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The Lake Bosumtwi meteorite impact structure, Ghana— A magnetic image from a third observational level

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Abstract–The Bosumtwi impact structure in Ghana is the youngest and best-preserved medium-sized impact structure on Earth, and because of the vast amount of prior geophysical and geological data gathered in the area, it constitutes a great natural laboratory to try to develop new geophysical interpretation and modeling techniques.

During the 2004 International Continental Scientific Drilling Program (ICDP) drilling campaign at Lake Bosumtwi, we made magnetic field observations at 162 stations around the lake. This study differs from all previous magnetic surveys at Bosumtwi, which only measured the scalar portion of the Earth's magnetic field, in that we measured the full magnetic vector at each station. Acquisition of the full magnetic vector was made possible by innovative use of a borehole deviation probe, which uses a magnetic sensor for absolute orientation reference. Estimates of the magnetic vector orientation and magnitude at each observation station were derived from a series of measurements collected at 50 cm spacing over a depth range of 25 m.

In this study, we report a comparison between the scalar total field intensity derived from this new survey approach with the other two previously acquired marine and airborne magnetic data sets. The scalar total magnetic intensity (TMI) computed from the vector data set compares in close agreement with the other two data sets. Some discrepancies between the data sets can be explained by differences in the distances between the sensor and the magnetic sources for the various surveys. The highlight of this study is that we demonstrate that is possible to acquire at least partial vector data with readily available instrumentation.

INTRODUCTION

Geophysical studies are essential in the identification and study of impact structures (Pilkington and Grieve 1992). A number of crater structures have been identified based on the discovery of geophysical anomalies. This is especially true for craters that are deeply eroded or covered by postimpact sediments, and therefore do not have a direct surface expression.

The Bosumtwi impact structure in Ghana is the youngest and best-preserved medium-sized impact structure on Earth, and because of the vast amount of geophysical and geological data gathered before and during the International Continental Scientific Drilling Program (ICDP) drilling campaign in 2004 (Koeberl et al. 2006; Milkereit et al. 2006), it constitutes a great natural laboratory to try to develop new techniques.

Measurements of the Earth's magnetic field are among the most common geophysical mapping techniques (Nabighian and Asten 2002). In planetary exploration, magnetic measurements have proven to be important for the study of the crustal evolution of the Moon (Hood et al. 2003), and the definition of the magnetic mineralogy and the extent of shock effects on Mars (Dunlop and Arkani-Hamed 2005; Mohit and Arkani-Hamed 2004). However, interpretation of magnetic data in areas of low magnetic latitudes, or where remanent magnetization dominates over the induced field, is not straightforward. Most modern magnetic surveys only record the scalar magnitude of the Earth's magnetic field. The vector orientation of the magnetic field is not detectable with the sensors currently used in most airborne or marine magnetic platforms. The present contribution gives the details of the acquisition, processing, and preliminary interpretation of a 3-D vector magnetic data set collected in the lake during

