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Integrated 3-D model from gravity and petrophysical data at the Bosumtwi impact structure, Ghana

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Abstract–The Bosumtwi impact structure of central Ghana was drilled in 2004 as part of the International Continental Scientific Drilling Program (ICDP). A vast amount of geoscience data is available from the pre-site surveys and the actual drilling phase. A 3-D gravity model was constructed and calibrated with the available data from the two ICDP boreholes, LB-07A and LB-08A. The 3-D gravity model results agree well with both the sediment thickness and size of the central uplift revealed by previously collected seismic data, and with the petrophysical data from the LB-08A and LB-07A core materials and the two borehole logs. Furthermore, the model exhibits lateral density variations across the structure and refines the results from previous 2.5-D modeling. An important new element of the 3-D model is that the thickness of the intervals comprising polymict lithic impact breccia and suevite, monomict lithic breccia and fractured basement is much smaller than that predicted by numerical modeling.

INTRODUCTION

The Bosumtwi impact structure in central Ghana has a rim-to-rim diameter of 10.5 km and is nearly completely filled by Lake Bosumtwi, which has a diameter of 8 km and a maximum water depth of 75 m (Scholz et al. 2002) (Fig. 1). With an age of 1.07 Myr, Bosumtwi is one of the youngest large impact structures with a well-established age on Earth and within the solar system (Grieve et al. 1995). The crater structure is well preserved and therefore comparable to impact structures on the Moon and other planetary bodies.

The structure was drilled in August–October 2004 as part of the International Continental Scientific Drilling Program (ICDP). Since then, a vast amount of geoscience data has become available from the pre-drilling geophysical site surveys and the actual drilling phase.

Gravity data were acquired over the lake and in its surroundings between 1999 and 2001 (Danuor 2004; J. Pohl, personal communication). These data were used to create a 3-D model of the Bosumtwi structure. The model integrates gravity, petrophysics, and seismic data. The results obtained refine a previous 2.5-D model by Danuor (2004).

REGIONAL GEOLOGY

The Bosumtwi structure was formed by a large meteorite impact about 1.07 ± 0.05 Myr ago in lower greenschist facies metasediments of the 2.1–2.2 Gyr old Birimian Supergroup (Koeberl et al. 1997). More important regional geological features are the northeast-southwest trends of the volcanic and sedimentary belts, which have steep dips either to the northwest or southeast (Koeberl and Reimold 2005). However, variations in this trend due to folding have been observed (Reimold et al. 1998). The lithology in and around Lake Bosumtwi is dominated by meta-graywackes and meta-sandstones, as well as shale, phyllite, and schist that occur particularly in the northeastern and southern rim sectors (Reimold et al. 1998; Koeberl and Reimold 2005). A variety of granitoid intrusions (mainly biotite or amphibole granites, some granodiorites and diorites) were mapped by Junner (1937) and Moon and Mason (1967). Small granite intrusions, probably connected with the Kumasi granite to the northwest of the crater structure, outcrop around the northeast, west, and south sides of the lake (Jones et al. 1981; Koeberl and Reimold 2005). In addition, numerous narrow (less than 1 m wide) dikes of biotite granitoid have been observed at many

