The Bosumtwi meteorite impact structure, Ghana: A magnetic model

J. PLADO1*, L. J. PESONEN2,3, C. KOEBERL4 AND S. ELO3

1Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
2Department of Geophysics, University of Helsinki, P.O. Box 4, FIN-00014 Helsinki, Finland
3Geological Survey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland
4Institute of Geochemistry, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

*Correspondence author's e-mail address: jplado@math.ut.ee

(Received 1999 August 18; accepted in revised form 2000 March 7)

Abstract—A magnetic model is proposed for the Bosumtwi meteorite impact structure in Ghana, Africa. This relatively young (~1.07 Ma) structure with a diameter of ~10.5 km is exposed within early Proterozoic Birimian–Tarkwaian rocks. The central part of the structure is buried under postimpact lake sediments, and because of lack of drill cores, geophysics is the only way to reveal its internal structure. To study the structure below and beyond the lake, a high-resolution, low altitude (~70 m) airborne geophysical survey across the structure was conducted, which included measurements of the total magnetic field, electromagnetic data, and gamma radiation. The magnetic data show a circumferential magnetic halo outside the lakeshore, ~12 km in diameter. The central-north part of the lake reveals a central negative magnetic anomaly with smaller positive side-anomalies north and south of it, which is typical for magnetized bodies at shallow latitudes. A few weaker negative magnetic anomalies exist in the eastern and western part of the lake. Together with the northern one, they seem to encircle a central uplift. Our model shows that the magnetic anomaly of the structure is presumably produced by one or several relatively strongly remanently magnetized impact-melt rock or melt-rich suevite bodies.

Petrophysical measurements show a clear difference between the physical properties of preimpact target rocks and impactites. Suevites have a higher magnetization and have low densities and high porosities compared to the target rocks. In suevites, the remanent magnetization dominates over induced magnetization (Koenigsberger ratio > 3). Preliminary palaeomagnetic results reveal that the normally magnetized remanence component in suevites was acquired during the Jaramillo normal polarity epoch. This interpretation is consistent with the modelling results that also require a normal polarity magnetization for the magnetic body beneath the lake. The reverse polarity remanence component, superimposed on the normal component, is probably acquired during subsequent reverse polarity events.

INTRODUCTION

An impact origin for the nearly circular Bosumtwi structure in Ghana, Africa (centered at 06°30' N and 01°25' W) was first suggested by Maclaren (1931). The structure has a rim-to-rim diameter (D) of ~10.5 km (Figs. 1 and 2) and is mostly filled by Lake Bosumtwi, which has a diameter of ~8 km and maximum depth of 80 m (Jones et al., 1981). The structure has an age of ~1.07 Ma (Koeberl et al., 1997), which is the same as for tektites found in the neighbourhood at Ivory Coast (Fig. 1c) and for microtektites found in deep-sea sediment cores off the West African coast. The common age, as well as chemical and isotopic data (Lippolt and Wasserburg, 1966; Schnetzler et al., 1966), indicate that the Lake Bosumtwi impact event is most likely the source crater for these tektites. Chemical data indicate a minor meteoritic component in the Ivory Coast tektites (Palme et al., 1981; Jones, 1985; Koeberl and Shirley, 1993).

Because the crater is buried under the water and lake sediments, and because of the lack of drillings, geophysics have to be used to investigate its subsurface structure. The first magnetic field studies of the structure were made in 1960 by Hunting Surveys Ltd. for the Ghana Geological Survey Department (Jones et al., 1981). The occurrence of a central negative anomaly of ~40 nT, with a positive flank anomaly of ~20 nT on the northern side (which is intersecting regional magnetic anomalies) was detected in this early survey. The anomaly was attributed to a breccia lens below the lake sediments. In addition, gravity measurements were collected around the lake (Jones et al., 1981); yet because of the sparseness of data (none over

the lake), the gravity data reflect regional trends only and cannot be used to constrain the magnetic models.

In 1997, a high-resolution airborne geophysical survey across the Bosumtwi structure was carried out by the Geological Survey of Finland (GSF) in cooperation with the University of Vienna and the Ghana Geological Survey Department (Ojamo et al., 1997; Pesonen et al., 1998, 1999). It included measurements of the total magnetic field, electromagnetic field, and gamma radiation. Here we present a magnetic model of the structure, which is based on the new high-resolution residual maps, and constrained by petrophysical data of nine oriented and four oriented rock samples (for location, see Fig. 2) collected around the structure.

