Results of pre-drilling potential field measurements at the Bosumtwi crater

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(Received 25 July 2006; revision accepted 29 December 2006)

Abstract—Gravity and magnetic measurements were carried out at the Bosumtwi crater to determine the geophysical signature of the crater. Land gravity data was acquired at 163 locations around the structure and on the shore of the lake. The separation between the gravity stations was 500 m for radial profiles, but 700–1000 m along roads and footpaths that ran parallel to the lake’s shore. Additionally, a marine gravity survey was carried out along 14 north-south and 15 east-west profiles on the lake. Magnetic data was also acquired along 14 north-south profiles on the lake. In all marine surveys, the line spacing was 800 m, and navigation was provided by a Garmin 235 Echo Sounder/GPS. The gravity signature of the crater is characterized by a negative Bouguer anomaly with an amplitude of about –18 mgal. Using the seismic results as constraints, the gravity model obtained indicates the central uplift at a depth of 250 m. The negative anomaly is the contribution of the gravity deficiencies due to fractured and brecciated rocks in the rim area and below the crater floor, the impact breccias within the crater, and the sedimentary and water infilling of the lake. Magnetic modeling yielded a model for the causative body, which is located north of the central uplift: the model has a magnetic susceptibility of 0.03 S.I. and extends from a depth of 250 to 610 m. The causative bodies have been interpreted as impactites.

INTRODUCTION

The Bosumtwi impact crater is located about 30 km southeast of Kumasi, the regional capital of the Ashanti region of Ghana. It has a rim-to-rim diameter of 10.5 km and is almost completely filled by Lake Bosumtwi, which has a diameter of 8 km and a maximum depth of 75 m (Scholz et al. 2000). The crater was formed in metamorphosed crystalline rocks of the Precambrian Birimian System of Ghana about 1.07 Myr ago (Koeberl et al. 1997). The Bosumtwi crater is a complex impact crater that is characterized by a central uplift situated at a depth of 250 m below the water surface and has a diameter of about 1.9 km, as shown by seismic reflection and wide-angle experiments (Scholz et al. 2002; Karp et al. 2002).

Potential field methods, especially gravity and magnetics, can provide complementary information to seismic results and therefore additional constraints for numerical modeling of the Bosumtwi impact process. Previous gravity measurements carried out at Bosumtwi crater in 1960 were limited only to the land area. Due to the sparseness of the data (none on the lake), the results reflected only regional trends of the gravity field (Jones et al. 1981), and therefore could not reveal anything about the impact-related crater structure. The first magnetic measurements of the lake also took place in 1960 when an aeromagnetic survey across the crater area was flown at an altitude of 200 m by Hunting Surveys, Ltd., for the Ghana Geological Survey Department, as reported by Jones et al. (1981). The occurrence of a central negative magnetic anomaly located to the north of the lake center was detected in this early survey and was attributed to a breccia lens below the lake sediments (Jones et al. 1981).

In 1997, a high-resolution airborne geophysical survey at an altitude of 70 m was carried out across the Bosumtwi structure by the Geological Survey of Finland in cooperation with the University of Vienna, Austria, and the Ghana Geological Survey Department (Ojamo et al. 1997; Pesonen et al. 1998, 1999). The measurements included total magnetic field, electromagnetic field, and gamma radiation. The results of this survey, which provide a more detailed image of the crater’s structure than the previous measurements, indicate the presence of magnetized bodies—probably suevitic impact breccias or impact melts—in the central area of the lake (Pesonen et al. 1998; Plado et al. 2000).

Within the framework of the Ghanaian-German joint research project on the Lake Bosumtwi crater, gravity and magnetic measurements were carried out to determine the impact-related crater structure. In October 1999, gravity
measurements were made at 163 locations on land around the crater. This was followed by a marine gravity survey on the lake in 2001. Between February and March 2002, detailed magnetic measurements were carried out on the lake. It is envisaged that a more detailed picture of the nature and form of the magnetized bodies would be obtained by this study.

The purpose of this article is to report on the Bosumtwi impact crater from the results of potential field measurements before the International Continental Scientific Drilling Program (ICDP) drilling in 2004.

