susceptibility; NRM = natural remanent magnetization; Q = Koenigsberger ratio.

are highest in metapelites, while meta-graywacke and impact breccia reveal distinctly lower values. This is in accordance with higher pyrrhotite content in metapelites (compare Kontny et al. 2007).

The remanent magnetization prevails over induced magnetization in all lithologies (average Q values ≥ 2.5). Only samples with high magnetic susceptibility and NRM show Q ratio higher than 10, presumably indicating higher content of fine grained ferrimagnetic material.

Magnetic Model

In 1997, an airborne geophysical survey across the Bosumtwi area was carried out (Pesonen et al. 2003). On the basis of the airborne geophysical maps and petrophysical data of exposed surface rocks, Plado et al. (2000) presented a magnetic model of the Bosumtwi impact structure. This magnetic model required a strongly remanently magnetized melt or melt-rich body between depths of 200 to 600 m to explain the magnetic anomaly. In general, all petrophysical values (especially remanence and Q ratio) of the current study are distinctly higher than the data reported by Plado et al. (2000) for exposed surface rocks (Table 1). Only the polymict lithic breccias from above about 260 m of the core LB-08A, where no or only minor pyrrhotite occur, are similar to the surface samples. Higher Q values can be attributed to the modification or production of ferromagnetic material as a result of the impact (Scott et al. 1996) due to higher pressure and temperature conditions. The petrographic features documented by Kontny et al. (2007) allocate a pre-impact formation of pyrrhotites. These features include numerous shock-induced nanostructures in pyrrhotites which, however, behave as single-domain grains and therefore carry relatively high and stable remanence. Another factor affecting these large-scale differences between core samples and surface rocks can be a near-surface alteration of pyrrhotite into pyrite and magnetite (Pucher 1994; see also Kontny et al. 2007). In the surface samples and uppermost part of LB-08A, a magnetic phase (magnetite; see below) carries the same (stable) paleofield direction than pyrrhotite and affirms a pre-impact alteration. In spite of the higher remanence of the cores the current remanence data is still below the values used in magnetic model ($k = 3300 \times 10^{-6}$ SI, NRM = 367 mA/m, Q = 4.43). Furthermore, the LB-07A and LB-08A drill cores did not show the predicted high content of melt in the rocks. To find out if our cores are just diluted by impact melt and the highly magnetized melt bodies occur at greater depths causing this magnetic anomaly, we separated a few melt particles by hand-picking and measured their magnetic properties. Results showed very low susceptibility and