STRUCTURE OF THE TARGET AND CRATER

Ghana occupies a major part of the Precambrian Shield, a segment of the West African Craton. The early Proterozoic (~2100 Ma) basement in Ghana is subdivided into the Birimian and Tarkwaian Supergroups (Eisenlohr and Hirdes, 1992). The Bosumtwi crater (Fig. 2) was excavated mainly in Birimian metasediments: graywackes, phyllites, and quartzites. Birimian metamorphosed volcanic rocks (basalts with some intercalated sediments) reach into the southeast corner of the lake (Jones et al., 1981). Bedding of Birimian formations strikes northeast and dips subvertically. The deformational event and deposition of the Tarkwaian Supergroup followed the Birimian sedimentation. Tarkwaian coarse elastic sedimentary rocks, which are regarded as the detritus of Birimian rocks (Leube et al., 1990), occur to the

© Meteoritical Society • Provided by the NASA Astrophysics Data System
southeast of the crater. Some syndeformational granitic intrusions of "Cape Coast" type (Jones et al., 1981) are cropping out around the north, west, and south sides of Lake Bosumtwi (Fig. 2).

The lake (with circular bathymetry (McGregor, 1937) and maximum water depth of ~80 m) and post-impact lake sediments hide the subsurface structure of the central part of the Bosumtwi crater but have preserved it against erosional processes. Based on the size criteria for terrestrial impact structures (e.g., Grieve and Pesonen, 1996), Bosumtwi should be a complex impact structure, but no evidence exists of a central uplift in lake bathymetric data (McGregor, 1937). It is possible that the central uplift has collapsed during the modification stage of the crater formation and is hidden underneath the lake sediments. The morphometric estimates of the structure, including the diameter of the central uplift, are given in Table 1.

### METHODS AND DATA

#### Geophysical Field Surveys

In the 1997 survey, the total magnetic intensity was recorded with a Scintrex CS-2 magnetometer at a resolution of 0.001 nT. The nominal flight altitude was 70 m, flight directions north-south, and line spacing was 500 m. Magnetic recordings were obtained at every ~6.25 m along the flight lines. Positioning was done using differential global positioning system and flight elevations were measured with radar altimeters. Altogether, 30 profiles were recorded with an average length of 22 km. All original data (corrected for aircraft disturbances and for variations in elevation) were transformed into a grid of 100 x 100 m, from which various maps were prepared (see Pesonen et al., 1998).

### TABLE 1. Dimensions of the Bosumtwi structure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation/dimension</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rim-to-rim diameter</td>
<td>[ D = 10.5 \text{ km} ]</td>
<td>Jones et al. (1981)</td>
</tr>
<tr>
<td>Diameter of the collapsed disruption</td>
<td>[ D_{DC} = 10.5^{0.15} D^{0.85} \approx 9 \text{ km} ]</td>
<td>Croft (1985), for definition see</td>
</tr>
<tr>
<td>(i.e., transient) cavity</td>
<td></td>
<td>Hildebrand et al. (1998)</td>
</tr>
<tr>
<td>Diameter of the central uplift</td>
<td>[ D_{CU} = 0.22 D \times 2.3 \text{ km} ]</td>
<td>Pike (1985)</td>
</tr>
<tr>
<td>Apparent depth</td>
<td>[ d_A = 0.15 D^{0.43} \approx 0.4 \text{ km} ]</td>
<td>Grieve and Pesonen (1992)</td>
</tr>
<tr>
<td>True depth</td>
<td>[ d_T = 0.52 D^{0.2} \approx 0.8 \text{ km} ]</td>
<td>Grieve and Robertson (1979)</td>
</tr>
<tr>
<td>Maximum thickness of the allochthonous</td>
<td>[ h_B = d_T - d_A \approx 0.4 \text{ km} ]</td>
<td>Lange and Ahrens (1979)</td>
</tr>
<tr>
<td>breccia lens</td>
<td>[ V_M = 3.8 \times 10^{-4} D^{3.4} \approx 1.1 \text{ km}^3 ]</td>
<td>Grieve and Cintala (1992)</td>
</tr>
<tr>
<td>Volume of impact melt</td>
<td>[ V_M = c D_{DC}^{3.8} ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ 2.9 &lt; V_M &lt; 3.4 \text{ km}^3 ]</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: \( D_{DC} \) = the transition diameter for simple-to-complex crater (4 km for crystalline targets on Earth); apparent depth = depth from the rim to the upper surface of crater-filling allochthonous breccia; true depth = depth from the rim to the base of breccia lens, \( c \) = constant that depends on the impact velocity and type of the projectile. The volume of impact melt was calculated for iron and chondrite projectiles at impact velocities from 15 to 25 km s\(^{-1}\).
Petrophysics