GEOPHYSICAL MEASUREMENTS

Gravity Measurements on Land

In 1999, gravity measurements were made at 163 points located on land around the crater, including the road linking the 22 villages close to the lakeshore, to determine the impact-related crater structure. The gravity measurements were carried out with a Lacoste-Romberg gravimeter model G 256, which has an accuracy of 0.01 mgal. The main base and the auxiliary base stations were re-occupied between every one to two hours. Differential global positioning system (GPS) equipment from Leica was used to determine the locations (geographic coordinates) and the elevations of gravity stations with an accuracy of 2–3 cm. The measurements were carried out along accessible roads and footpaths around the crater due to the largely inaccessible nature of the terrain. However, no gravity stations were located close to the Obuom Range in the southeast because it is not directly linked to the crater formation and also inaccessible. In general, the separation between the gravity stations was 500–1000 m. Since the objective of the measurements was to determine the gravity signature of the crater structure, the radial profiles were found to be important. Therefore, an interval of about 500 m was fixed between gravity stations along roads which ran radially towards the center of the lake. For roads and paths which ran...
Potential field measurements at Bosumtwi

Parallel to the lakeshore, station distances of 700–1000 m were chosen. In all, 163 gravity stations were measured. Figure 1 shows both the land and marine gravity profiles displayed in the Ghana Transverse Mercator (Ghana TM) projection system.

Gravity Measurements on the Lake

In October 2001, a second gravity survey on a grid of 18 profiles, consisting of 11 north-south and 7 east-west profiles (Fig. 1) completely covering the lake, was conducted using a LaCoste-Romberg air-sea gravimeter model S-124 belonging to the GeoForschungsZentrum (GFZ), Potsdam, Germany. The instrument has an accuracy of 1.0 mgal or better at sea (Instruction Manual, Lacoste and Romberg Model S Air-Sea Dynamic Meter, 1998). The measurements were carried out using the motor-driven research platform. The distance between the gravity profiles was about 800 m and the station spacings about 10 m. A LaCoste-Romberg land gravimeter was stationed at one of the land gravity stations on the shore of the lake to monitor the base station gravity. Navigation was done using a Garmin 235 Echo Sounder/GPS equipment, which also made it possible for bathymetric data to be collected at the same time. The bathymetric measurements were carried out along 14 north-south and 15 east-west profiles (Fig. 3) to determine water depths of the lake.

However, differences in gravity values at the crossing points were observed. The following procedure was used to minimize the differences: plots of some of the north-south and east-west crossing points were made (i.e., where the east-west profiles cross the north-south profiles). The difference between the crossing point values of the north-south and east-west profiles was noted and used as a constant correction factor to correct the gravity values for all profiles. The final data set was found to be good.

Magnetic Measurements on the Lake

Magnetic measurements were carried out on the lake using two proton precession magnetometers of type GEM GSM-19 TG3. The equipment has a resolution of 0.01 nT and an absolute accuracy of 0.2 nT. One of the magnetometers served as the base station (or reference station) set up at a quiet location (i.e., free from traffic and human activities) on a hill at the Nyamieni-Abonu junction, while the other was used as mobile field equipment throughout the survey. On the lake, the mobile field magnetometer and sensor were mounted in a rubber boat (unmanned) and towed 50 m behind the motor-driven research platform. The base station readings were quite consistent throughout the survey, with differences ranging between 0.03 and 0.20 nT. The profiles spacing on the lake was 800 m and the interval between stations was 10 m. Navigation was provided by a Garmin 235 Echo Sounder equipment.
attached to the platform and equipped with a GPS. Magnetic measurements were conducted along 14 north-south and 15 east-west profiles. However, only the north-south profiles have been used for the analysis in this work. The objective is to allow a comparison of the marine magnetics with earlier airborne surveys. Figure 2 shows a plan view of the magnetic profiles on the lake.