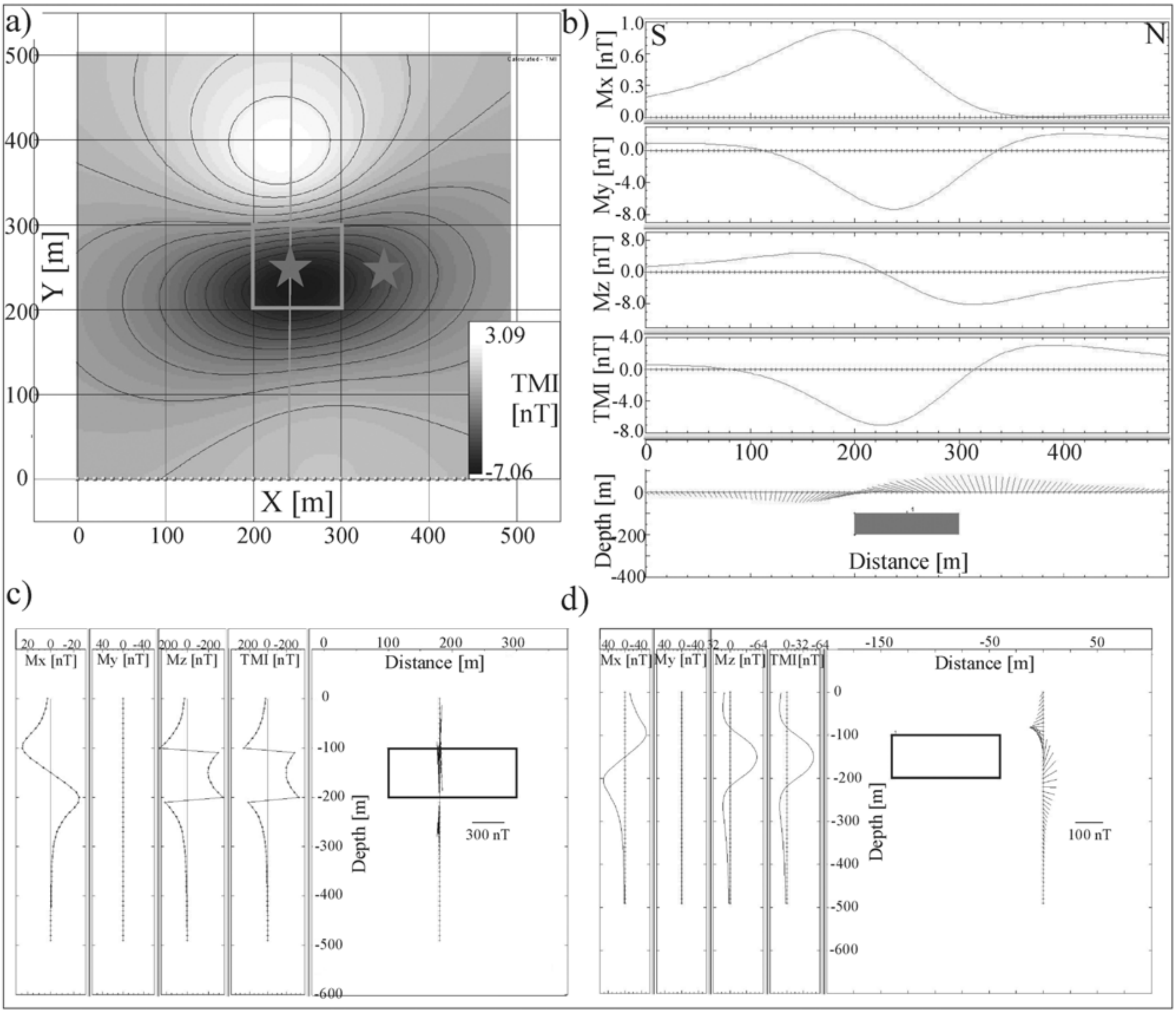

Fig. 1. Surface and borehole magnetic field responses of a magnetized prism of 100 × 100 × 100 m. Top of the body at 100 m below observation surface (Z = 0). Modeling parameters: k = 0.01 SI. Inducing field: Int = 32500 nT; Inc = –10°; Dec = –5°. No remanence was considered. a) Total magnetic intensity (TMI) observed at Z = 0. The outline of the body is marked in gray. The stars mark the location of the borehole responses in (c) and (d). b) NS magnetic profile along the line marked in (a), through the center of the body (X = 240). The three components of the magnetic field are shown for reference (Mx, My, Mz). $TMI = \sqrt{Mx^2 + My^2 + Mz^2}$. c) Borehole magnetic response through the center of the body (X = 240). d) Borehole magnetic response at the side of the body (X = 340). See text for details.

the drilling campaign (Ugalde et al. 2006). The veracity of this information is assessed through a comparison of the scalar magnetic signal from three independent surveys.

LOCATION AND OVERVIEW OF PREVIOUS GEOPHYSICAL SURVEYS

The Bosumtwi impact crater in Ghana is located about 30 km southeast of Kumasi (see Fig. 1 of Ugalde et al. 2007). The crater is occupied by Lake Bosumtwi and has a rim-to-rim diameter of 10.5 km (Koeberl and Reimold 2005). It is the youngest of the medium-sized, well-preserved impact craters on Earth. The lake itself has a diameter of 8 km and a maximum depth of 75 m (Scholz et al. 2002). The crater was formed by a meteorite impact about 1.07 Myr ago when a bolide hit lower greenschist facies supracrustal rocks of the 2.1–2.2 Gyr Birimian Supergroup, which are intruded by various intrusive crystalline rocks (Koeberl et al. 1997; Koeberl and Reimold 2005; Fig. 2 of Ugalde et al. 2007).