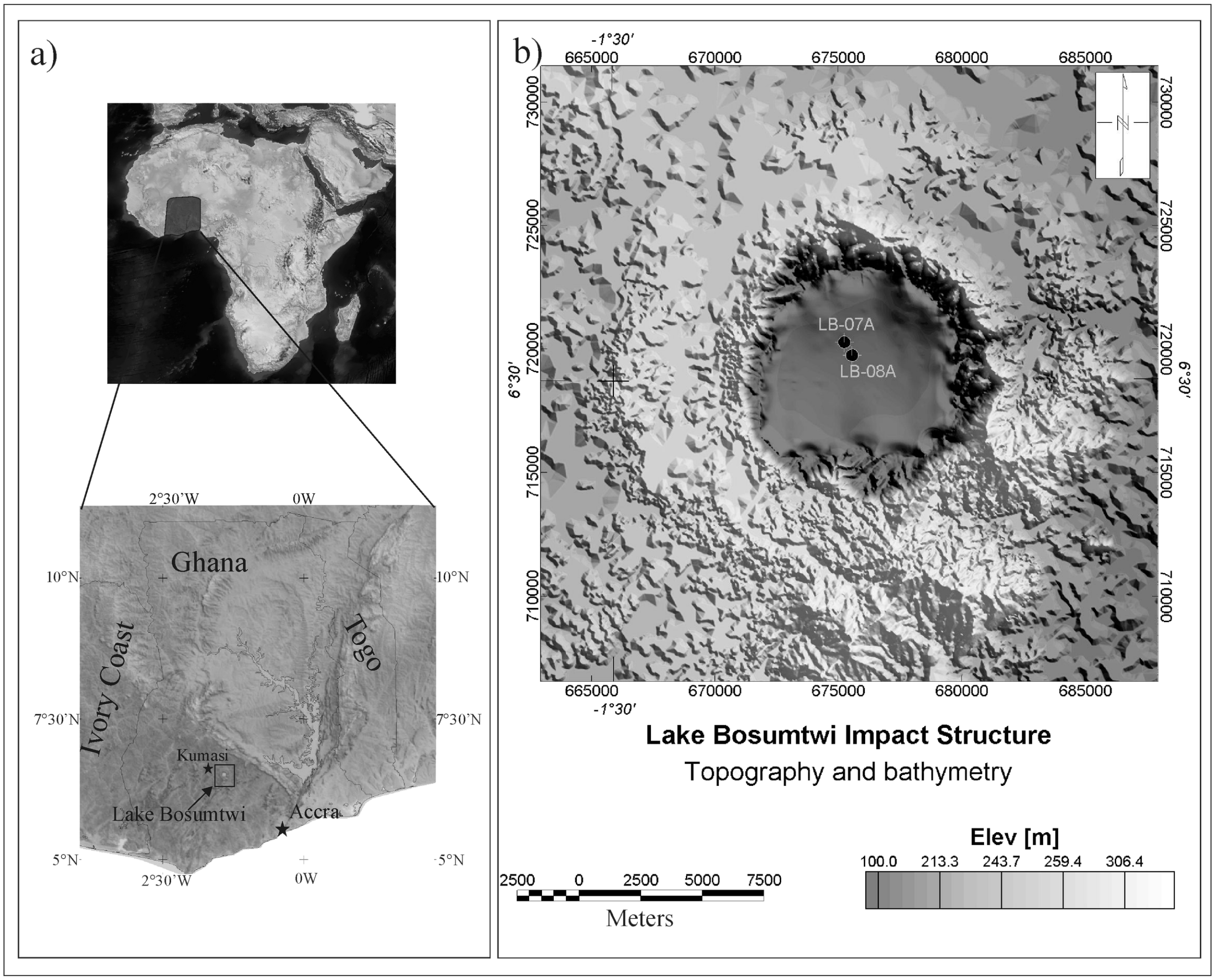

Fig. 1. a) The location of Lake Bosumtwi in Africa (top) and Ghana (bottom). The bottom panel shows topography data from SRTM. The cities of Accra and Kumasi are marked for reference. The rectangle in the bottom panel marks the location of the detailed image on the right. b) The topography of the lake surroundings. The 2004 ICDP deep boreholes are shown for reference.

basement exposures in the crater rim (Reimold et al. 1998). Recent rock formations include the Bosumtwi lake beds, as well as soils and breccias associated with the formation of the crater (Jones et al. 1981; Reimold et al. 1998). A detailed description of the geology is given by Koeberl and Reimold (2005). Lithological descriptions of the rocks recovered by the ICDP deep drilling are given by Coney et al. (2007), Ferrière et al. (2007), Deutsch et al. (2007), and Koeberl et al. (2007).

GRAVITY DATA

The first gravity measurements in the Lake Bosumtwi area were carried out in 1960. They were limited to only the land area around the Bosumtwi impact structure. Therefore, the results reflect only the regional trends of the gravity field (Jones et al. 1981) and could not reveal anything about the impact-formed crater structure.

In 1999, 163 gravity measurements were obtained at points located around the Bosumtwi crater structure to determine the gravity signature of the impact structure itself (Danuor 2004; Danuor et al. 2007; J. Pohl, personal communication). The stations were positioned with Differential Global Positioning System (DGPS) equipment, with an accuracy of 2–3 cm. The separation between the gravity stations was 500 m along profiles that ran radially toward the center of the lake. For roads and paths that ran parallel to the lake shore, station distances of 700–1000 m were chosen.

In 2001, a second gravity survey on a grid of 18 profiles (11 north-south and 7 east-west profiles) was conducted on the lake using a LaCoste-Romberg air-sea gravimeter (Danuor 2004; Danuor et al. 2007; J. Pohl, personal communication). The measurements were obtained using a motor-driven marine research platform. The distance between the gravity profiles was about 800 m. Navigation was provided using a Garmin 235 Echo Sounder/GPS, which allowed the acquisition of bathymetric data at the same time (Danuor 2004; Danuor et al. 2007; J. Pohl, personal communication).