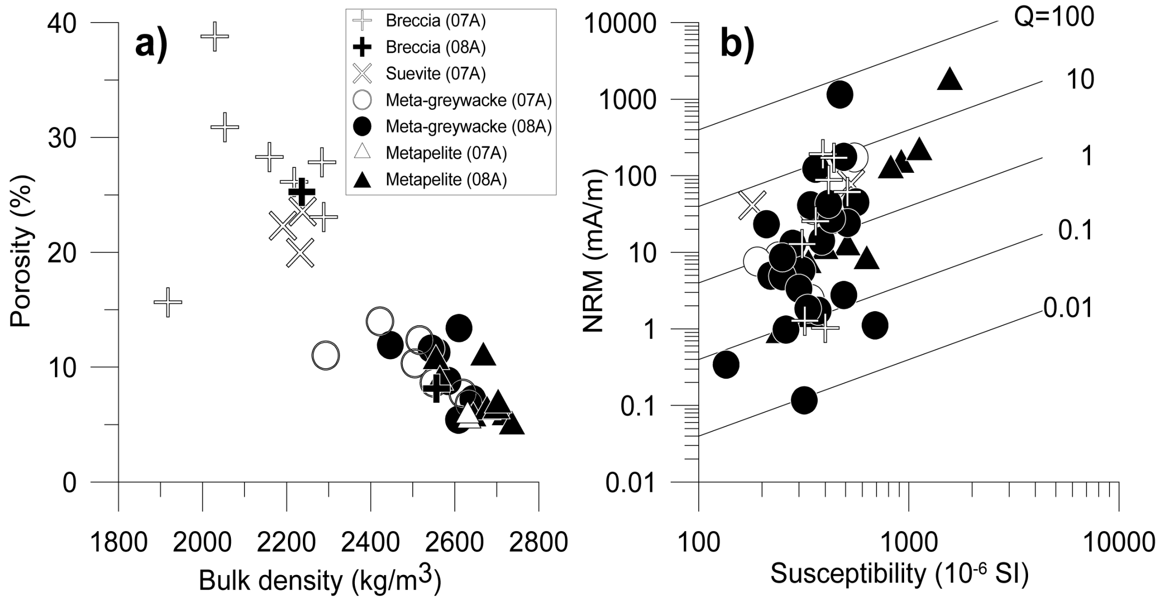

Fig. 2. Correlation between a) porosity and bulk density, and b) NRM and magnetic susceptibility where the third parameter is Koenigsberger ratio (Q), of different lithologies.

remanence values which were even below the ones of bulk rock itself, suggesting that the anomaly cannot be caused by melt. X-ray diffraction (XRD) of melt showed that the melt inside Bosumtwi crater has been altered to clay minerals (chlorite group; see also Ferrière et al. 2007). These data imply that the interpretation of magnetic model must be revised (see also Ugalde et al. 2007) and magnetic parameters of impactites and slightly higher values of target rocks must be taken into account.

Petrophysical Properties versus Core Scanning Data

The laboratory petrophysical data of core samples were also compared with whole-core scanning data (Fig. 3; see also Morris et al. 2007). The petrophysical scanning of whole cores was carried out at GFZ in Potsdam, Germany, in December 2004 for magnetic susceptibility and gamma density. Laboratory measurements show a good agreement with density and magnetic susceptibility in core LB-08A. However, core LB-07A gave different results. While susceptibility of cores correlates positively with scanning data, the bulk density obtained in this study from LB-07A core is mostly slightly higher than in core scanning. The core scanning of gamma density required samples with regular diameter and flat surface (Ugalde et al. 2006). This was rather difficult task due to the fragile character of core LB-07A and therefore may have resulted in error of gamma-density values. On the other hand, the scanning data could take into account the presence of macrofractures which laboratory measurements could not track due to smaller samples. Thus, the actual density values of core LB-07A should be somewhere in between.

Paleomagnetism

Specimens of cores LB-07A and LB-08A were used for paleomagnetic study to determine the various remanence components. Both, alternating field and thermal demagnetization were carried out. Since the cores were not oriented for azimuth (declination), only the magnetic inclination is used. However, specimens were oriented relatively to each other using fiducial lines downward the cores.

Alternating field demagnetization is shown in Fig. 4 for LB-07A and Fig. 5 for LB-08A specimens. Most of the specimens have two remanence components. The first remanence component is weak and magnetically soft. It is removed at demagnetization fields of ≤20 mT. We anticipate this component to be viscous. The second remanence component is more resistant against demagnetization. This characteristic component has a fairly high coercivity, which is removed between 50 and 100 mT; in some cases it is stable even up to 130 mT. This component carries a shallow normal polarity magnetization (in a few cases shallow reversed, see also Plado et al. 2000). Similar to alternating field demagnetization, the thermal demagnetization (Figs. 4 and 5) reveals also two remanent components. The main magnetic mineral, based on unblocking temperatures (~320 °C), is pyrrhotite. In some cases, mostly from the upper part of the LB-08A drill core, also magnetite is present, which is indicated by unblocking temperature of 580 °C.

Previous age determinations (^{87}Rb-^{87}Sr, ^{39}Ar-^{40}Ar, and fission-track dating; e.g., Kolbe et al. 1967; Koeberl et al. 1997) have shown that the impact structure formed about 1.07 Ma ago during the Lower Jaramillo normal-polarity