Our petrophysical data, which we use to constrain the geophysical modelling, are based on 13 samples collected in 1997. Sampling localities are shown in Fig. 2. Most of the samples were weathered. Eleven samples (6 granites, 4 graywackes, and 1 shale) were unshocked target rocks in the surrounding terrain of Lake Bosumtwi. The two impactites from an outcrop located ~2.8 km north of the crater rim are melt-rich suevites from the ejecta layer. These suevites, one graywacke and one granite sample, were collected in the field as oriented samples of which several specimens were prepared.

Density (δ), magnetic susceptibility (κ), and intensity of the natural remanent magnetization (NRM) were measured at the Paleomagnetic Laboratory of the GSF–Espoo, using techniques described in Puranen and Salminen (1985). The porosities (φ) were measured using the water-saturation technique as described in Pesonen et al. (2000).

All oriented specimens were demagnetized with alternating magnetic fields (AF) to study their palaeomagnetic behaviour. Some specimens were also thermally demagnetized. The measurements were made using a superconducting quantum interference device (SQUID) magnetometer as described by Ojaj and Pesonen (1990). To determine the various remanence components in the samples, joint analyses of stereographic plots, demagnetization decay curves, vector diagrams (Zijderveld, 1967), and principal-component analysis were used (Kirschvink, 1980; Leino, 1991).

RESULTS

Magnetic Maps

The regional magnetic field (Fig. 3) in the Bosumtwi crater area reveals several types of regional anomalies, the most striking ones being the northeast–southwest lineations by Birimian-Tarkwaian supracrustal strata (Eisenlohr and Hirdes, 1992). These anomalies have a range of wavelengths between 2 and 20 km, and amplitudes up to ~250 nT. Higher amplitudes and smaller wavelengths are measured to the southeast of the Bosumtwi Lake at the Birimian metavolcanic and, in particular, Tarkwaian quartzites. Similar short wavelength northeast–southwest trending regional anomalies appear to the northwest and southwest of the crater, which suggests that buried metavolcanic rocks are also present there. The regional features partially mask the more circular magnetic signatures of the Bosumtwi structure. As the impact-induced anomalies have wavelengths that are similar to the regional ones, it is difficult to separate them. For example, the negative anomaly, ~5 km in length, at the northern part of the lake (Fig. 3), interpreted as having an impact origin (Jones et al., 1981), certainly includes some
component from the negative linear regional anomaly from southwest of the crater. However, the structure shows clearly a group of differently shaped negative anomalies that are surrounded by two positive anomalies, one on the northern and one on the southern side. This type of anomaly pattern can, at low latitudes, be produced in two different ways.

First, a body with reversed magnetization at shallow latitudes can produce a positive anomaly with minor negative anomalies to the north and south. This case seems to be unlikely at Bosumtwi, as the northern positive feature lacks a negative side anomaly to the north, and the southern one lacks a side anomaly to the south. Moreover, the positive features are located too close to the rim of the structure to be produced by a large reversely magnetized body. Second, this type of anomaly pattern can be produced by a normally magnetized structure at shallow latitudes. Our preliminary modelling exercise showed that a highly magnetic anomalous source body with the remanent magnetization parallel to the ancient dipole field gives rise to a negative anomaly at low latitudes. At Bosumtwi latitude (~5°N), the negative anomaly occurs slightly to the north of the body's centre and is accompanied with positive side anomalies on the northern and southern side of the major peak. This explanation is also supported by palaeomagnetic studies and further modelling experiments.