Previous geophysical studies date from 1960, when an airborne magnetic study of the structure was made by Hunting Surveys, Ltd. (Jones et al. 1981) with a flight altitude of 300 m and a line spacing of 500 m. Later in 1997, a high-resolution, low-altitude (70 m) airborne geophysical survey across the structure was carried out by the Geological Survey of Finland in cooperation with University of Vienna and Ghana Geological Survey Department (Pesonen et al. 1997; Pesonen et al. 2003). This survey collected total magnetic field, electromagnetic field, and gamma radiation data. In 2001, the Kwame Nkrumah University of Science and Technology (KNUST, Kumasi, Ghana) collected a marine magnetic data set to complement the existing airborne data (Danuor 2004; Ugalde et al. 2007). This new data set had a wider spacing of 800 m, and the magnetometer was towed behind the marine platform used for that purpose. Although it had wider line spacing, this data set had the advantage of measuring the magnetic field closer to the magnetic sources, and because of the slower movement of the platform, the sampling rate was improved as well. The shorter distance to the sources and enhanced sampling rate allows a better representation of the magnetic anomalies, which cannot be achieved by pure downward analytic continuation from the much higher observation surface of the airplane data to the lake level. Interpretation and modeling of these data sets are discussed by Ugalde et al. (2007), and we will therefore concentrate on the new data here.

NEW VECTOR MAGNETIC DATA

Fundamentals of 3-D Vector Magnetics

Magnetic surveys are the most commonly used geophysical technique (Nabighian and Asten 2002). The Earth's magnetic field is a vector quantity having both amplitude and orientation. The orientation of the magnetic vector at any point is a consequence of the interaction between the geometry of the source body and the orientation of the effective magnetic vector. The effective magnetic vector is the vector summation of the induced and remanent magnetic fields. In some locations, for example, over ocean basins, remanent magnetization dominates the magnetic signal. Failure to allow for the presence of magnetic remanence simplifies the magnetic inversion procedures (Li and Oldenburg 2000), but results in models that are geometrically and hence geologically invalid. Existing magnetic surveys record only the amplitude (total magnetic intensity [TMI]) of the magnetic vector, which is a direct consequence of the sensor technology currently employed by most commercial operators: cesium-vapor-based sensors are incapable of detecting the orientation of the magnetic vector (Nabighian and Asten 2002).

Measuring the full magnetic vector presents many advantages, namely: a) differentiation of 2-D and 3-D magnetic source bodies, b) separation of the geometrical aspects of the source body from the geometrical aspects of the effective magnetic field, and c) an estimate of the orientation and magnitude of the remanent magnetic vector (Morris et al. 1995; Mueller et al. 1998). However, little has been published on the application of vector magnetic data as compared to its total magnetic field counterpart (Collar et al. 2005). Early works by Levanto focus on the use of vector magnetics in a borehole situation (Levanto 1959, 1963). More recently, Korenaga (1995) demonstrated how it is possible to use a comparison of vector magnetic components to differentiate between 2-D and 3-D magnetic sources; Lesur et al. (2004) reported initial tests of a marine vector magnetic system capable of estimating the absolute strength and direction of the geomagnetic field.

Borehole vector magnetic measurements can provide constraints on the depth distribution of anomalous source bodies, and differentiate between source body geometry and magnetic field geometry effects (Mueller et al. 1998; Morris et al. 2007). Figure 1 shows the calculated surface and borehole total magnetic fields due to a 100 ×100 × 100 m magnetized prism that extends from 100 to 200 m below the surface. The surface profile shows the usual TMI response that is common on any magnetometric study: a dipolar signature due to the inclination and declination of the effective magnetization vector (induced plus remanence). The bottom panels (c) and (d) show the magnetic response of two synthetic boreholes passing through the body (on-hole) and 50 m far from it (off-hole). Unlike the surface TMI survey, both borehole surveys are able to map the top and bottom of the body through abrupt gradients in the X and Z components of the magnetic field (Mx and Mz, respectively). Furthermore, the more rapid change in polarity on the magnetic field at the interfaces of the body allow to distinguish between on-hole and off-hole anomalies.

Data Collection

The work presented here is based on the use of a commercial borehole deviation or navigation probe. Borehole deviation probes commonly comprise three orthogonal accelerometers and three orthogonal fluxgate magnetometers. The three accelerometers provide an estimate of the dip of the probe relative to the local horizontal surface, and the direction of the dip relative to some internal reference point within the probe. Fluxgate magnetometers are directionally sensitive: they measure only the magnetic field in the direction of the orientation of the individual sensor. Three orthogonally oriented fluxgates therefore provide a measure of the amplitude and orientation of the full magnetic vector relative to the internal reference frame within the probe (Morris et al. 1995). For its common use in borehole navigation, the orientation information provided by the magnetic sensor is used to provide an absolute reference frame for the relative dip direction information provided by the accelerometers. The fundamental assumption is of course that the orientation of the magnetic vector is constant over the area of the survey. It is the failure of this assumption that permits us to derive full vector magnetic data.