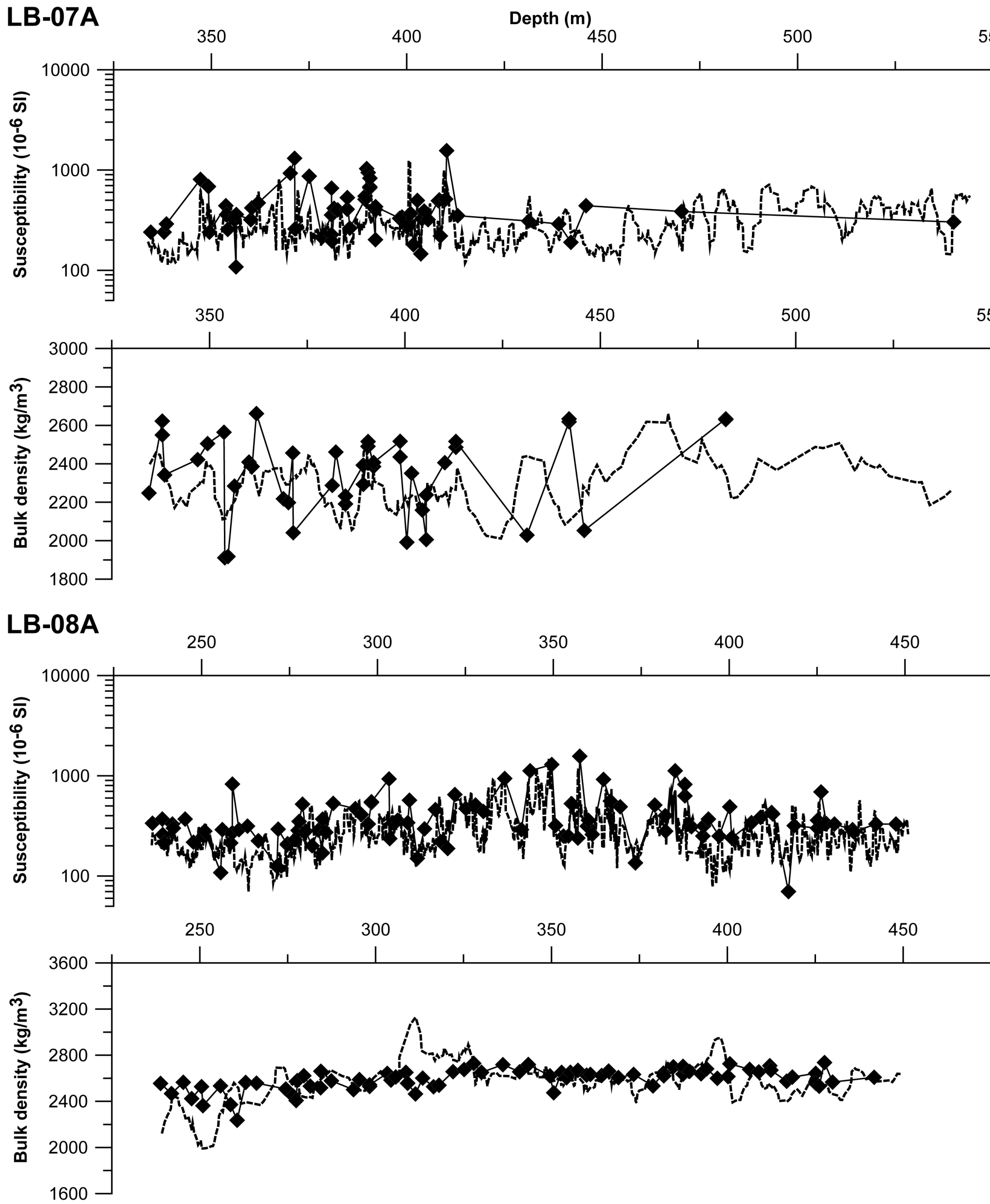

Fig. 3. A comparison of whole-core petrophysical scanning data (dashed line; Morris et al. 2007) and laboratory measurement of selected specimens (closed diamonds; this study).

magnetic chron. This age is also supported by paleomagnetic data from the suevites and fractured target rocks from surface outcrops (Plado et al. 2000). Our study revealed that the characteristic remanent magnetization component has a shallow N polarity (in a few cases shallow reversed) magnetization, which is also consistent with Plado et al. 2000. We assume this component to be impact-related and most likely our remanence component represents the Lower Jaramillo N-polarity chron.

