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An international and multidisciplinary drilling project into a young complex impact structure: The 2004 ICDP Bosumtwi Crater Drilling Project—An overview

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Abstract–The Bosumtwi impact crater in Ghana, arguably the best-preserved complex young impact structure known on Earth, displays a pronounced rim and is almost completely filled by Lake Bosumtwi, a hydrologically closed basin. It is the source crater of the Ivory Coast tektites. The structure was excavated in 2.1–2.2 Gyr old metasediments and metavolcanics of the Birimian Supergroup. A drilling project was conceived that would combine two major scientific interests in this crater: 1) to obtain a complete paleoenvironmental record from the time of crater formation about one million years ago, at a near-equatorial location in Africa for which very few data are available so far, and 2) to obtain a complete record of impactites at the central uplift and in the crater moat, for ground truthing and comparison with other structures.

Within the framework of an international and multidisciplinary drilling project led by the International Continental Scientific Drilling Program (ICDP), 16 drill cores were obtained from June to October 2004 at six locations within Lake Bosumtwi, which is 8.5 km in diameter. The 14 sediment cores are currently being investigated for paleoenvironmental indicators. The two impactite cores LB-07A and LB-08A were drilled into the deepest section of the annular moat (540 m) and the flank of the central uplift (450 m), respectively. They are the main subject of this special issue of *Meteoritics & Planetary Science*, which represents the first detailed presentations of results from the deep drilling into the Bosumtwi impactite sequence. Drilling progressed in both cases through the impact breccia layer into fractured bedrock. LB-07A comprises lithic (in the uppermost part) and suevitic impact breccias with appreciable amounts of impact melt fragments. The lithic clast content is dominated by graywacke, besides various metapelites, quartzite, and a carbonate target component. Shock deformation in the form of quartz grains with planar microdeformations is abundant. First chemical results indicate a number of suevite samples that are strongly enriched in siderophile elements and Mg, but the presence of a definite meteoritic component in these samples cannot be confirmed due to high indigenous values. Core LB-08A comprises suevitic breccia in the uppermost part, followed with depth by a thick sequence of graywacke-dominated metasediment with suevite and a few granitoid dike intercalations. It is assumed that the metasediment package represents bedrock intersected in the flank of the central uplift. Both 7A and 8A suevite intersections differ from suevites outside of the northern crater rim.

Deep drilling results confirmed the gross structure of the crater as imaged by the pre-drilling seismic surveys. Borehole geophysical studies conducted in the two boreholes confirmed the low seismic velocities for the post-impact sediments (less than 1800 m/s) and the impactites (2600–3300 m/s). The impactites exhibit very high porosities (up to 30 vol%), which has important implications for mechanical rock stability. The statistical analysis of the velocities and densities reveals a seismically transparent impactite sequence (free of prominent internal reflections). Petrophysical core analyses provide no support for the presence of a homogeneous magnetic unit (= melt breccia) within the center of the structure. Borehole vector magnetic data point to a patchy distribution of highly magnetic rocks within the impactite sequence.

The lack of a coherent melt sheet, or indeed of any significant amounts of melt rock in the crater fill, is in contrast to expectations from modeling and pre-drilling geophysics, and presents an interesting problem for comparative studies and requires re-evaluation of existing data from other terrestrial impact craters, as well as modeling parameters.

INTRODUCTION

Bosumtwi is the largest young impact structure currently known on Earth and is associated with one of only four known tektite strewn fields. The structure has an age of 1.07 Myr (e.g., Koeberl et al. 1997a) and a rim-to-rim diameter of about 10.5 (±0.5) km. Bosumtwi is centered at 06°30′N and 01°25′W in the Ashanti region of Ghana, West Africa, about 32 km from Kumasi, the regional capital, where the crater represents a regional tourist attraction (e.g., Boamah and Koeberl 2007). Figure 1 shows the location of the crater in relation to the Ivory Coast tektite strewn field. This tektite strewn field extends beyond occurrences on land, as microtektites have been found in deep-sea cores off the coast of West Africa (Glass 1968, 1969) and were related to the tektites found on land. The similar age, as well as chemical and isotopic data (see, e.g., Koeberl et al. 1997a, 1998) and the magnetostratigraphic age of the microtektites (e.g., Glass et al. 1991), all indicate that the Ivory Coast tektites were generated in the Bosumtwi impact event.

The well-preserved complex impact structure displays a pronounced rim and is almost completely filled by Lake Bosumtwi, which is 8 to 8.5 km in diameter (Figs. 2 and 3). The crater is excavated in 2 Gyr old metamorphosed and crystalline rocks of the Birimian Supergroup. The crater is surrounded by a slight, near-circular depression and an outer ring of minor topographic highs (Fig. 3) with a diameter of about 20 km (Jones et al. 1981; Garvin and Schnetzler 1994; Reimold et al. 1998; Wagner et al. 2002).

The existence of the crater and its lake has been discussed in European literature since the late nineteenth century. Historical information, mainly regarding the importance of the lake for the Ashanti people, is given by, e.g., Rattray (1923). The origin of the lake and crater was debated early on. For example, Fergusson (1902) proposed that the crater was not of volcanic origin, Kitson (1916) interpreted it as a subsidence feature, and Maclaren (1931) seems to have been the first to suggest the crater was of impact origin, whereas Rohleder (1936) preferred an explosive (endogenic) explanation. Only in the 1960s was evidence for an impact origin found, in the form of high-temperature minerals (such as baddeleyite), high-pressure phases (such as coesite), and possible meteoritic remnants (Fe-Ni rich spherules in impact glass). The presence of a meteoritic component in both Ivory Coast tektites and Bosumtwi impact glasses was confirmed by Os isotopic studies by Koeberl and Shirey (1993), and planar deformation features in quartz from suevitic breccias were described by Koeberl et al. (1998). Investigations of the structural geology along the crater rim were done by Reimold et al. (1998). Detailed aerogeophysical studies were conducted at about the same time (e.g., Pesonen et al. 1998, 2003).