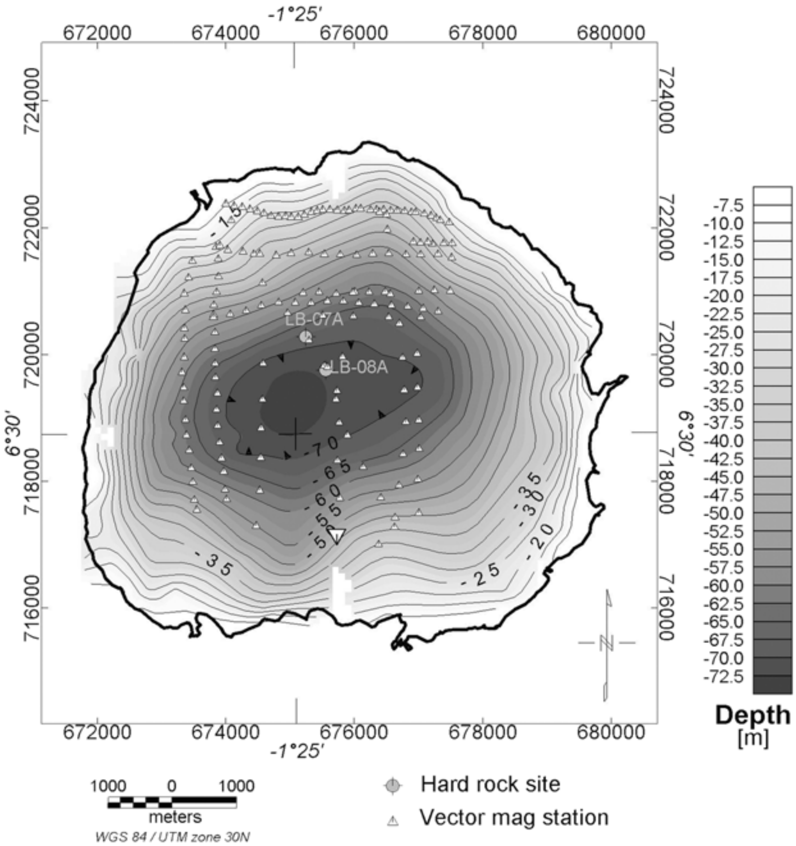

Fig. 2. The locations of the 3-D vector magnetic stations (triangles). The map is colored with the lake bathymetry. The two ICDP deep boreholes LB-07A and LB-08A are shown for reference. Station 411 (Fig. 3) is marked with a larger inverted triangle.

During the 2004 ICDP drilling campaign at Lake Bosumtwi, we collected 162 3-D vector magnetic stations at the lake (Ugalde et al. 2006). At each of the stations, the borehole deviation probe was lowered into the lake from a boat while continuously recording three components of the Earth's magnetic field and three accelerometer readings. Separate data files were collected for the downward- and upward-moving probe. As a result, data was collected at 50 cm spacing over a depth range of 25 m. Figure 2 shows the location of the stations across the lake. Spacing between stations varies from 100–125 m on the northern edge of the lake to 500–600 m along the north-south traverses on the east side. A finer sampling was chosen on the north edge in order to have a better control on the northern-positive part of the main magnetic anomaly (Plado et al. 2000; Ugalde et al. 2007).

Data Processing

At each observation point in the log, the borehole probe provided measurements of the three orthogonal components of the Earth's magnetic field, and three orthogonal axes of acceleration. With this type of multisensor configuration, it is necessary to apply a number of cross-sensor calibration corrections. It is imperative that each sensor give the same response when excited by the same signal. This is achieved by adjusting the gain and offset of co-planar sensors such that any rotation about an axis orthogonal to the common plane produces no change in the amplitude of the vector sum of the two sensors. The orientation of the magnetic vector is computed assuming that the three measurement axes are mutually orthogonal. Testing indicated that there was no significant orthogonality error with this probe.