In a few samples the REM ratio (the ratio between NRM and the saturation remanence JSR [Wasilewski 1977; Kletetschka et al. 2004]) was calculated and REM (AF) curve (Kletetschka et al. 2005) was made (Fig. 6). The REM ratio shows values of ~1–2% for stable remanence component, which is typical for thermal (TRM) or chemical (CRM) magnetization acquired in the Earth's magnetic field (Wasilewski 1977; Kletetschka et al. 2004). Slightly lower values of some samples (Fig. 6) may be related to less efficient TRM magnetization process at temperatures slightly lower than blocking temperature of pyrrhotite or shock-related demagnetization (T. Kohout and G. Kletetschka, personal communication). Shock-related TRM idea is also supported by

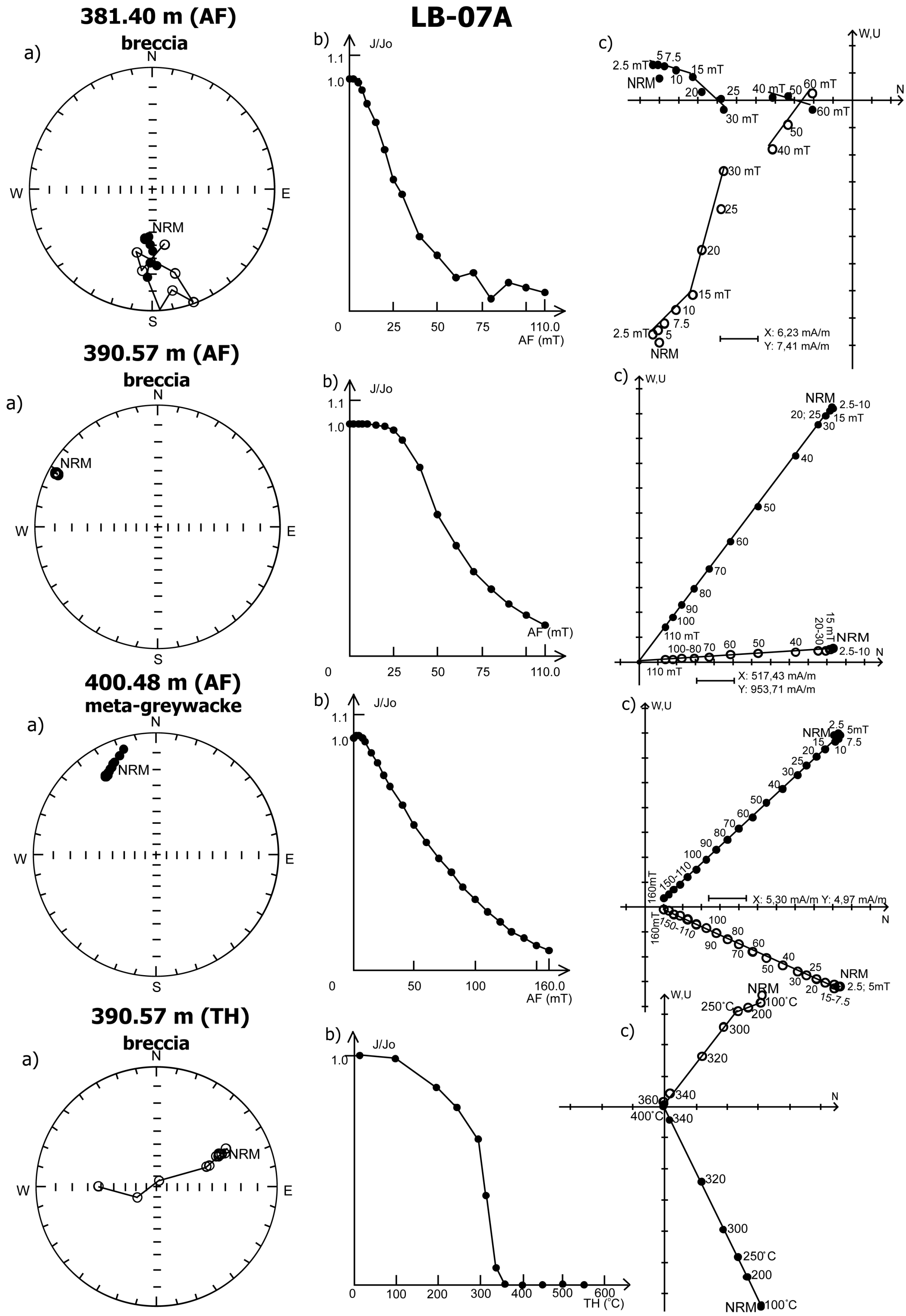

Fig. 4. Examples of alternating field and thermal demagnetization behavior of specimens from LB-07A drill core. a) Stereographic projections of remanence directions. b) Intensity decay curves. c) Orthogonal (Zijderveld) vector projections. Closed (open) circles mark projections of the total magnetization vector tip onto the horizontal (vertical) plane, respectively. Numbers show alternating field or temperature steps, and remanence components are united with lines.