In order to remove the regional trends and to amplify the Bosumtwi related anomalies, we applied a two-dimensional-smoothing window with an areal operator of 4 x 4 km in a grid of 100 x 100 m. However, this technique removes mainly the large wavelength regional effects as shown by the regional magnetic map (Fig. 4). Because of similar wavelengths of impact anomalies and elongated regional features, the usage of a smaller areal operator would affect impact anomalies. Because of the complicated magnetic field, other methods to describe the regional features (e.g., polynomial regression) did not give reasonable results. The residual magnetic anomaly (Fig. 5) is obtained by subtracting the regional field from the original total field. It shows that both impact-induced and elongated regional anomalies are present, but the Bosumtwi structure is clearly truncating the regional magnetic trends. A circumferential magnetic halo with very low gradients (h in Fig. 5), correlating with the rim, ~0 nT in amplitude and ~12 km in diameter, appears around the lake. Because its diameter is larger than that of the collapsed disruption cavity, it likely represents fracturing and uplift of the rim that randomized the preexisting remanence magnetizations of the target rocks. The central part of the structure is characterised by relatively high gradients. At the center of the lake, there are four or six negative magnetic anomalies (c, dark spots) with two positive side anomalies (white spots), one on the northern side of the lake (n) and one on the southern side (s). The negative magnetic features surround the positive one, which points to a possible location of a central uplift (cu).

**Physical Properties**

Table 2 summarises the petrophysical data of the samples. A clear difference exists between the physical properties of target rocks and impact-derived suevites. The latter have low densities,
higher porosities, and higher magnetizations compared to the target rock values. The remanent magnetization of suevites prevails over induced magnetization (Koenigsberger ratio $Q > 3$). The target rocks have strikingly homogeneous physical properties with noticeable weak remanent magnetizations ($Q < 0.5$). Some minor differences in their magnetizations exist: the Pediakese granites have a relatively low susceptibility and the graphic shale has a fairly high remanent magnetization.

The palaeomagnetic behavior of melt-rich suevites differs significantly from those of the target. Suevite LB-40 (Table 3) has two superimposed NRM components (normal (N) and reversed (R)) that are directed either parallel or nearly antiparallel to the present-day normal polarity magnetic field. In Fig. 6a, as an example, the palaeomagnetic behavior of the specimen LB-40-1a in the process of AF treatment is shown. It shows that the R component is much weaker and magnetically softer (can be removed at demagnetization fields of $\leq 15$ mT) than the N polarity component, and we anticipate that the latter is a prevailing characteristic remanence component.

Sample LB-46 also shows dual polarities (R and N) during AF treatment (Table 3), but the R component is much more scattered. In Fig. 6b, the behavior of LB-46-1b in the course of thermal demagnetization treatment is shown. In this sample, the R component is magnetically harder than the (N) component. The main magnetic mineral in the suevite is magnetite, because most of the NRM is removed by thermal demagnetization up to 580 °C. However, a part of the NRM shows a Curie temperature of $\sim 680$ °C, indicating that hematite, carrying mainly the reversed component of NRM, is also present.

**Fig. 5.** Residual magnetic field (nT) map of the Bosumtwi impact structure. To obtain it, the regional effect (Fig. 4) was subtracted from the original total field aeromagnetic map (Fig. 3). The lakeshore is indicated. See text for description of different anomalies. Abbreviations: $h =$ magnetic halo; $c =$ central negative anomaly; $n =$ northern positive anomaly; $s =$ southern positive anomaly; $cu =$ central positive anomaly, correlating with the possible location of the central uplift. Contour interval is 6 nT.

**Fig. 6.** (A) The AF demagnetization behavior of LB40-1a, and (B) thermal demagnetization behavior of LB46-1b, melt-rich suevite specimens: (a) Stereographic projection of directional data on demagnetization. NRM shows the natural remanent magnetization (without demagnetization); (b) intensity decay of the NRM during the treatment, where $J_{0}$ denotes the original intensity and $J$ the intensity at the particular demagnetization step; (c) orthogonal demagnetization diagram. Solid (dotted) lines denote vertical (horizontal) planes. Numbers by each demagnetization step denote peak alternating field (mT) or temperature (°C). $N$ ($R$) denote the normal (reversed) component, respectively.
TABLE 2. Petrophysical properties of the rocks at Lake Bosumtwi structure.