The three magnetic field components provided a measure of the amplitude and orientation of the Earth's magnetic field relative to the orientation of the probe. Corrections for varying tilt of the probe were computed by applying a rotation correction. All of the data files were collected from a boat. One of the two boats used in this study (the RV Kilindi) had a strong magnetic signature. All the down and up data files collected from the Kilindi exhibited a well-defined change in magnetic inclination with increasing distance from the boat. The signal was pointing to the magnetic source just as we would wish; however, in this case, the magnetic source was the boat. To eliminate this effect, we deleted all data collected within 7.5 m of the surface. The amplitude and orientation of the magnetic vector at each observation point was computed from a vector average of at least 50 individual observations of

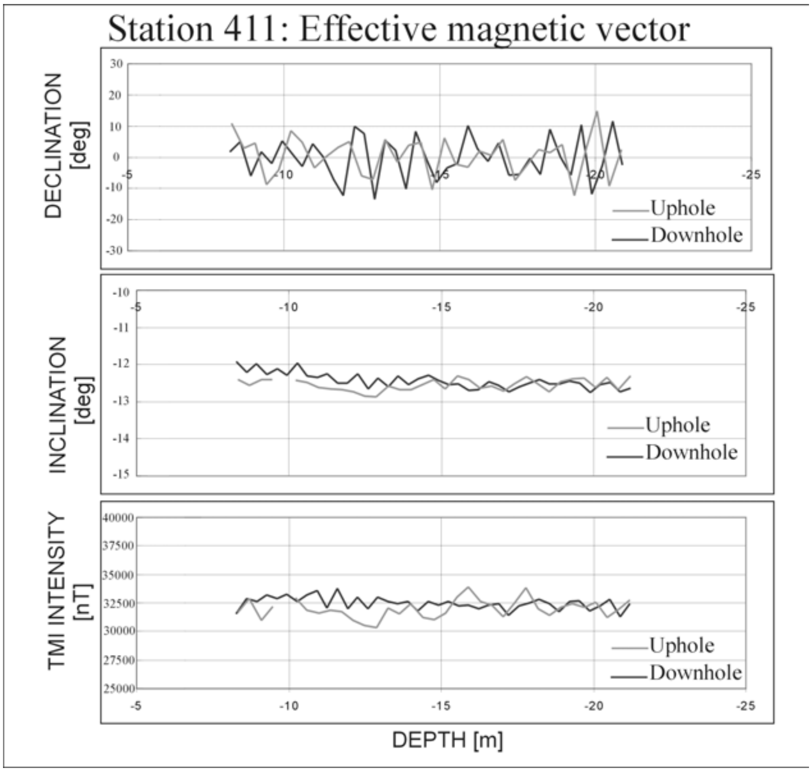

Fig. 3. Measured and upward magnetic data for station 411. Top: inclination; middle: declination; bottom: amplitude. Note the high internal repeatability of the inclination and intensity data. The declination data shows larger variation associated with poor probe orientation control. The magnetic effect of the Kilindi boat is apparent in the first few meters of the survey.

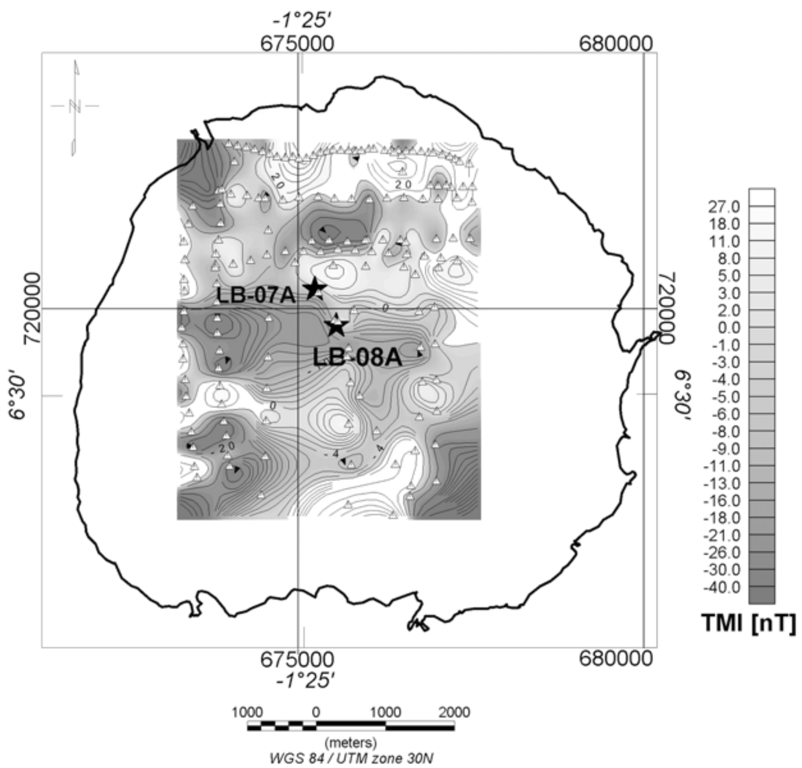

Fig. 4. Total magnetic intensity, as computed from the vector data set. Station locations are marked in blue crosses. The location of the two deep ICDP boreholes is given for reference. Contour interval is 2 nT.