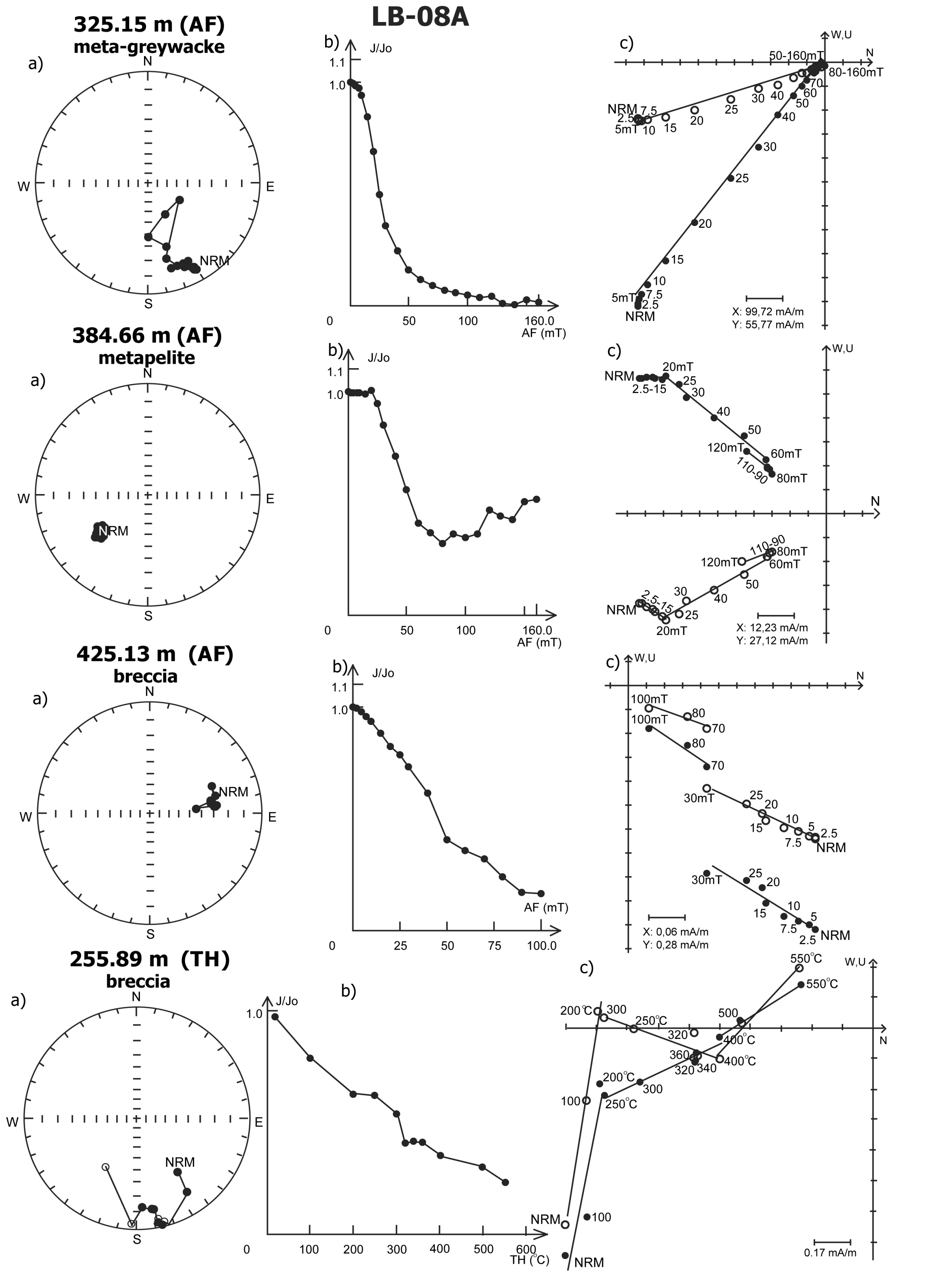

Fig. 5. Examples of alternating field and thermal demagnetization behavior of specimens from LB-08A drill core. For explanation, see Fig. 4.