<table>
<thead>
<tr>
<th>Sample</th>
<th>n</th>
<th>$\delta_s$</th>
<th>$\delta_w$</th>
<th>$\phi$</th>
<th>$\chi$</th>
<th>NRM</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target rocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phyllite-graywacke</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-02</td>
<td></td>
<td>240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-10</td>
<td>2640</td>
<td>2470</td>
<td>10.4</td>
<td>230</td>
<td>0.15</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>LB-22</td>
<td>2730</td>
<td>2640</td>
<td>4.9</td>
<td>250</td>
<td>0.14</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>LB-33</td>
<td></td>
<td></td>
<td></td>
<td>160</td>
<td>0.18</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td><strong>Granite dikes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-18</td>
<td>2610</td>
<td>2410</td>
<td>9.7</td>
<td>240</td>
<td>0.33</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>LB-20</td>
<td>2680</td>
<td>2550</td>
<td>6.7</td>
<td>180</td>
<td>0.09</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>LB-36</td>
<td>2630</td>
<td>2480</td>
<td>8.0</td>
<td>180</td>
<td>0.55</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td><strong>Pepiakese granite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-34</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>0.10</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>LB-35</td>
<td>2610</td>
<td>2510</td>
<td>6.0</td>
<td>30</td>
<td>0.20</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td><strong>Shale</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-51</td>
<td>2730</td>
<td>2510</td>
<td>12.4</td>
<td>230</td>
<td>3.86</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>Mean of target</td>
<td>10</td>
<td>2680</td>
<td>2510</td>
<td>8.3</td>
<td>150</td>
<td>0.6</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt-rich suevite (ejecta)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-40</td>
<td>2200</td>
<td>1770</td>
<td>36.2</td>
<td>430</td>
<td>34.90</td>
<td>3.22</td>
<td></td>
</tr>
<tr>
<td>LB-46</td>
<td>2540</td>
<td>2310</td>
<td>15.0</td>
<td>230</td>
<td>38.73</td>
<td>6.68</td>
<td></td>
</tr>
<tr>
<td>Mean of suevites</td>
<td>2</td>
<td>2370</td>
<td>2040</td>
<td>25.6</td>
<td>330</td>
<td>36.8</td>
<td>4.43</td>
</tr>
</tbody>
</table>

For sample locations, see Fig. 2a.

Abbreviations: $n$ = number of samples; $\delta_s$ = grain density (kg m$^{-3}$); $\delta_w$ = wet density (kg m$^{-3}$); $\phi$ = porosity (%); $\chi$ = weak field susceptibility ($10^{-6}$ SI); NRM = intensity of natural remanent magnetization (mAm$^{-1}$); Q = Koenigsberger ratio (-).

The existence of both N and R components in the same specimens of suevites (Table 3) is puzzling. Because the samples are taken from small fall-out suevite outcrops, they have probably cooled rapidly. Therefore, it is unlikely that they represent two stable polarities acquired during the polarity change from Matuyama (R) to Jaramillo (N), ~1.027 Ma ago (Langer et al., 1997). More likely, only the N component, acquired during the Jaramillo period, is primary and the R component, carried mainly by hematite, is secondary, perhaps locked in during the weathering processes at later R epoch. This opinion is supported by the work of Glass et al. (1991), who found that Ivory Coast microtectonites were deposited ~8,000 years after the onset of the Jaramillo N polarity epoch. The magnetic model also requires a presence of a net N polarity magnetization.

Palaeomagnetic data on target granite and graywacke samples reveal a high stability of NRM in the course of AF demagnetization. Due to relatively weak magnetizations and uncertain directions, the component analyses did not yield clear results. However, at weak fields, target-rock samples showed some evidence of stable components (Table 3), which may represent the N and R components obtained during the Birimian and Tarkwaian igneous and metamorphic episodes (Piper and Lomax, 1973), or the viscous remanent magnetization.

---

TABLE 3. Palaeomagnetism of the early Proterozoic basement in Ghana, and rocks of the Lake Bosumtwi structure (latitude 6.53°N; longitude 359.58°E).