The paleoclimatic significance of Lake Bosumtwi was recognized early, and in the 1970s M. Talbot and D. Livingstone began the first detailed paleoenvironmental studies using a suite of short sediment cores (up to 16.9 m in length). With a variety of analytical methods (e.g., stratigraphy, sedimentology, geochemistry, and palynology) they documented a complex record of changes in lake level, lake chemistry, climate, and vegetation history stretching back 27,500 years (e.g., Talbot and Delibrias 1977; Hall et al. 1978; Talbot and Kelts 1986). These records indicated that the then held concept of tropical climate and vegetation stability was outdated (e.g., Talbot et al. 1984). A widely used result of this work is the often-cited Bosumtwi record of lake level fluctuations spanning the last 13,500 years (Talbot and Delibrias 1980; Talbot et al. 1984). This pioneering work, including the suspicion that the lake sediment record might be varved for most of the 1 Myr record since crater formation, led to renewed interest in Bosumtwi during the mid- to late 1990s, at about the same time as the structure gained new importance in impact crater studies.

This renewed interest from different disciplines (impact studies, geophysics, paleoenvironmental studies) led, around the year 2000, to the conception of a deep drilling program at Bosumtwi. Besides providing crucial paleoclimatic data, understanding the subsurface crater structure is important to understand the relation between various crater rocks, breccias, and melts, and for providing constraints for geophysical studies. In this paper we present an overview of the Bosumtwi impact structure and its geology, its importance for impact and paleoclimatic research, a summary of the drilling program, and a brief review of the most important findings, mainly in terms of impact and geophysical studies. In addition, this paper serves as the introduction to this issue of *Meteoritics & Planetary Science*, which contains 26 other papers with results on various aspects of Bosumtwi and the drilling project.

BRIEF SUMMARY OF THE GEOLOGY OF BOSUMTWI

The first detailed geological studies of the region around Lake Bosumtwi were begun in the 1930s (Junner 1937) and later in the 1960s (e.g., Woodfield 1966; Moon and Mason 1967), whereas Jones et al. (1981) reported the first geophysical data from the crater region. More recent geological studies were carried out along a section across the western crater rim and on exposures around the northern and northeastern parts of the crater (Reimold et al. 1998). The region around Bosumtwi is largely covered by dense, tropical rainforest and woodland. Thus, only studies of rare exposures along streams and road cuts are possible. Figure 4 gives a schematic view of the general geology around the Bosumtwi structure, based on the new map by Koeberl and Reimold (2005). In terms of rim structure, the upper and outer parts of the crater rim typically exhibit steeply inward-dipping or overturned bedding, which has been displaced by inward-dipping thrust planes. Radial fracturing is superimposed on these structures. The upper rim section comprises mega-breccia, with block sizes decreasing radially outwards. More complex, thrust-related, features (duplex thrusts forming lenses of faulted rock with generally inward-dipping bedding) characterize the inner crater rim. More details on these structural aspects are given by Reimold et al. (1998).

The Bosumtwi impact crater was excavated in lower greenschist facies metasediments of the 2.1–2.2 Gyr Birimian Supergroup (cf. Wright et al. 1985; Leube et al. 1990). The Birimian Supergroup has traditionally been subdivided into the Lower Birimian, dominated by metasediments, and the Upper Birimian, dominated by greenstone-type metavolcanics (e.g., Junner 1937). However, more recent studies (e.g., Leube et al. 1990; Hirdes et al. 1996) have shown that the two units were formed roughly contemporaneously. On the basis of Sm/Nd age data, Taylor et al. (1992) deduced an isochron age of Birimian supracrustal rocks of 2.0–2.3 Gyr, whereas Feybesse et al. (2006) placed somewhat tighter constraints on the age of these rocks, around 2.10–2.15 Gyr. These supracrustal rocks are composed of interbedded phyllites and meta-tuffs together with meta-graywackes, quartzitic graywackes, shales, and slates. Birimian metavolcanic rocks (altered basic intrusives with some intercalated metasediments) extend toward the southeast of the crater. Rocks in these parts contain altered basic intrusives (Birimian metavolcanics) in addition to metasediments. Further to the east and southeast occur clastic Tarkwaian sediments, which are thought to have formed by erosion of Birimian rocks (e.g., Leube et al. 1990).