The recorded gravity data were processed by applying standard drift, theoretical gravity, and free air (FA) corrections. The Bouguer anomaly (BA) was then obtained by subtracting the effect of a slab of homogeneous density (ΔB_R). For the marine data, this slab introduces an overcorrection because of the higher density of rocks as compared to that of fresh water, and therefore the effect of the body of water had to be considered (ΔB_W). The equations used for the processing are described in detail in the Appendix. Figure 2a shows the preliminary gravity data that included Bouguer data around the lake and free air data of the lake area (Danuor 2004; Danuor et al. 2007; J. Pohl, personal communication). Figure 2b shows the final Bouguer gravity anomaly after correction for the water effect and compilation of all the data. The map is characterized by a negative anomaly of about −15 mGal and a diameter of about 11 km. The steepest gradients are found within the lake area. The anomaly is elongated in a southwest-northeast direction in analogy with the bathymetric results. The observed strong negative anomaly represents the cumulative gravity deficiencies caused by the fractured and brecciated rocks in the rim area and below the crater floor, the impact breccias within the crater, and the sedimentary and water infill (Pilkington and Grieve 1992; Ugalde 2006).

PETROPHYSICAL DATA AND CONSTRAINTS FROM THE ICDP DRILLING

The ICDP drilling project at Lake Bosumtwi involved drilling at six sites to obtain a complete record of the post-impact sediment accumulation and at two sites to sample the impact breccia crater fill and underlying basement (Koeberl et al. 2007). The sediment boreholes allowed the measurement of average density and thickness of the post-impact sediments, which will serve as calibration points for our 3-D model. The locations of the boreholes into hard-rock were selected to investigate the central uplift (borehole LB-08A), and the crater interior just outside from it (borehole LB-07A). Reflection seismic data outlined the post-impact sediment pile and the top of the central uplift; however, the base of the central uplift is not well defined (Karp et al. 2002; Scholz et al. 2002). Thus, any modeling able to define the different units that compose the structure is essential.

Borehole logging and scanning of the core recovered from the deep ICDP boreholes allowed to build a petrophysical database, which is vital to constrain the depth extent of the units that compose the structure (Milkereit et al. 2006; Morris et al. 2007). The borehole logging survey collected gamma-radiation, susceptibility, resistivity, P-wave sonic, and orientation (azimuth and deviation) logs (Morris et al. 2007). Core scanning was accomplished in December 2004 at the ICDP research facility at GFZ in Germany. This consisted of laboratory measurements of density from gamma-ray absorption and magnetic susceptibility. Gamma-ray attenuation density was measured at irregular intervals, depending on the availability of suitable samples (regular diameter and flat surfaces); magnetic susceptibility was measured at ~10 cm spacing (Morris et al. 2007).

Figure 3a shows the depth profiles obtained for density and P-wave velocity on both cores (Ugalde 2006). Borehole LB-08A exhibits both greater density and P-wave velocity than LB-07A. The laboratory measurements (Fig. 3) corroborate the velocity model of Karp et al. (2002), and the porosity logs extracted from resistivity logs (Qian et al. 2006). All this evidence constitutes the basis for the 3-D gravity model presented below. Figures 3c and 3d present histograms of the density measurement results for all the samples from the two boreholes. As noted by Morris et al. (2007), high-frequency density variations within each borehole are irrelevant for the purposes of geophysical modeling, as they are beyond the resolution of the surface gravity data.

3-D GRAVITY MODEL OF THE BOSUMTWI CRATER

Danuor (2004) performed 2.5-D gravity modeling for a south-north profile across the center of the lake. A linear gravity gradient was removed from the observed data before the modeling. The computations were carried out using 2.5-D geological bodies with half-strike length. Three geological bodies with different densities were assumed: the water in the lake with a density of 1.0 g/cm^3, the underlying sediments with ρ = 1.8 g/cm^3, and a breccia layer with ρ = 2.0 g/cm^3. The background density value was taken as 2.6 g/cm^3. Figure 4 shows the final model with the observed (solid) and calculated (dashed) gravity, obtained by using forward modeling and the model geometry from available seismic data (Karp et al 2002). A central uplift is clearly shown at a depth of 250 m below the water surface, which causes a subtle gravity anomaly high within the prominent gravity anomaly low. The observed gravity minimum is located northward of the central uplift. It is also observed that the central zone of the lower boundary of layer three (breccia) at a depth of about 780 m is uplifted. These results are compatible with the seismic interpretation. However, a new 3-D model that integrates the ICDP borehole results was required to better constrain the model of the Bosumtwi impact crater structure.