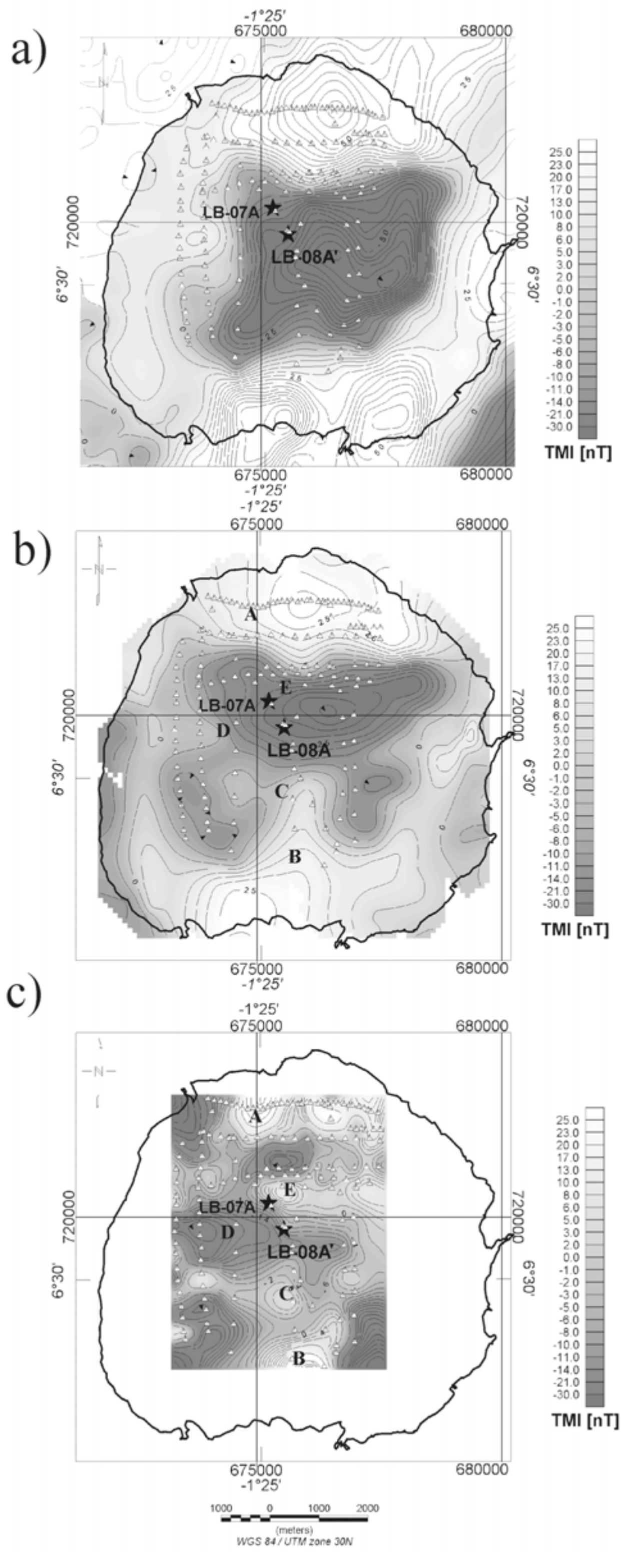

Fig. 5. A comparison of all the total magnetic field data sets available at Lake Bosumtwi. a) The airborne magnetic data set, flown by the Geologic Survey of Finland at 70 m above the lake level. The lake outline is shown in black and the vector magnetic stations are marked as white triangles for reference. b) The marine magnetic data set, collected by KNUST in 2001. Upward continued to 70 m above the lake. Contour interval is 5 nT. The vector magnetic stations and the ICDP deep boreholes are marked for reference as white triangles and black stars, respectively. c) The total field computed from the vector magnetic stations, upward continued to 70 m above the lake level. The stations are marked as white triangles and the ICDP deep boreholes as black stars. A–E are anomalies discussed in the text. For consistency, the color scheme and scale are the same in all the maps.

the Earth's magnetic field. Any short period magnetic fluctuations would be eliminated by this station mean calculation. No attempt was made to make any corrections for day-to-day changes in the Earth's magnetic field amplitude. The residual magnetic field for each observation point is simply the vector difference between the value at each station and the vector average of all 162 stations. This computation removes any undesired long-wavelengths such as the diurnal variation. The amplitude of the resultant magnetic vector is directly equivalent to the scalar magnetic field that is measured by standard TMI instruments. The computed residual vector does not represent the true vector changes over the study area. In order to achieve correct full vector information it would be necessary to know the orientation of the probe in absolute geographical coordinates at each station prior to the survey.