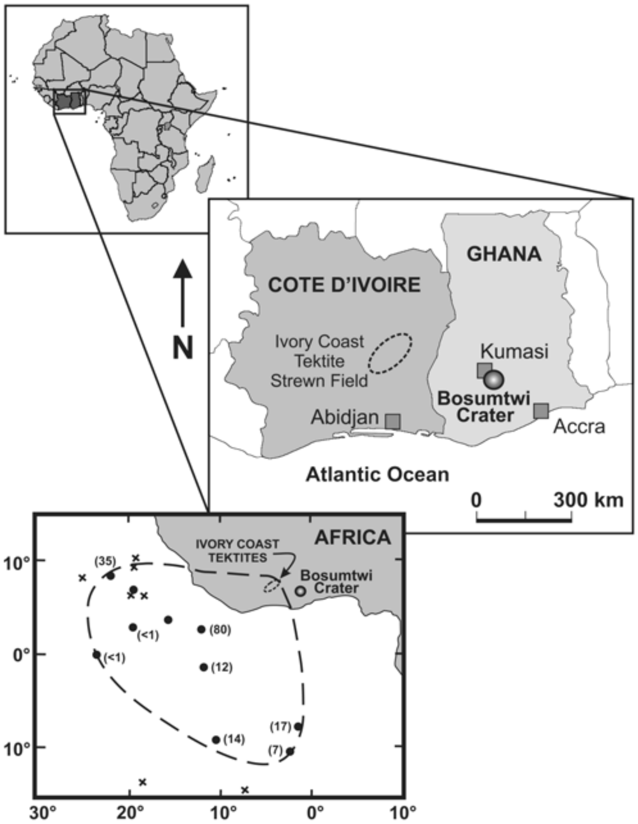

Fig. 1. A location map of the Bosumtwi crater in Ghana, and the relation of the crater to the tektite strewn field in the neighboring country of Ivory Coast, and to the offshore microtektite strewn field, indicating locations of deep-sea cores in which Ivory Coast microtektites were found (both together comprising the Ivory Coast tektite strewn field). For the latter, full circles indicate locations with microtektites, whereas X marks locations where no microtektites were found. The numbers indicate the integrated numbers of microtektites per cm^2 (from Glass et al. 1991).

Several Proterozoic granitic intrusions are found in the structure, and some strongly weathered granitic dikes occur in the crater rim (e.g., Reimold et al. 1998). These aplitic granitoid dikes have granophyric texture (Reimold et al.

Fig. 2. An aerial photograph of Lake Bosumtwi from the southeast, taken in September 2004, showing the distinct crater rim. Photo: C. Koeberl.

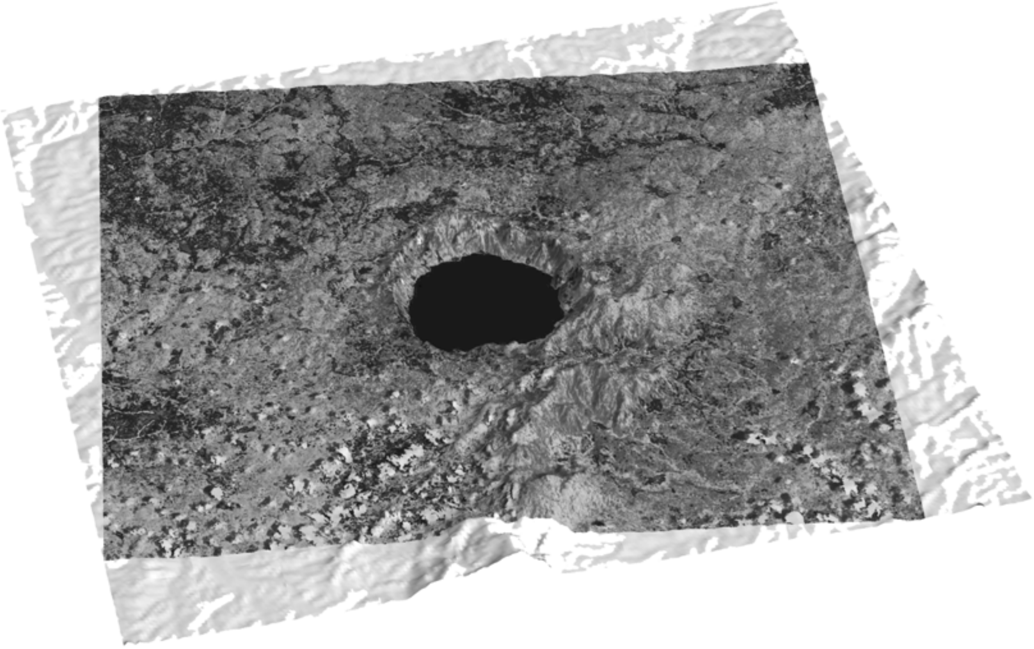

Fig. 3. A combined Aster satellite image (band combination 7, 3, and 1, contrast-enhanced) overlaid with a projection of gray-shaded Shuttle Radar Topography Mission (SRTM) data of the Bosumtwi area (north is toward the upper left), showing the crater rim, the elevation of the Obuom Range (front right), and the faint outer ring feature, enhanced by the form of the concentric drainage pattern.

1998). The granitic complexes and dikes probably mainly belong to the Kumasi-type granitoid intrusions, for which an age of 2.0–2.2 Gyr was obtained (Taylor et al. 1992; Hirdes et al. 1992; Feybesse et al. 2006). On the northeast side of the crater, there are also limited outcrops of an intrusion called “Pepiakese granite,” comprising a variety of rock types ranging from hornblende- to biotite-muscovite granite (Jones 1985) and diorite (Koeberl et al. 1998). In addition, a few dikes of dolerite, amphibolite, and intermediate rocks (minor intrusives) occur around the crater (e.g., Koeberl and Reimold 2005). In the immediate environs of the crater, meta-graywacke and sandstone/quartzitic rocks dominate, but especially in the northeastern and southern sectors, shale and mica schist are also present (e.g., Reimold et al. 1998). Quartz veins and stringers up to 20 cm wide cut through all the rock formations in the area; pod-like occurrences of quartz pegmatite also occur. In addition to information in Koeberl et al. (1998) and Koeberl and Reimold (2005),