<table>
<thead>
<tr>
<th>Sample</th>
<th>N/n</th>
<th>Pol.</th>
<th>$D$ (°)</th>
<th>$I$ (°)</th>
<th>$k$</th>
<th>$\alpha_{95}$ (°)</th>
<th>$Plat$ (°)</th>
<th>$Plon$ (°)</th>
<th>$A_{95}$ (°)</th>
<th>$dp$ (°)</th>
<th>$dm$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early Proterozoic rocks of Ghana (after Piper and Lomax, 1973)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greenstone (age 2.2 Ga; latitude 6.2°N; longitude 359.3°E)</td>
<td>5/74</td>
<td>N</td>
<td>320</td>
<td>26</td>
<td>11</td>
<td>19</td>
<td>50</td>
<td>282</td>
<td>15</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>Dolerite dyke (age 2.1 Ga; latitude 6.2°N; longitude 359.3°E)</td>
<td>1/14</td>
<td>N</td>
<td>328</td>
<td>-11</td>
<td>21</td>
<td>11</td>
<td>56</td>
<td>249</td>
<td>8</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Dolerite intrusions (age 2.1 Ga; latitude 5.5°N; longitude 352.8°E)</td>
<td>5/29</td>
<td>R</td>
<td>156</td>
<td>40</td>
<td>20</td>
<td>14</td>
<td>53</td>
<td>212</td>
<td>13</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td><strong>Lake Bosumtwi target rocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phyllite-graywacke</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-33</td>
<td>1</td>
<td>N</td>
<td>314</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>44</td>
<td>273</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LB-34</td>
<td>2</td>
<td>R</td>
<td>171</td>
<td>-18</td>
<td>-</td>
<td>-</td>
<td>81</td>
<td>287</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pebiakese granite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-34</td>
<td>3</td>
<td>N</td>
<td>16</td>
<td>-4</td>
<td>5</td>
<td>63</td>
<td>72</td>
<td>117</td>
<td>45</td>
<td>32</td>
<td>63</td>
</tr>
<tr>
<td>LB-33</td>
<td>1</td>
<td>R</td>
<td>180</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>77</td>
<td>178</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean of target*</td>
<td>4/7</td>
<td>N+R</td>
<td>351</td>
<td>4</td>
<td>8</td>
<td>36</td>
<td>80</td>
<td>246</td>
<td>25</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td><strong>Lake Bosumtwi impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt-rich suevite (ejecta)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LB-40</td>
<td>3</td>
<td>N</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>43</td>
<td>81</td>
<td>145</td>
<td>31</td>
<td>22</td>
<td>43</td>
</tr>
<tr>
<td>LB-46</td>
<td>3</td>
<td>R</td>
<td>186</td>
<td>14</td>
<td>66</td>
<td>15</td>
<td>75</td>
<td>156</td>
<td>11</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>LB-51</td>
<td>3</td>
<td>N</td>
<td>359</td>
<td>7</td>
<td>32</td>
<td>22</td>
<td>81</td>
<td>186</td>
<td>16</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>Mean of suevites*</td>
<td>3/9</td>
<td>N+R</td>
<td>3</td>
<td>-1</td>
<td>44</td>
<td>19</td>
<td>81</td>
<td>159</td>
<td>13</td>
<td>9</td>
<td>19</td>
</tr>
</tbody>
</table>

For sample locations, see Fig. 2a.

*For mean calculations, the reversed polarity data were inversed.

Abbreviations: N/n = number of sites / number of specimens used to calculate the mean direction; pol. = polarity; $D = \text{declination}$; $I = \text{inclination}$; $k = \text{Fisher's (1953) precision parameter}$; $\alpha_{95} =$ the radius of a cone of 95% confidence about the mean; Plat and Plon = the latitude and longitude of the virtual geomagnetic poles (VGP); $A_{95} =$ the radius of a cone of 95% confidence about the pole determined from sample means $D$ and $I$; $dp, dm =$ semiaxes of an oval of 95% confidence of the pole.
The Bosumtwi meteorite impact structure, Ghana: A magnetic model

720000N A B C
730000N D
710000N A' B' C'
670000E 681000E

Fig. 7. Perspective view of the Lake Bosumtwi magnetic model from the south. The model consists of eight polygonal layers, each with a thickness of 50 m. The top of the largest uppermost layer is at the depth of 200 m below the sea level. All the layers have identical magnetic properties as described in text. Dotted lines denote the location of profiles A-A', B-B', C-C', and D-D'.