A 3-D model was created with the gravity data. As one of the purposes of this model was to find out the extent of fracturing due to the impact, we used the free air gravity data instead of the final Bouguer gravity anomaly. This way, the model could allow lateral density variations in the basement and upper layers, something that is not possible when using the terrain-corrected Bouguer anomaly, where a constant density slab is subtracted from the data. The 3-D structure was

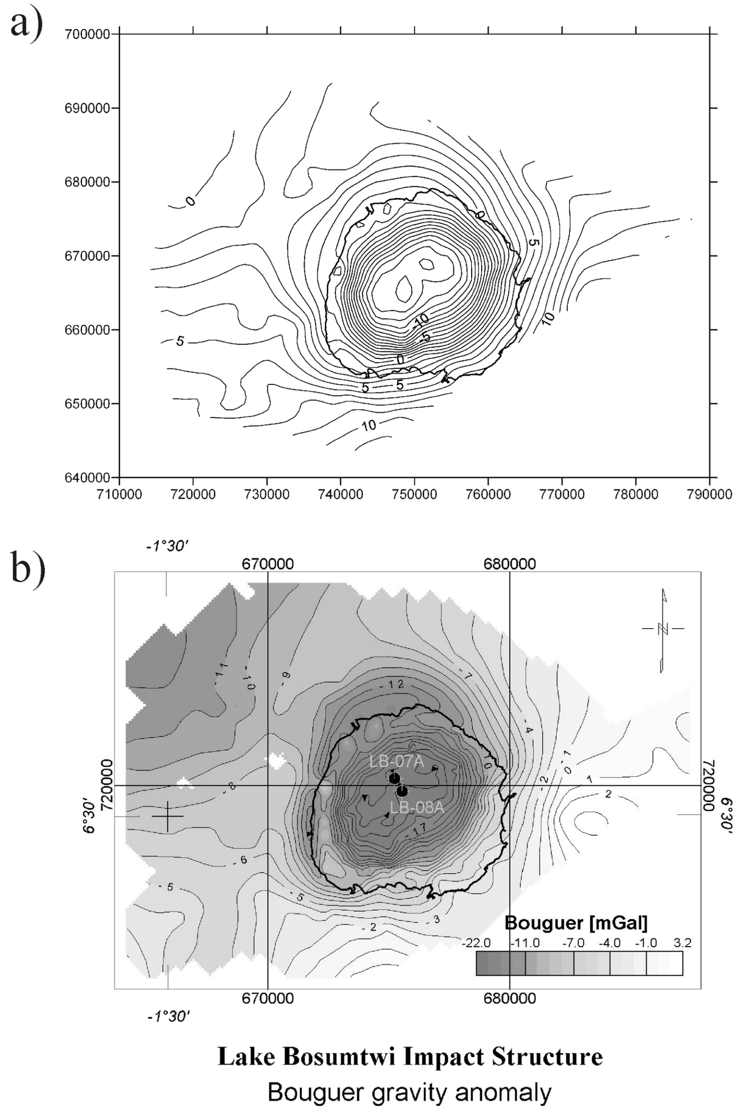

Fig. 2. Gravity data at Lake Bosumtwi. a) The original compilation of free air gravity data on the lake and Bouguer gravity inland (courtesy of J. Pohl). Contour interval is 1 mGal. Coordinate system is Transverse Mercator, Accra Ghana grid. b) Final Bouguer gravity anomaly after correcting for water depth on the marine data set and its integration with the land data. Contour interval is 1 mGal, with black triangles marking the more negative anomalies. Coordinate system is UTM Zone 30 North, WGS84.

constructed from 1 km spaced east-west profiles. Each section is 1 km wide and it is draped over the lake bathymetry (Figs. 5 and 6). The model is composed of a series of 3-D polygonal bodies, each with its own density. Together, all the adjacent bodies that share a similar density can construct very complex geological units. The model is made up of three layers: water, sediment, and impact breccia. From the original geometry, adjustments were made line-by-line to reproduce the observed anomalies. The observed data were matched to the computed data from the entire 3-D model geometry via forward modeling and inversion, ending up with a mean residual error <0.2 mGal.