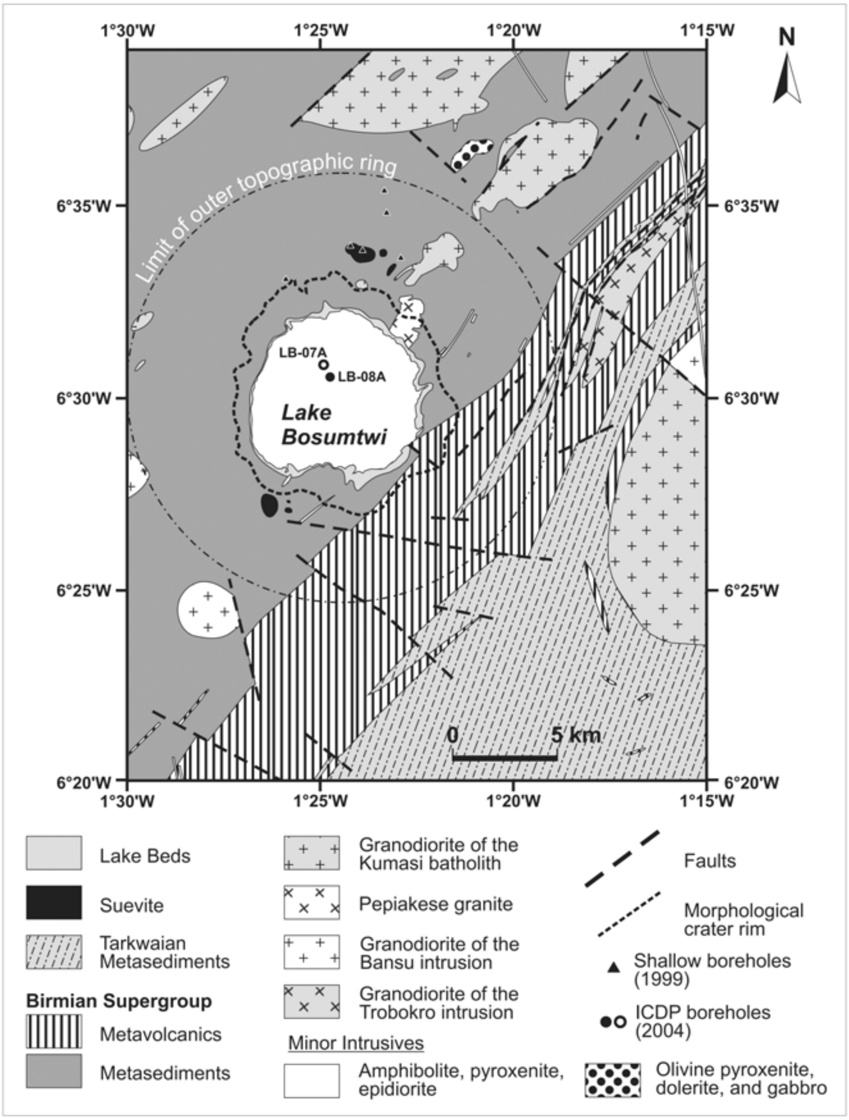

Fig. 4. A schematic geological map of the Bosumtwi impact structure and its immediate environs, after Koeberl and Reimold (2005).

petrographic and geochemical details of the country rocks at Bosumtwi are given by Karikari et al. (2007).

Recent rock formations in the Bosumtwi area include the Bosumtwi lake beds, as well as soils and breccias associated with the formation of the crater (Junner 1937; Kolbe et al. 1967; Woodfield 1966; Moon and Mason 1967; Jones et al. 1981; Jones 1985; and Reimold et al. 1998). The breccias at Bosumtwi can be grouped into three types, based on composition and texture. These are the apparent monomict breccia (autochthonous?), lithic breccia or polymict breccia (allochthonous?), and breccia with melt and glass fragments (suevite) (see, e.g., Boamah and Koeberl 2002, 2003, 2006; Koeberl and Reimold 2005). Monomict breccias often grade into unbrecciated rock. The rocks are shattered more or less in situ, without much relative displacement. This type is found, e.g., on the road from Nyameani to Asisiriwa, and along the crater wall.

Rarer is the Bosumtwi suevite, a melt/glass-bearing breccia similar to the suevite of the Ries crater in Germany. Suevite occurrences outside the north and southwestern parts of the crater rim were first mentioned by Junner (1937), who referred to the deposit as volcanic tuff and agglomerates. Suevite is defined (Stöffler and Grieve 1994) as polymict impact breccia including cogenetic impact melt particles which are in a glassy or crystallized state, set in a clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism. The Bosumtwi suevite from outside the crater rim is grayish in color, with a lot of glass and melt clasts up to about 40 cm in size.

The suevite contains target rock fragments (e.g., meta-graywacke, phyllite, shale, granite) in all stages of shock metamorphism, including vitreous and devitrified impact glasses. The Bosumtwi suevite occurs as large blocks up to several meters wide and as patchy massive deposits more or less covered by thick vegetation in a marginal zone (about 1.5 km^2) outside the rim of the crater in the north, about 2.5 km from the lakeshore. Shallow drill cores into suevite occurrences (see Boamah and Koeberl 2002, 2003, 2006) were obtained to the north of the crater rim. Meta-graywacke/phyllite rocks and granite from dikes seem to be important contributors to the compositions of the suevite and the road cut samples (fragmentary matrix), with a minor contribution of Pepiakese granite. The thickness of the fallout suevite outside the northern rim of the Bosumtwi crater is 15 m, and this facies occupies an area of about 1.5 km^2 (Boamah and Koeberl 2002, 2003). The present distribution of the suevite is likely a result of differential erosion and does not reflect the initial distribution.