MODEL INTERPRETATIONS
AND DISCUSSION

The magnetic model interpreted from the residual magnetic map is shown in Figs. 7 and 8. For the model, we used the following International Geomagnetic Reference Field (Pesonen et al., 1994) parameters: field intensity $F = 31 500$ nT; inclination $I = -12.5^\circ$; declination $D = 354.1^\circ$. Susceptibility of the background ($\chi_B$) was set to 0. The model consists of eight polygonal 50 m thick layers with horizontal upper and lower surfaces and vertical sides. The top of the largest uppermost layer is at the depth of 200 m below sea level. All layers have identical magnetic properties: $\chi = 3300 \times 10^{-6}$ SI, NRM = 0.367 Am$^{-1}$, $Q = 4.43$, and remanence directions ($D = 3^\circ$; $I = -1^\circ$). The forward modelling technique was used, where we calculated a magnetic response curve along several north–south and west–east profiles. By changing the shapes of polygonal prisms, we tried to match the model curves to fit the observed data by trial-and-error techniques. The best matching was achieved when the depth range for the prisms varied between 200 and 600 m, which is consistent with theoretical impact models of this size and with the previous model of Jones et al. (1981). Because of the number of several independent variables (susceptibility, remanent magnetization, thickness, dip, and depth of the polygons), the model is not unique.

The polygonal layers form a homogeneous structure with a relatively complicated shape in plan view (Fig. 7). In cross-sections (Fig. 8), the model can be described as a half-lens. It is surrounding the possible location of the central uplift on the northern side but also exists on the western and eastern side of this possible uplift. This magnetically homogeneous model has a maximum thickness of 400 m at the northern part of the structure.

We assume the modelled structure to be melt-rich-suevite breccia or an impact-melt lens. The relative "freshness" of the crater and the lack of postimpact deformation and erosion in the central depression suggests that the impact-produced rocks may be deposited around the central uplift, that is, the depression is filled more or less symmetrically. Thus, there should be also breccias in the southern part of the crater filling, but they did not acquire a high magnetization. The presence of biotite-rich granite intrusion, cut by the lake in its northeastern part (Fig. 2), may give some clues for the high magnetization at the northern part of the lake. It is possible that shock decomposed biotite partly into ferromagnetic iron oxides; therefore, the suevites have acquired their NRM directions by the postshock thermochemical processes.

Modelling required stronger magnetizations than those measured for suevite (Table 2) outside the crater, because they are too weak to produce the observed magnetic anomaly. The supposed melt-rich material inside the structure has to be several times more magnetic than the fall-out suevite. It is possible that ejected breccias have lost some of their magnetization because of weathering on the surface, or that they are less magnetic than possible melt rocks within the crater. The relatively high Koenigsberger ratio used in the model was the same as that observed for the ejected suevites. Therefore, we assume that most of the impact anomaly is due to a therrmanent magnetization (TRM). The direction of remanent magnetization ($D = 3^\circ$; $I = -1^\circ$) is very similar to the direction of the magnetic field ($D = 354.1^\circ$; $I = -12.5^\circ$) at Bosumtwi.

Slowly cooling crystalline impact-melt rocks may acquire TRM in the direction of the magnetic field at the time of impact, for example, Manicouagan, Canada (Larochelle and Currie, 1967), and Lappajärvi (Pesonen et al., 1992). At a given crater size, composition and properties of target rocks largely control the volume and magnetic contrast of melt rocks and, therefore, the magnetic anomaly. High magnetization is observable if high amounts of ferrimagnetic minerals are produced by the cooling melt, as in impactites of the Mien ($\chi = 2000 \times 10^{-6}$ SI) or Dellen ($\chi = 20 000 \times 10^{-6}$ SI) structures (Henkel, 1992). Bosumtwi, with its Fe-rich target (0.5–9.2 wt% of Fe$_2$O$_3$; Koeberl et al., 1998), could yield melt rocks with this type of magnetization as well. However, Lappajärvi melts and breccias show relatively low susceptibilities (200–700 $\times 10^{-6}$ SI; Kukkonen et al., 1992). In some cases, the observed magnetic anomalies are mainly due to remanent magnetization. High Koenigsberger ratios of breccias and impact-melt rocks are observed at, for example, Mien ($Q = 10$; Stanfors, 1973) and Haughton ($Q > 10$; Pohl et al., 1988).