RESULTS AND DISCUSSION

Results of Bathymetric Measurements

The bathymetric data as well as the gravity and magnetic data were all gridded using a minimum curvature algorithm. Figure 3 shows the results of the bathymetric measurements that were carried out along 14 north-south and 15 east-west profiles to determine water depths of the lake. The maximum depth of the lake was found to be 75 m. The depth contours are elliptical in shape and elongated in approximately NE-SW direction, probably as a result of the general SW-NE trending of the Birimian rocks. The maximum depth of the lake is not exactly in the center, but rather displaced south-westward from the center.

Results of Gravity Measurements

Bouguer Anomaly

For gravity measurements on land no terrain corrections have been carried out. However, topographic near-field corrections were carried out and simple Bouguer anomalies computed. The simple Bouguer anomalies obtained from the land measurements and the free-air anomalies on the lake were combined by comparing them using as reference the start/landing point of the research platform on the lake close to the shore (at Abono). Figure 4 shows a map of the Bouguer anomalies of the combined results. The profile for which gravity modeling has been carried out is indicated as A-B in the figure.

Ugalde et al. (2007b) used the bathymetric data to compute a Bouguer correction that included the effect of the body of water and generated an integrated Bouguer gravity anomaly map from both inland and lake data sets.

The gravity field of the Bosumtwi area, as shown in Fig. 4 is characterized by a negative Bouguer anomaly, with an amplitude of about –18 mgal and a half amplitude width of about 6.5 km. The steepest gradients are found within the lake area. The central part of the anomaly is rather flat with a tiny deflection, which could be caused by the central uplift that was inferred from seismic studies. The effect cannot be the result of lake floor topography, which is known to be smooth. The gravity anomaly is elongated in a SW-NE direction and elliptical in shape due to the general trend of the rocks in the area and the deep structure of the lake as observed from the bathymetric results (Fig. 3).

Pre-Drilling Gravity Modeling of the Bosumtwi Crater

Gravity modeling was carried out for a south-north profile across and through the center of the lake (see line A-B in Fig. 4). The modeling was done for 2.5-D geological bodies with half-strike length of 1 km with the profile assumed to be perpendicular to the strike. Information obtained from the seismic results (Scholz et al. 2002; Karp et al. 2002) and the pre-drilling data on the petrophysical properties and lithologies (Plado et al. 2000) were used to constrain the models. Three geological bodies (1, 2, 3) with different densities were assumed: 1) the water in the lake with a density of 1.0 g/cm$^3$, 2) the underlying sediments with a density of 1.8 g/cm$^3$ (Peck, personal communication), and 3) a breccia layer with a density of 2.0 g/cm$^3$. The background density value was taken as 2.6 g/cm$^3$.

Polygonal prisms were used as the starting models. Figure 5 shows one final model with the observed (solid curve) and calculated (dashed curves) anomalies. A central uplift is clearly shown at a depth of 250 m below the water surface. The observed gravity minimum is located northward of the central uplift. It is also observed in the model that the central zone of the lower boundary of layer three (breccia) at a depth of about 780 m is uplifted, indicating the depth extent to which rocks in this area have been affected by the impact.

Results of Magnetic Measurements

The results of the magnetic measurements on the lake are similar to those of Plado et al. (2000). Figure 6 shows the results of the magnetic anomalies along north-south profiles across the lake. The main feature of the magnetic field on the lake is a large negative anomaly with a minimum value of about 55 nT.
to the north and a less pronounced positive anomaly to the south. Three to four additional but weaker negative anomalies are indicated in the southwest and southeast.

In general, the regional magnetic anomalies of the Bosumtwi area have northeast trends. The magnetic low associated with the Bosumtwi structure has therefore manifested itself as a result of the truncation of the regional anomalies similar to what is observed at the Deep Bay crater, Saskatchewan, Canada (Pilkington and Grieve 1992).