The thickness for the post-impact sedimentary unit in the 3-D model was constrained based on the sedimentary boreholes, and also on a minimum thickness grid that was generated from the available seismic data. The bottom of the post-impact sediment unit was digitized from the reflection seismic line 1 (Fig. 2 of Scholz et al. 2002) and extrapolated radially. This grid was then used to provide a range for the depth extent of the post-impact sediment pile across the structure. Good correlation was obtained between the model and the seismic interpretation, with an average thickness of the post-impact sediment unit of 140–180 m. This unit has a density of 1.6 g/cm^3, which is the average density from drill cores of sedimentary sequences drilled in the lake (J. Peck, personal communication).

The 3-D model (Fig. 6) supports a unit of impact breccia and shocked rocks with a density of 2.3 g/cm^3 that is located in

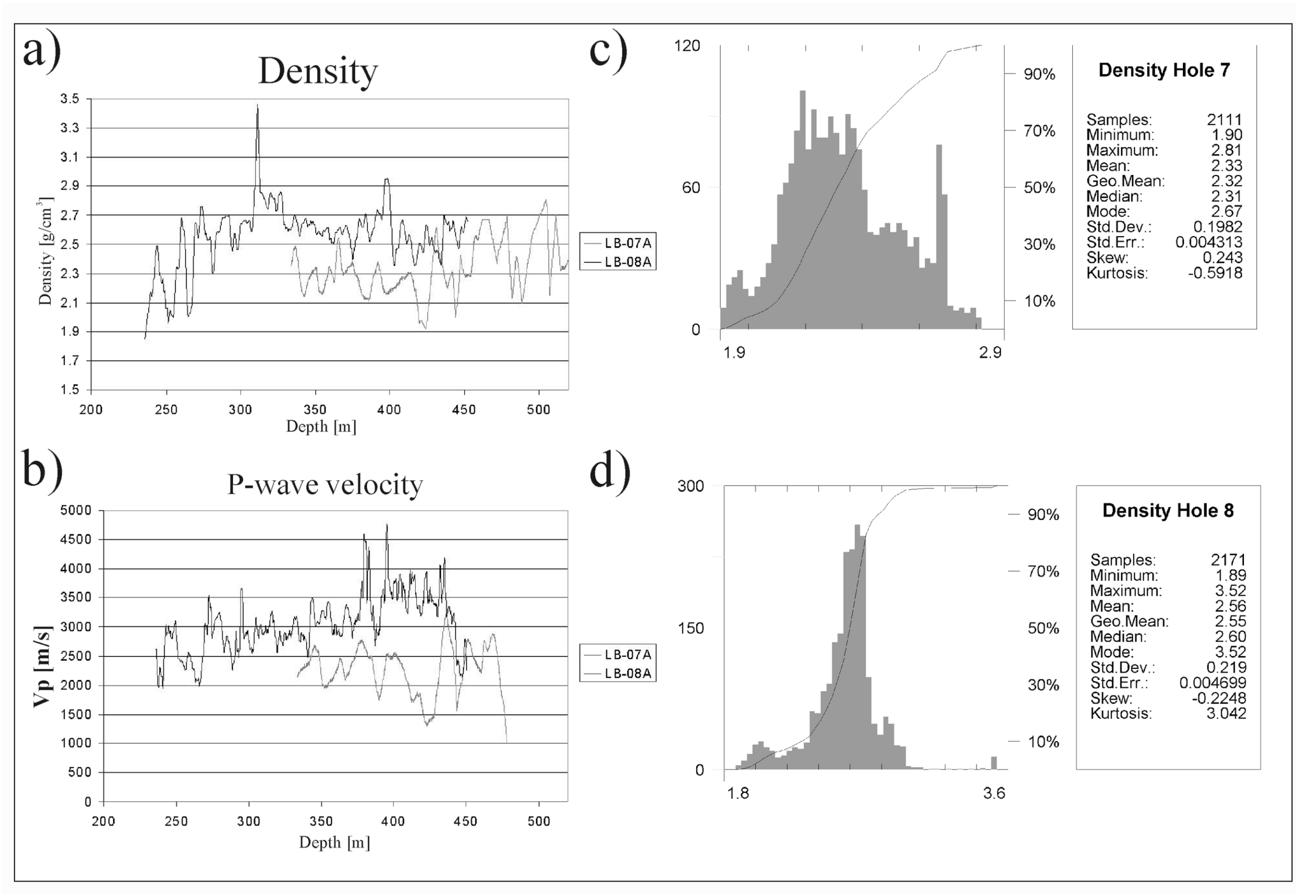

Fig. 3. Density (a) and P-wave velocity (b) profiles obtained from core scanning and borehole logging respectively. c) and d) are histograms of the density measurements done on the core obtained from Lake Bosumtwi. The median values of 2.3 g/cm^3 for LB-07A and 2.6 g/cm^3 for LB-08A are the values used in the gravity model.