In 1997, a high-resolution aerogeophysical survey was conducted in collaboration between the Geological Surveys of Finland and Ghana and the University of Vienna to obtain more detailed information of the subsurface structure below and beyond the lake (cf. Koeberl et al. 1997b; Pesonen et al. 1998, 2003). From some of these data, Plado et al. (2000) produced a magnetic model for the Bosumtwi structure. The magnetic data show a circumferential magnetic halo outside the crater, at a radial distance from the center of ~6 km. The central-north part of the lake reveals a central negative magnetic anomaly with smaller positive side anomalies to the north and south of the central anomaly, which is typical for magnetized bodies at equatorial latitudes. A few weaker negative magnetic anomalies exist in the eastern and western part of the lake. Plado et al. (2000) also reported petrophysical data on Bosumtwi impactites and country rocks, which show a clear difference between the physical properties of pre-impact target rocks and impactites. Suevites have comparatively higher magnetization and have lower densities and higher porosities than the target rocks. For the suevites, the remanent magnetization dominates over induced magnetization. The shallow, near-circular, very slight depression ~14–17 km in diameter, and an outer ring feature, a few meters higher than the surrounding area, 18–20 km in diameter (Jones et al. 1981; Garvin and Schnetzler 1994; Wagner et al. 2002), are evident not only in radar satellite images (e.g., Figs. 3c–e in Koeberl and Reimold 2005), but also in aeroradiometry data (Pesonen et al. 2003), indicating lithological as well as topographic control. Wagner et al. (2002) suggested that preferential removal of ejecta within the area just outside of the crater rim could be the reason for this shallow depression; original depositional patterns as well as impact-induced concentric fracturing could also be involved.

As noted above, the Bosumtwi crater is also of special interest as the likely source crater for the Ivory Coast tektites, which were first reported in 1934 (Lacroix 1934) from a small area with a radius of about 40 km within the Ivory Coast (Côte d'Ivoire), West Africa (Fig. 1). Later, microtektites were found in deep-sea cores off the coast of West Africa (Glass 1968, 1969) and were interpreted as being related to the tektites found on land. The geographical distribution of microtektite-bearing deep-sea cores was used to determine the extent of the strewn field (Glass and Zwart 1979; Glass et al. 1979, 1991). A variety of arguments supported the conclusion that Bosumtwi was most likely this source crater, including similar chemical compositions (Schnetzler et al. 1967; Jones 1985), similar isotopic characteristics for the tektites and rocks found at the crater (e.g., Schnetzler et al. 1966; Lippolt and Wasserburg 1966; Shaw and Wasserburg 1982), and the similar ages of tektites and Bosumtwi impact glasses (e.g., Gentner et al. 1964, 1967). Koeberl et al. (1998) found that the oxygen isotopic composition of the country rocks (δ^{18}O = 11.3–13.6‰) and those of the tektites (δ^{18}O = 11.7–12.9‰) agree fairly well, and showed that in a ^{87}Sr/^{86}Sr versus 1/Sr plot, as well as in an ε_{Sr} versus ε_{Nd} diagram, the tektites plot within the field defined by the metasedimentary and granitic Bosumtwi country rocks. The available geochemical data (Koeberl et al. 1997a, 1998) support the conclusion that the Ivory Coast tektites formed from the same rocks that are currently exposed at Bosumtwi. Precise fission track and step-heating ^{40}Ar-^{39}Ar dating on both Ivory Coast tektites and Bosumtwi impact glass established a reliable and currently accepted age of 1.07 ± 0.05 Myr for the Bosumtwi impact event (Koeberl et al. 1997a).

IMPORTANCE FOR PALEOENVIRONMENTAL STUDIES

Lake Bosumtwi is a closed-basin lake, with its water balance being dominated by rainfall on the lake surface and direct evaporation, and has a present-day area of 52 km^2 and a maximum depth of 78 m. Groundwater sources are thought to be negligible. A low salinity of the lake water suggests that dissolved material was removed by lake overflow in the relatively recent geologic past. Rainfall at Bosumtwi is lowest in January (average 17.0 mm) and highest in June (average 233.9 mm), and is highly variable from year to year. As a result of its impact origin, Lake Bosumtwi has several important characteristics that make it well suited to provide a record of regional (in this case, tropical) climate change. First, because of the age of the crater (1.07 Myr) and its location in West Africa, the lake sediments can provide a million-year-long record of change in the strength of the North African monsoon. Lake Bosumtwi lies in the path of the seasonal migration of the Intertropical Convergence Zone (ITCZ), the atmospheric boundary between northeasterly continental trade winds and onshore southeasterly trade winds, which is of importance for the development of hurricanes that reach Central and North America. As indicated in Fig. 5, during the summer months the ITCZ migrates to the north of Lake Bosumtwi and moisture-laden winds deliver strong monsoonal precipitation to western Africa. During the northern hemisphere winter the ITCZ is displaced towards the south of Lake Bosumtwi, and dry, aerosol-rich northeasterly continental trade winds from the Sahara and Sahel regions (known as Harmattan) dominate over southern Ghana. Second, the high crater rim surrounding the lake results in a hydrologically closed lake with a water budget extremely sensitive to the precipitation/evapotranspiration balance. Third, the steep crater wall and deep lake basin limit wind-wave mixing of the water column, resulting in the accumulation of anoxic deeper parts of the lake (see below), thereby limiting bioturbation and allowing for the preservation of laminated sediment varves, and thus providing the potential for high resolution (annual) paleoclimate reconstruction.

As noted above, the importance of Lake Bosumtwi for paleoenvironmental research was recognized early, resulting in studies of the Bosumtwi record in terms of lake level, lake chemistry, climate, and vegetation history stretching back 27,500 years (e.g., Talbot and Delibrias 1977; Hall et al. 1978; Talbot and Kelts 1986). Already these early studies showed that the lake level fluctuated significantly during the last 13,500 years (Talbot and Delibrias 1980; Talbot et al. 1984). Subsequently, Talbot and Delibrias (1977) and Talbot and Johannessen (1992) showed that lake-level variations correlate with the amount of rainfall in the Sahel region. Short drill cores showed that sediments in the deep basin of the lake are typically varved and contain sapropels (discrete black or dark-colored sedimentary layers that contain greater than 2 wt% organic carbon). Rapid increases in lake level might trigger episodes of sapropel deposition as a result of the rapid drowning of forests on the inner slopes of the crater rim and introduction of lignin-rich biomass to the deep lake basin (Turner et al. 1996a, 1996b).