### Magnetic Modeling of the Crater

The shape of the central negative anomaly suggests a normal polarity for the magnetization of the causative bodies (located north of the central uplift) at the latitude of Lake Bosumtwi (Plado et al. 2000). Magnetic modeling was done for the main anomaly by considering a 2.5-D model with a half-strike length of 1 km. It is assumed that the anomaly is caused by magnetized bodies formed during the impact process. Evidence of this is found in similar situations observed in many other impact structures, e.g., Ries crater (Pohl 1977). For the modeling of the data, no regional field had been removed and induced magnetization was assumed. In this case, we are dealing with an impact crater that is only approximately 1 Myr old. Any remanence would be parallel, or anti-parallel to the current Earth’s field direction,
depending on the exact time of impact. Therefore, in attempting to model this structure, we can ignore any remanence effect, since it is taken care of by the susceptibility. Thus, the same effect can be accomplished by reducing the intensity of NRM and increasing susceptibility or vice-versa, but reasonable limits on the amount of each are imposed by magnetic mineralogy. In our case, the higher values of magnetic susceptibility required by the model mean that the effective susceptibility \( k_{\text{eff}} = k(1 + Q) \), where \( k \) is the magnetic susceptibility, \( Q \) is the Koenigsberger ratio of remanent to induced magnetization, and \( k_{\text{eff}} \) is the effective susceptibility, is high and therefore our model is consistent with the high values of remanent magnetization observed by Plado et al. (2000), Kontny et al. (2007), Morris et al. (2007), and the improved 3-D model by Ugalde et al. (2007a).

The following parameters of the International Geomagnetic Reference Field (2002) were used for Earth’s magnetic field (see also Plado et al. 2000):

- Field intensity = 31860 nT
- Inclination I = –12.5°
- Declination D = 354.4°

Polygonal prisms were used as the starting models. The upper limit of the models was chosen as 250 m, in agreement with the top of the central uplift (Scholz et al. 2002; Karp et al. 2002). The final model obtained for the causative body is shown in Fig. 7. It has a susceptibility value of 0.03 S.I., corresponding to an induced magnetization of 0.075 A/m and the causative body extends down to a depth of about 610 m. The source bodies have been interpreted to be impactites.

In principle, the results are in agreement with Plado et al. (2000). However, results from the deep drilling in the lake did not show the presence of appreciable amount of impact melt rocks. Only centimeter-wide suevite dikes on boreholes LB-08 and less than 50 m of suevite on LB-07A (Koeberl et al. 2006) have been encountered.

Comparing the gravity and magnetic models, one observes that the causative bodies are located to the north of the central uplift, as indicated by the location of the minima on the anomaly curves.

**CONCLUSIONS**

The typical gravity signature of impact craters is a gravity low over uneroded and well-preserved craters such as the Bosumtwi crater. The negative Bouguer anomaly observed is therefore in conformity with the gravity signature of known impact craters. The negative anomaly is interpreted to be due to the effects of fractured and brecciated rocks in the rim area and below the crater floor, from breccias within the crater, and from sedimentary and water infilling of the lake. The results also indicate that rocks in the zone below the central uplift at a depth of about 780 m have been affected by the impact.

The cause of the magnetic anomaly is attributed to
magnetized bodies located in the central northern area of the lake. Magnetic modeling yielded a model that extends from a depth of 250 m to 610 m below the lake’s surface and is found to be the best model that explains the likely cause of the Bosumtwi magnetic anomaly. The magnetized bodies have been considered as impactites. However, the ICDP drilling did not encounter an appreciable amount of melt rocks in the depression north of the central uplift.

Acknowledgments—The authors wish to thank the German Ministry for Economic Cooperation and Development (BMZ) and the German Research Foundation (DFG) for financial support. We also thank all scientists on both the Ghanaian and German sides who participated in the joint research project on Lake Bosumtwi. We especially thank J. Pohl for the gravity data. We further express our sincere thanks to institutions such as GEOMAR in Kiel and the GeoforschungsZentrum (GFZ) in Potsdam for making their equipment readily available for this work in Ghana. We thank Hernan Ugalde for his input in the revision of the manuscript. We also thank Associate Editor C. Koeberl and reviewers J. Plado and Alan Hildebrand for the helpful comments and useful suggestions that improved the manuscript. The present work is based on S. Danuor’s Ph.D. thesis (Danuor 2004).

Editorial Handling—Dr. Christian Koeberl

REFERENCES