the region outside of the central uplift, as well as similar but less porous unit located at the central uplift, with a higher density of 2.6 g/cm^3. The density contrast between these two units is supported by the laboratory-measured densities on cores from both boreholes (Figs. 3a and 3b) (Morris et al. 2007), and by the porosity logs inferred from the borehole resistivity measurements indicating higher porosities along core LB-07A as compared to LB-08A (Qian et al. 2006). In addition, the 3-D model (Fig. 6) is compatible with the velocity model of Karp et al. (2002), which predicted higher velocities (and, thus, lower porosity) in the area underneath the central uplift, and lower velocities (thus higher porosity) at the sides of it. Both impact breccia and shocked rock units (inside and outside of the central uplift) have a thickness <300 m.

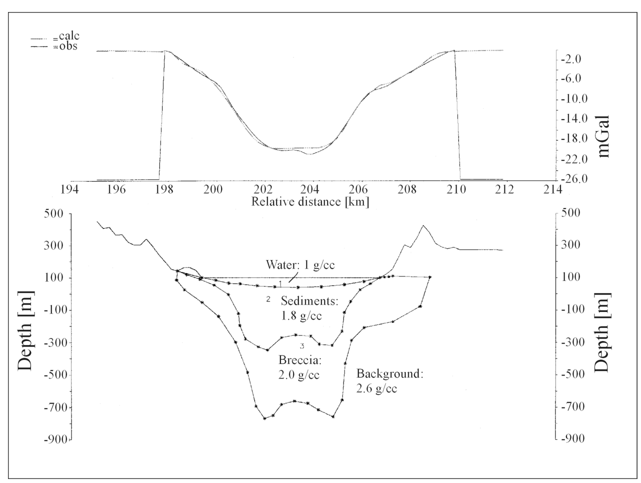

Fig. 4. A 2.5-D model of the structure based on gravity data. Observed gravity anomaly (solid curve) and calculated result (dashed curve). Vertical exaggeration is 10× (modified from Danuor 2004).

DISCUSSION

Previous estimations of the maximum shock pressure distribution within the Bosumtwi impact structure from numerical modeling can be used to predict the extent of fracturing and brecciation caused by the impact, related to the area where P > 1 GPa (Artemieva et al. 2004; Ugalde et al. 2005). Those results predicted fracturing across the entire crater, within a volume of ~5200 m radius (Artemieva et al. 2004; Fig. 6b in Ugalde et al. 2005). However, the density

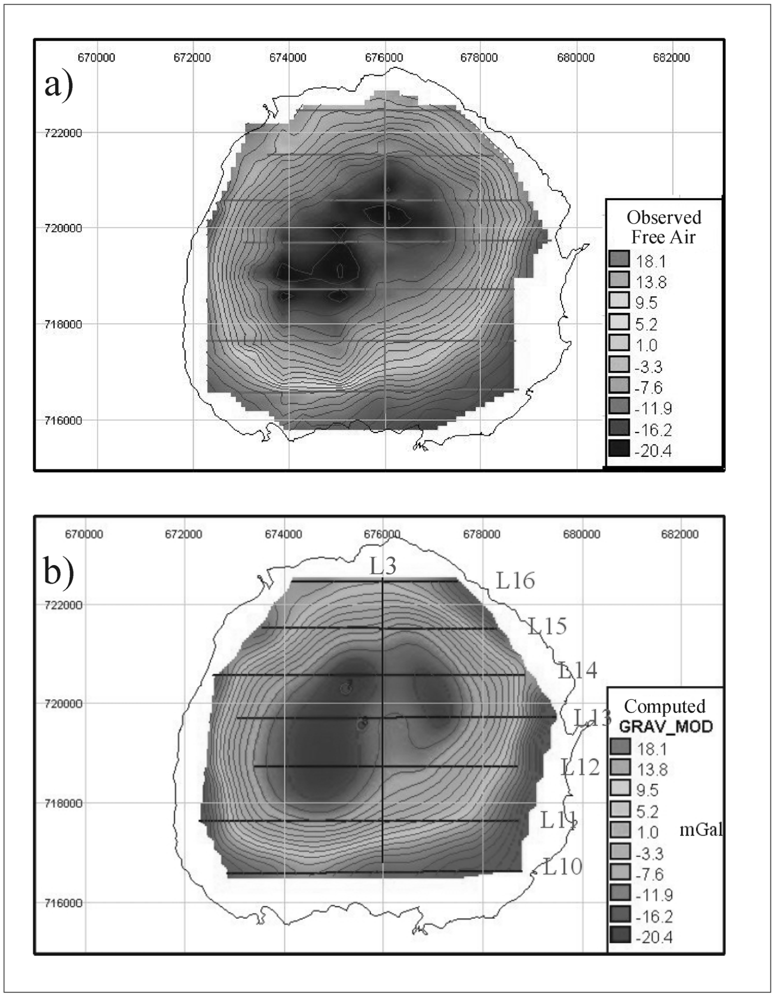

Fig. 5. a) Observed gravity data over Lake Bosumtwi. b) Modeled data.