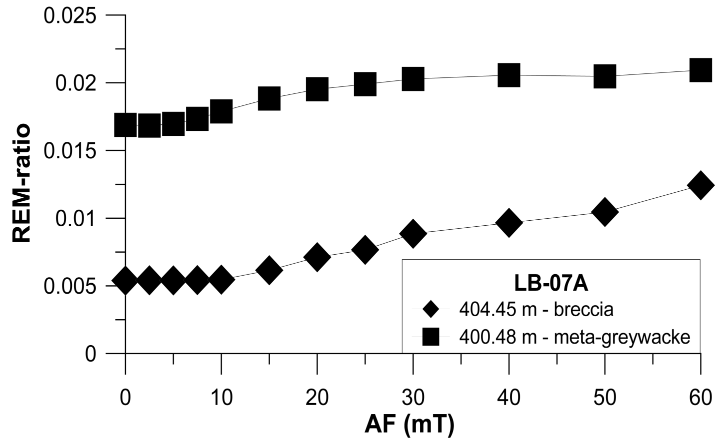

Fig. 6. An example of REM (AF) curves where REM ratio of ~2% denotes a stable remanence component (15–100 mT) on the upper plot and a slightly lower REM ratio (~1%, 20–60 mT) in the lower graph. Lower REM values in the beginning of plots are related to viscous component.

magneto-mineralogical investigations by Kontny et al. (2007), according to which the pyrrhotite (the main carrier of remanence) shows shock-induced nanostructures, and suggest shock-related thermal remagnetization.

The target and impact lithologies of the Bosumtwi drill cores do not show different paleomagnetic properties, perhaps because NRM directions of target rocks are similar to the impact rocks (see Plado et al. 2000). In addition, the specimens with low remanence and magnetic susceptibility have noisier paleomagnetic behavior than specimens with high remanence and susceptibility. Therefore, the amount of ferrimagnetic pyrrhotite most likely controls the quality of paleomagnetic results.

CONCLUSIONS

The present study of petrophysical parameters of the Bosumtwi drill cores LB-07A and LB-08A revealed no depth dependence. The various lithologies, such as impactite layers and different target lithologies, however, can be characterized by their petrophysical values. The measured porosities of impactites in both cores are extremely high (up to 38%) and bulk densities significantly lower than in metasediments, indicating a clear relation to the formation mechanism of the impactite units. Thus, the density and porosity data provide new constrains for seismic and gravity models. The magnetic susceptibility shows mostly paramagnetic signature and the remanent magnetization prevails over induced magnetization in all lithologies (average Q values ≥ 2.5). Only samples with high magnetic susceptibility and NRM show high Q ratio presumably suggesting the higher content of fine-grained ferrimagnetic phase. The paleomagnetic data reveals mainly two magnetic components: a viscous (low coercivity) component and high-coercivity component. The latter is the characteristic direction and has a shallow normal (in a few cases shallow reversed) magnetization, which is in agreement the Lower Jaramillo N-polarity chron. The main magnetic mineral and the carrier of characteristic remanence component, based on unblocking temperatures (~320 °C), is pyrrhotite.

With the exception of a few thin magnetic spikes, drilling did not reveal the expected highly remanent magnetized body suggested by Plado et al. (2000) in their magnetic model. The studies of individual melt particles revealed that magnetic properties of melt are not sufficient to produce the magnetic anomaly, implying that the magnetic model must be revised.

Acknowledgments–Drilling was funded by ICDP, the U.S. NSF, the Austrian FWF, the Canadian NSERC, and the Austrian Academy of Sciences. Drilling operations were performed by DOSECC. We would like to thank Tomas Kohout for several helpful discussions and notes. We thank Jüri Plado for his comments and Martti Lehtinen for helping to separate the melt and for measuring the XRD of the melt. H. C. Halls, M. Salisbury, and B. Milkereit helped us to improve the original manuscript.

Editorial Handling—Dr. Bernd Milkereit

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