RESULTS AND DISCUSSIONS

Figure 3 shows an example of one magnetic log at station 411, over the positive anomaly at B in Fig. 5. This figure shows the change in computed magnetic vector versus depth. The intensity and magnetic inclination data are very repeatable. The magnetic declination appears to be much noisier, as a direct consequence of two factors. First, in this study, the accuracy of the declination measurement provided by the accelerometers is very poor because the amplitude of the X and Y accelerometers have less than 5% of the total signal: the probe was nearly vertical. Second, fluctuations in the sense of dip of the probe create large apparent changes in the orientation of the magnetic vector. Both of these problems could be overcome with improved survey design.

The main result extracted from the processing of all the stations is the scalar total field intensity (Fig. 4), which can be compared with the other two similar data sets available (airborne and marine) (Pesonen et al. 2003; Danuor 2004). In order to do that and since the three data sets were collected at different distances to the magnetic sources, they first must be brought to a similar elevation. An upward continuation was applied to the both the marine data set (from the lake level to 70 m above it), and to the scalar total field computed here (from −25 to 70 m above the lake level), to match the airborne data set elevation of 70 m above the lake. The upward continuation is regularly applied in the Fourier domain as a filter that enhances long wavelengths and diminishes the (shallow) short wavelength content of the signal (Blakely 1996).

Figure 5 shows the airborne magnetic data set compared with upward continued versions of the marine and scalar ones. As expected, both the airborne and marine data set share strikingly similar features. This is because the analytic continuation removes all the higher-frequency content of the marine magnetic data related to its closer distance to the magnetic sources and its finer sampling rate along the lines. The long-wavelengths are related to deeper magnetic sources and therefore are common to both data sets. The scalar TMI computed from the vector data set closely compares with the other two data sets. The main features are the positive anomalies at the north (A, B, and C in Fig. 5), and the negative anomaly at the west (D in Fig. 5). The positive anomalies within the main negative at the center (E in Fig. 5) are related to the closer distance of the sensor to the magnetic sources and the finer sampling rate (50 cm down the vertical) of the vector data set.

CONCLUSIONS

In this study we have demonstrated a new approach to magnetic data acquisition that could potentially lead to the full vector magnetic surveys. It is apparent that full vector magnetic data has many powerful unexplored advantages, such as the analysis of the vector orientations and 3-D mapping of magnetic sources. The scalar magnetic data derived from the vector data produces a TMI image that is very similar to those acquired using conventional marine and airborne survey techniques. These multiple data sets indicate that proximity between the source and the sensor can have a significant effect on the resulting TMI. Acquiring data using a standard airborne sensor can lead to significant loss of detail.

Further processing of the 3-D magnetic vectors should allow the refinement of the 3-D model presented by Ugalde et al. (2007).

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REFERENCES

Blakely R. J. 1996. *Potential theory in gravity and magnetic applications*. Cambridge: Cambridge University Press. 461 p.

Collar F., Fenning P., and Mora C. 2005. Application of drillhole vector magnetic measurements to resolve the position of existing underground structures. *NDT&E International* 38:231–236.

Danuor S. K. 2004. Geophysical investigations of the Bosumtwi impact crater and comparison with terrestrial meteorite craters of similar age and size. Ph.D. thesis, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

Dunlop D. J. and Arkani-Hamed J. 2005. Magnetic minerals in the Martian crust. *Journal of Geophysical Research* 110:1–26.

Hood L. L., Richmond N. C., Pierazzo E., and Rochette P. 2003. Distribution of crustal magnetic fields on Mars: Shock effects of basin-forming impacts. *Geophysical Research Letters* 30, doi: 10.1029/2002GL016657.

Jones W. B., Bacon M., and Hastings D. A. 1981. The Lake Bosumtwi impact crater, Ghana. *Geological Society of America Bulletin* 92:342–349.

Koeberl C., Bottomley R., Glass B. P., and Storzer D. 1997. Geochemistry and age of Ivory Coast tektites and microtektites. *Geochimica et Cosmochimica Acta* 61:1745–1772.