profile computed from the gravity data requires a much faster porosity decrease, and therefore the density increases to its zero-porosity or unfractured value at about 500 m, bringing density back to that of unfractured basement rock at that relatively shallow depth and thus not leaving any space for fracturing to be found in the basement.

The lateral density and porosity changes inside and outside the central uplift agree with similar results obtained by Tsikalas et al. (2002) at the Mjølnir impact structure in the Barents Sea. At Mjølnir, porosity increased by up to 6.3% at the crater periphery, whereas it decreased by 1% at the crater center (Tsikalas et al. 2002). Tsikalas et al. (2002) attributed this variation to cratering effects (brecciation, gravitational collapse, structural uplift) and differential compaction. The mechanism for porosity reduction at the central uplift of the Bosumtwi structure is not clear, although differential compaction should not have played an important role because of the young age of the structure.

The 3-D model and the previously computed 2.5-D model by Danuor (2004) differ in the thickness of the impact breccias and shocked rock layer. Danuor (2004) estimated the post-impact sediment and impact breccia thickness as ~300 m and 500 m, respectively. He used a density of 2.0 g/cm^3 for impact breccia, and 1.8 g/cm^3 for the post-impact sediment. By considering a lower density, he required a larger thickness of breccia to reproduce the observed anomalies. However, the new 3-D model incorporates density measurements on the recovered core from drilling (Fig. 3a) that support the density values utilized.

Unlike the predictions made by numerical modeling (Artemieva et al. 2004), our 3-D model does not include a separate layer of fractured basement underneath the impact breccia and shocked rock units. One explanation is that the impact breccias and shocked rocks do not have a sufficiently large density contrast between them and the unfractured basement, so that for gravity modeling purposes they are grouped together as one impact breccia and shocked rock unit about 300 m thick, as shown in Fig. 6. The so-called impact breccia unit (actually polymict and suevitic impact breccia, monomict breccia and fractured basement) outside the central