Today the highest position where lake sediments occur along the inner crater rim is located about 110 m above the present lake level. The lowest topographic point on the crater rim has an elevation of 210 m, about 110 m above the present lake level, which is the elevation at which the lake will overflow (Turner et al. 1996a, 1996b). Data presented by these authors, as well as by Peck et al. (2004) and Brooks et al. (2005), indicate that the lake level has shown significant fluctuations during the past 20,000 years or so. Peck et al. (2004), from a study of magnetic parameters of minerals in an 11 m long core, spanning 26,000 years of deposition, found abrupt shifts in the magnetic parameters that were interpreted to represent pronounced arid conditions when the summer monsoon was greatly weakened. These authors correlated these arid intervals to the Younger Dryas and Heinrich event 1 and 2, thus showing a coupling between high- and low-latitude climate change.

Brooks et al. (2005), using high-resolution, single-channel seismic-reflection profiles and sedimentological data from a ^{14}C-dated sediment piston core, found four seismic sequence boundaries and an exposure surface from a sediment core, which they interpreted as erosional surfaces formed during lake lowstands. The most recent severe lowstand occurs as much as 31 m below present lake level (bpll), which was interpreted by Brooks et al. (2005) to be coeval with the late-Holocene dry period between 500 to 1000 calendar years before present (cal yr BP). Another apparent exposure surface observed in a sediment core was interpreted to have developed prior to 16.8 cal ky BP when the lake was ~60 m bpll. Three older, erosional surfaces have estimated ages of ~65, ~86, ~108 cal ky BP (Brooks et al. 2005). These lowstands of Lake Bosumtwi are likely a response to increased aridity in this part of the equatorial tropics and may correlate with other observed continent-wide shifts in African climate over the past 100 ky. More recent fluctuations in lake level have also been documented (e.g., Talbot and Delibrias 1977; Russell et al. 2003; Shanahan et al. 2005, 2006). In particular, the fossil grass epidermal record in the lake sediments shows a distinct response to seasonal changes in terms of the difference between moist and dry conditions (Beuning et al. 2003).

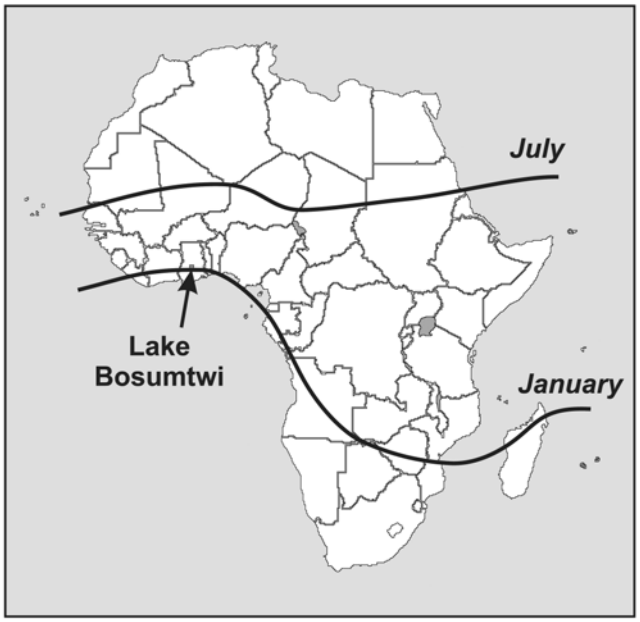

Fig. 5. An overview map of Africa, showing the location of Lake Bosumtwi and the maximum seasonal variation in the position of the intertropical convergence zone (ITCZ), after Shanahan et al. (2006).

MOTIVATION FOR THE 2004 ICDP DRILLING PROJECT

The recent studies led to the realization that further investigation of the crater still had the potential to provide much additional important information, but that this could only be obtained from comprehensive, deep drilling of the crater. Understanding the full range of climate variability in this region over the last 1 Myr will fill a major gap in our understanding of global climate dynamics, and thus also lead

Table 1. Goals of the ICDP deep drilling project at Bosumtwi from the impact perspective.

Crater morphology and geometry studies
Determine crater depth (apparent and to basement)
Determine structure of central uplift
Characterize target stratigraphy (central uplift stratigraphy)
Measure post-impact modification processes and effects (e.g., slumping)
Study of crater fill breccia and melt rocks
Determine whether massive melt rocks are present or not
Quantification of melt volume and breccia volume
Origin of various impact breccias, constraints on cratering process
Determine source rocks for tektites and fallout suevite
Determine meteoritic component in crater-fill breccia and melt rocks, and determine meteorite type
Occurrence of dyke breccias/pseudotachylitic breccias
Comparison between fallout and fallback breccias
Refine the crater age from dating of impact melt
Internal breccia stratigraphy
Study clast population
Melt breccias occurrence and distribution
Origin of melt rocks
Search for 0.8 Myr old Australasian tektite (microtektite) occurrences in crater-fill sediments
Geophysical studies
Provide ground-truth for inferences drawn from previous aeromagnetic and other geophysical studies
Petrophysical data for interpretation of gravity and magnetic models and seismic studies
Obtain boundary conditions for modeling calculations
Vertical seismic profiling to obtain 3-D image of crater subsurface
Shock metamorphism studies
Study of shock deformation within central uplift, including crater floor
Distribution through core of different grades of shock metamorphism: Origin of ejecta clasts/melt and implications for cratering physics
Carbon content in basement rocks and breccias
Search for impact diamonds
Search for shocked zircons
Paleomagnetic study of shocked rocks and melts
Study of post-impact events
Search for possible evidence of other <1 Myr old impact events (Australasian tektites) in post-impact sediments
Study the interface between fallback breccia and lake-fill sediments
Climatic influences from impact event

to an enhanced climate prediction capability over a broad part of the Earth. Planning for such a drilling project started in 2000, and in January 2001 a proposal was submitted to the International Continental Scientific Drilling Program (ICDP) to hold an international workshop in Potsdam in September 2001, which brought together the various research communities interested in Bosumtwi. The workshop was highly successful and resulted in the definition of the goals for a deep drilling project, namely 1) to obtain a complete 1-million-year paleoenvironmental record in an area for which so far only limited data exist, and 2) to study the subsurface structure and crater fill of one of the best-preserved, large, and young impact structures.