Koeberl C., Milkereit B., Overpeck J. T., Scholz C. A., Reimold W. U., Amoako P. Y. O., Boamah D., Claeys P., Danuor S. K., Deutsch A., Hecky R. E., King J., Newsom H., Peck J., and Schmitt D. 2006. An international and multidisciplinary drilling project into a young complex impact structure: The 2004 ICDP Bosumtwi impact crater, Ghana drilling project—An overview (abstract #1859). 37th Lunar and Planetary Science Conference. CD-ROM.

Koeberl C. and Reimold W. U. 2005. Bosumtwi impact crater, Ghana (West Africa): An updated and revised geological map, with explanations. *Jahrbuch der Geologischen Bundesanstalt, Wien (Yearbook of the Austrian Geological Survey)* 145:31–70 (+1 map, 1:50,000).

Korenaga J. 1995. Comprehensive analysis of marine magnetic vector anomalies. *Journal of Geophysical Research* 100:365–378.

Lesur V., Clark T., Turbitt C., and Flower S. 2004. A technique for estimating the absolute vector geomagnetic field from a marine vessel. *Journal of Geophysics and Engineering* 1:109–115.

Levanto A. E. 1959. A three component magnetometer for small drillholes and its use in ore prospecting. *Geophysical Prospecting* 7:183–193.

Levanto A. E. 1963. On magnetic measurements on drillholes. *Geoexploration* 2:8–20.

Li Y. and Oldenburg D. W. 2000. Joint inversion of surface and three-component borehole magnetic data. *Geophysics* 65:540–552.

Milkereit B., Ugalde H., Karp T., Scholz C. A., Schmitt D., Danuor S. K., Artemieva N., Kuek J., Qian W., and L'Heureux E. 2006. Exploring the Lake Bosumtwi crater—Geophysical surveys, predictions, and drilling results (abstract #1687). 37th Lunar and Planetary Science Conference. CD-ROM.

Mohit P. S. and Arkani-Hamed J. 2004. Impact demagnetization on Martian crust. *Icarus* 168:305–317.

Morris W. A., Mueller E. L., and Parker C. E. 1995. Borehole magnetics: Navigation, vector components, and magnetostratigraphy. Proceedings, 65th Annual International Meeting, Society of Exploration Geophysicists. pp. 495–498.

Morris W. A., Ugalde H., and Clark C. 2007. Physical property measurements: ICDP boreholes LB-07A and LB-08A, Lake Bosumtwi impact structure, Ghana. *Meteoritics & Planetary Science* 42. This issue.

Mueller E. L., Morris W. A., Killeen P. G., and Balch S. 1997. Combined 3-D interpretation of airborne, surface, and borehole vector magnetics at the McConell nickel deposit. Proceedings, Exploration 97: Fourth Decennial International Conference on Mineral Exploration. pp. 657–666.

Mueller E. L., Morris W. A., Killeen P. G., and Balch S. 1998. Combined 3-D interpretation of airborne, surface, and borehole vector magnetics at the McConnell nickel deposit. *Journal of Environmental & Engineering Geophysics* 3:203–214.

Nabighian M. and Asten M. 2002. Metalliferous mining geophysics—State of the art in the last decade of the 20th century and the beginning of the new millenium. *Geophysics* 67:964–978.

Pesonen L. J., Koeberl C., Reimold W. U., and Brandt D. 1997. New studies of the Bosumtwi impact structure, Ghana: The 1997 field season (abstract). *Meteoritics & Planetary Science* 32:A72–73.

Pesonen L. J., Koeberl C., and Hautaniemi H. 2003. Airborne geophysical survey of the Lake Bosumtwi impact structure (southern Ghana)—Geophysical maps with descriptions. *Jahrbuch der Geologischen Bundesanstalt, Vienna (Yearbook of the Austrian Geological Survey)* 143:581–604.

Plado J., Pesonen L. J., Koeberl C., and Elo S. 2000. The Bosumtwi meteorite impact structure, Ghana: A magnetic model. *Meteoritics & Planetary Science* 35:723–732.

Scholz C. A., Karp T., Brooks K. M., Milkereit B., Amoako P. Y. O. and Arko J. A. 2002. Pronounced central uplift identified in the Bosumtwi impact structure, Ghana, using multichannel seismic reflection data. *Geology* 30:939–942.

Ugalde H., Morris W. A., and Danuor S. K. 2006. 3-D vector magnetics at Lake Bosumtwi: Experiment and results (abstract #1064). 37th Lunar and Planetary Science Conference. CD-ROM.

Ugalde H., Morris W. A., Pesonen L. J., and Danuor S. K. 2007. The Lake Bosumtwi meteorite impact structure, Ghana—Where is the magnetic source? *Meteoritics & Planetary Science* 42. This issue.