Additionally to the TRM, several other processes may change the magnetization during the impact. Our model does not exclude any of them, but, because of the limitations of the data, we can not confirm them either. Shock may induce a drop in the magnetic susceptibility and often (but not always) also in the NRM (Hargraves and Perkins, 1969; Cisowski and Fuller, 1978; Pesonen,
Fig. 8. Magnetic profiles. (a) Profile A-A'; (b) profile B-B'; (c) profile C-C'; (d) profile D-D', across Bosumtwi structure. Panels (a–c) are from north to south; (d) from west to east. Location of profiles is shown in Fig. 7. Solid lines denote residual magnetic field. Open circles denote calculated values. Below the profile curves the cross-section of the magnetic model of the magnetic body producing the calculated values is shown. See text for magnetic field, background, and polygon properties.
The Bosumtwi meteorite impact structure, Ghana: A magnetic model

1996; Scott et al., 1997). However, the shocked bedrock may also acquire a new remanence by transient stresses, the shock remanent magnetization (SRM), along the direction of the Earth's magnetic field at the time of impact (e.g., Halls, 1979). Postimpact processes, such as alteration, may produce a chemical remanent magnetization (CRM), as was noticed at Lake St. Martin structure (Coles and Clark, 1982).

One possibility to constrain the model is to compare the volume of magnetic material in our model with the theoretical volume of the melt due to the impact. The latter depends on the kinetic energy of the projectile, and properties of target (Melosh, 1989). There are two estimates of the amount of melt at nearly noneroded impact structures formed into crystalline rocks and with a size comparable to Bosumtwi. The Kaluga structure (D = 15 km) was estimated (Masaitis et al., 1980) to contain 8 km$^3$ of melt rock. Gurov and Gurova (1985) have calculated the volume of impact-melt rock within the Bolyttysh structure (D = 25 km) to be 11 km$^3$. Algorithms proposed by Lange and Ahrens (1979) and Griewe and Cintala (1992) give 1.1 and 2.9-3.4 km$^3$ of melt in Bosumtwi (Table I), including the fraction of melt ejected outside the structure. Considering the fact that not all of the melt must be highly magnetic, and the model is not unique, the melt volume in our model (~2.2 km$^3$) corresponds quite well to the results of the calculations. According to the estimates by Pilkington and Griewe (1992) and Plado et al. (2000), one can expect that the Bouguer anomaly would be ~10 mGal at the Bosumtwi Lake. However, according to the present magnetic model and some modelling experiments, we assume that the negative gravity anomaly is weaker in the northern part of the lake. This is due to the high content of melt rocks, which are usually denser than melt-less impact breccias (e.g., Lappapajärvi; Kukkonen et al., 1992). Some gravity features due to the central uplift may appear.

CONCLUSIONS

The following conclusions can be drawn from the present study.

(1) The negative magnetic anomaly, associated mainly with the central-northern part of the Bosumtwi structure, is produced by a ≤400 m thick magnetic lens of normally magnetized material. This body could consist of impact-melt breccias and impact-melt rocks. Palaeomagnetic data, supported by a magnetic model, show that the magnetic body has acquired its bulk remanent magnetization during the Lower Jaramillo normal polarity event, after the Matuyama–Jaramillo polarity change.

(2) Physical properties of suevites collected north of the crater rim differ significantly from those of the surrounding preimpact metamorphic rocks. High porosity, low density, and relatively high magnetization characterize the suevites.

(3) Highly magnetic material inside the structure seems to have formed—and been preserved—mostly in the northern part of the structure and probably outlines the possible location of a central uplift. It is possible that shock decomposed biotite from the granitic intrusion at the northeastern edge of the lake into ferromagnetic iron oxides, which give rise to the magnetic anomaly in the north-central part of the structure.

(4) The model proposed here could be better constrained by a more extensive sampling of impactites and target rocks around the lake. The model is testable by detailed gravity and seismic reflection methods. However, to really prove its validity deep drilling into the structure is required.

Acknowledgements—We are grateful to Mauri Terho, Heli Ojamo, Heikki Hautanainen, Jukka Multila, Tarja Manninen (all GSF), and Herbert Henkel (Royal Institute of Technology, Stockholm) for help and discussions. Local support by the Ghana Geological Survey Department and its Director, C. E. Oduro, is appreciated. Help by W. U. Reimold and D. Brandt with collecting samples is acknowledged. We greatly appreciate the reviews of A. R. Hildebrand, J. Pohl, and H. Joedicke. This work was supported in part by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung, project Y58-GEO (to C. K.).

Editorial handling: A. Deutsch

REFERENCES


calibration of the last 1.1 Myr from an eastern Mediterranean piston core and dating of short events in the Brunhes. Geophys. J. Int. 129, 75–94.