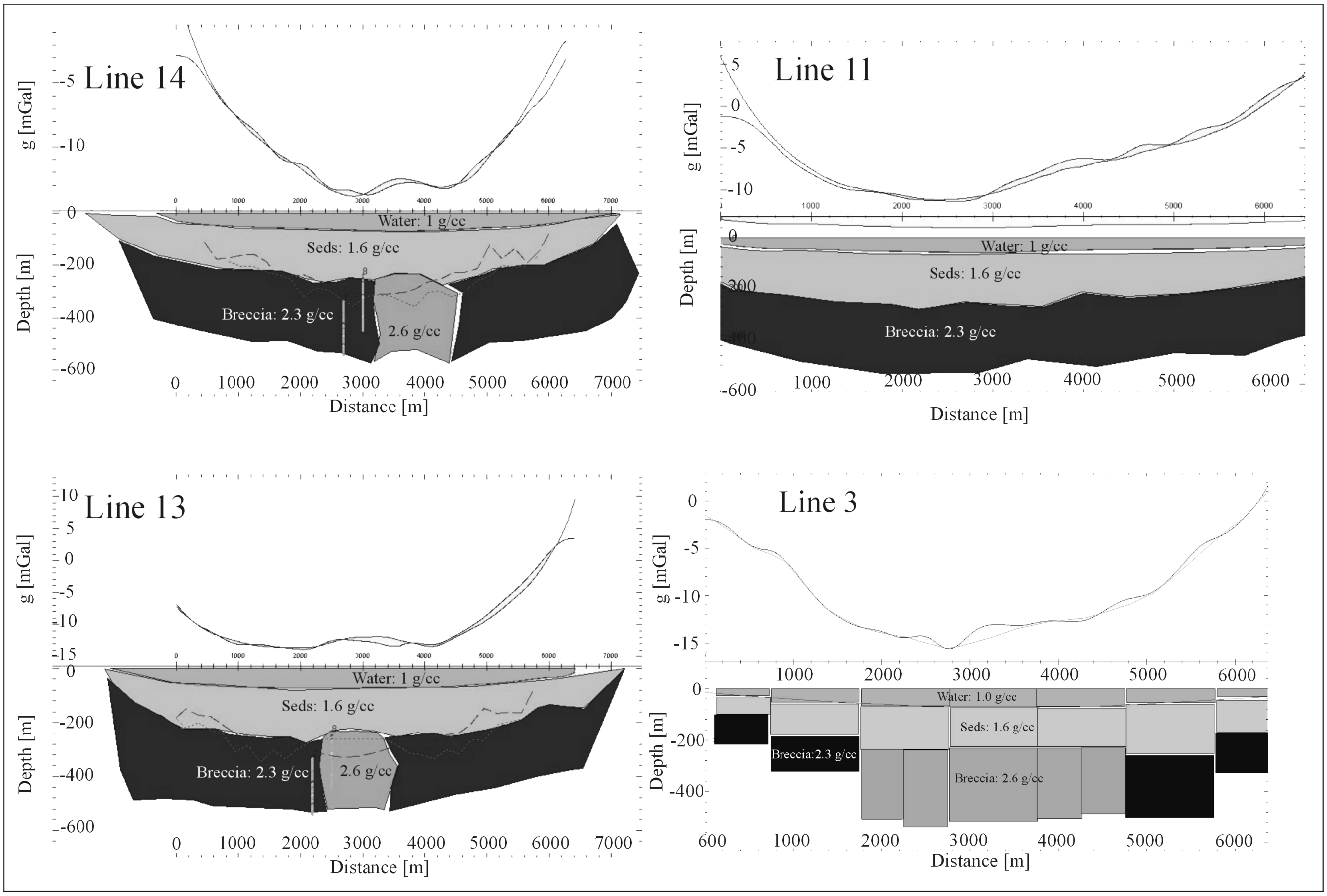

Fig. 6. Examples of three cross-sections of the model across the lake. See Fig. 9 for line locations. The dashed lines in profiles 13 and 14 indicate two estimations for the bottom of the sediment unit from reflection seismic data (see text for details). The ICDP boreholes LB-07A and LB-08A are projected on lines 13 and 14, for reference. Vertical exaggeration ~1:3. The breccia unit includes impact breccia and fractured basement.

uplift has a density of 2.3 g/cm^3, and the basement a density of 2.6 g/cm^3, which is sufficiently large to have a distinct gravity response. At the central uplift, the impact breccias have a density of 2.6 g/cm^3, which is the same as the basement and therefore unnoticeable in gravity modeling.

CONCLUSIONS

The present study allowed the integration of gravity, petrophysical, and seismic data over the Bosumtwi impact crater. The final 3-D model is compatible with the sediment thickness and size of the central uplift mapped on previously collected seismic data. A previous velocity model for the porosity changes inside and outside the central uplift, and the petrophysical logs from the ICDP boreholes for porosity, density, and P-wave velocity (LB-07A and LB-08A). The main outcome of our analysis is that for the first time a 3-D model is constructed over the impact structure, which reveals and allows lateral density variations and refines the previously obtained results from the pre-drilling 2.5-D model of Danuor (2004) and Danuor et al. (2007). We were able to generate a sediment thickness grid for the crater, which can be used later for the computation of the actual contribution of the sediments to the gravity signal, or a depth to basement map. Lateral density variations inside and outside of the central uplift are supported by a previous velocity-depth model, petrophysical data, and by this new 3-D model of the structure.

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APPENDIX

Equations used to process the gravity data:

$$\Delta B_R = 2\pi G \rho_c h \qquad \text{(A1)}$$

$$\Delta B_W = 2\pi G(\rho_c - \rho_w) d_w \qquad \text{(A2)}$$

$$BA = g_0 - g_t + \frac{dg}{dz}h - (\Delta B_R - \Delta B_W) \qquad \text{(A3)}$$

$$= FA - (\Delta B_R - \Delta B_W) \qquad \text{(A4)}$$

where:

g_o = observed gravity (Gal; 1 Gal = 1 cm s^{-2})
g_t = theoretical gravity at the surface of the reference ellipsoid (Gal)
$\frac{dg}{dz}$ = 0.3086×10^{-5} Gal/cm (average vertical gravity gradient per centimeter of elevation above sea level)
G = $6.672 \times 10^{-8} cm^3 g^{-1} s^{-2}$
h = station elevation (in meters) above mean sea level
d_w = depth (in meters) below surface observation (bathymetry)
ρ_c = 2.6 g cm^{-3} (density of basement)
ρ_w = 1.0 g cm^{-3} (density of fresh water)