In terms of cratering studies, Bosumtwi is one of only two known young craters of this size (the other being El'gygytgyn in northeast Siberia), and may have a crucial diameter at the changeover between a traditional "complex" crater with a central peak and a crater structure that has a central peak-ring system, maybe similar to that of the Ries crater in Germany (which, at 24 km in diameter, is twice as large). Zhamanshin (Kazakhstan) is of similar dimensions and age as Bosumtwi, but poorly preserved (e.g., Garvin and Schnetzler 1994). Detailed goals of the drilling project in terms of impact research, as submitted with the project application to ICDP, are summarized in Table 1. Drilling allows for correlation of all the geophysical studies and provides material for geochemical and petrographic correlation studies between basement rocks and crater fill in comparison with tektites and ejected material.

After the successful workshop in 2001, and supported by pre-drilling geophysical site surveys (see next section), a full proposal was submitted to ICDP in January 2002. It was proposed that drill cores at nine locations in the crater lake would be obtained, with core lengths ranging from 50 to 1035 m, resulting in a total of 3 km of sediment core and 1 km of impact-related hard-rock core. The proposal was accepted by ICDP in mid 2002 and logistical work to organize and plan the drilling started in late 2002. As ICDP provided about two thirds of the funds that were needed for the actual drilling and related logistics, additional funding from various national funding agencies in the US, Austria, and Canada had to be obtained. A variety of permits had to be procured, permission by government and tribal authorities had to be gained, and some construction work (such as road improvements and construction of a pier) was required as well. All this preparatory work was completed in early summer of 2004.

PRE-SITE SURVEYS, IMPACT MODEL PREDICTIONS, AND DRILL SITE SELECTION

Geophysical Surveys

In preparation for the scientific drilling of the Lake Bosumtwi crater, a wide range of geophysical and petrophysical studies were conducted over the past 10 years. In 1997, a high-resolution airborne geophysical survey revealed a halo-shaped magnetic anomaly (Pesonen et al. 1998, 2003; Plado et al. 2000). The physical properties of suevites collected north of the crater rim differ substantially from those of the surrounding pre-impact rocks in showing high porosity, low density, and high magnetization.

To determine the subsurface structure of the crater, a joint Ghanaian-German research project using geophysical

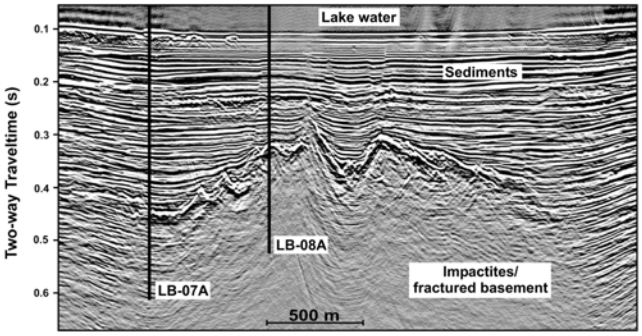

Fig. 6. Reflection seismic section (profile 1) with boreholes LB-07A and LB-08A with a layered post-impact sedimentary sequence of strong reflections from the sediment-impactite interface, and the seismically transparent central uplift. Core LB-05 cannot be shown here because it is on a different seismic profile.

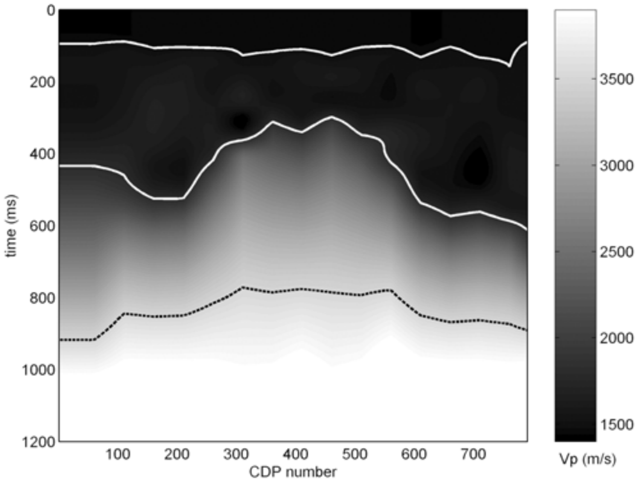

Fig. 7. A velocity model (Karp et al. 2002) derived from refraction seismic and reflection data. Contour lines at 1480, 1800, and 3500 m/s indicate the approximate boundaries at the lake floor, the base of the sediments, and the base of the brecciated impactite sequence, respectively.

techniques started in 1999. The seismic surveys and seismic data processing were conducted in close collaboration with researchers at Syracuse University, USA. Wide-angle and refraction seismic data were acquired along two lines. A 0.85-liter airgun was used as the source and ocean bottom hydrophones (OBH) and PDAS land seismometers were used as receivers. The refraction lines are each 6.5 km long, and average shot distances are 20 m on line 1 and 30 m on line 2. Land seismometers were only used on line 2. In addition, a grid of multichannel seismic reflection lines (MCS) enabled imaging of the central uplift structure (Scholz et al. 2002; Scholz et al. 2007). Two of the MCS lines are coincident with the wide angle lines and therefore allow an integrated interpretation.

Gravity and magnetic data were acquired on land and on the lake (J. Pohl, personal communication; Danuor and Menyeh 2007). Gravity stations on land, inside and outside the crater, were measured using a LaCoste-Romberg gravity meter G256. The instrument’s time shift was corrected by repeated measurements at a number of base stations within a maximum time of 2 h. Most of the stations were located along roads, because the area is densely forested and not easily accessible. No measurements were taken in the Obuom Range Mountains to the south and southeast of the crater structure. On the lake, gravity and magnetic profiles in the north-south and east-west directions were acquired using a LaCoste-Romberg air-sea gravity meter. A summary of the potential field data acquisition and preliminary data interpretation is given by Danuor and Menyeh (2007).

Seismic reflection and refraction data have been interpreted in an integrated approach (Karp et al. 2002; Scholz et al. 2007; Danuor and Menyeh 2007). P-wave velocities were determined to a depth of 1.6 km. Synthetic seismic refraction data have been modeled in order to estimate S-wave velocities. The MCS and wide-angle profiles show that the seismic velocity in the crater rocks increases with depth. Under the central uplift the velocity gradient is higher than within the annular moat that surrounds it. This velocity difference was interpreted as due to a material difference: the central uplift is formed by deformed and rebounded target rock, whereas the annular moat is thought to be filled by fallback impact breccia. Very low values of the seismic quality factor Q support the model of strongly fractured rocks (Karp 2002). Apparent depth and structural uplift of the crater are within the range of predicted values for complex craters (Grieve and Pilkington 1996).

The identified central uplift has a diameter of almost 2 km and a height of more than 100 m; the total amount of uplift is estimated to be at least 800 m, and the apparent crater depth 550 m. The crater floor or a melt layer were not detected in the seismic study. The pre-drilling site surveys determined a consistent velocity-depth model for seismic reflection, refraction, gravity, and magnetic data consisting of 3 layers. Layers 1 and 2 represent the lake water and the post-impact sediments, respectively. For traveltime modeling, layer 3 is referred as the bedrock layer without any geological or mineralogical implications, but rather to emphasize the contrast to the overlying layers. Hard-rock (LB-07A and LB-08A) drill sites with the depth-migrated reflection profile across the center of the Lake Bosumtwi structure are shown in Fig. 6. The three-layer gradient velocity model inverted from refraction and reflection seismic data is displayed in Fig. 7.

Note the overall low velocities of post-impact sediments. The sedimentary cover of the crater has seismic velocities of 1.5–1.65 km/s, a common value for young, water-saturated and unconsolidated sediments (Scholz et al. 2007). The sediment-impact breccia interface is marked by a strong increase in P-wave velocities. Nevertheless, the P-wave velocities for the central uplift and the annular moat are relatively low, even if highly fractured material is assumed. The unusually low P-wave velocities observed in the rocks of the Bosumtwi structure were a problem for any derived depth models and posed a risk for the drill site selection process. The velocity of 3.5 km/s is the lowest velocity that is found in the maximum depth of 1.2 km of the refraction seismic model. It does not represent a lithologic boundary, but illustrates the variations in the velocity-depth structure of the crater. As P-wave velocity is closely related to density, the contour lines in Fig. 7 rather represent the vertical and lateral trend in porosity.

Numerical Models

The pre-drilling geophysical models of the Lake Bosumtwi structure (Karp et al. 2002; Scholz et al. 2002; Danuor and Menyeh 2007) formed the basis for a comprehensive numerical modeling study of the impact process. Prior to drilling, numerical modeling by Artemieva et al. (2004) estimated melt and tektite production by impacts with different impact angles and projectile velocities. The most suitable conditions for the generation of tektites are high-velocity impacts (>20 km/s) with an impact angle between 30 and 50 degrees (Artemieva 2002). Not all the melt is deposited inside the crater. In the case of a vertical impact at 15 km/s, 68% of the melt is deposited inside the crater. Results of the numerical impact modeling compared well with the geophysical data, calculated crater size and morphology, with the distribution of tektites and microtektites of the Ivory Coast strewn field and the seismic, gravity, and magnetic models available prior to the ICDP project.

Site Selection

The pre-siting geophysical results not only contributed to the investigation of terrestrial complex impact structures, but were essential for the planning of the drilling at Lake Bosumtwi. To reach the goals for the impact and paleoclimatic aspects of the drilling program (see above), a drilling strategy was conceived. From the impact-study point of view, the most important part of the crater is near its center, i.e., on and immediately around the central uplift. The uplift structure measures 1.9 km in diameter and has a maximum height of ~130 m above the adjacent annular moat, which comprises the deepest part of the crater floor (Scholz et al. 2002, 2007). The maximum post-impact lacustrine sediment thickness above the annular moat is ~310 m, but the crest of the central uplift is within ~150 m of the lake bottom in one locality. The maximum crater rim-to-floor height is 750 m, as measured from the maximum elevation of the crater rim, exclusive of elevations in the Obuom Range, to the base of the lacustrine section. Seismic data quality is excellent in the basin center, with the lacustrine section clearly imaged as a set of continuous, moderate to high amplitude reflections; data quality is severely degraded on the basin margins due to gas charging of the lacustrine sediment section, by what is interpreted to be biogenically derived methane.

Based on seismic images and modeling of potential field data, two sites were selected for the bedrock drilling phase of the scientific drilling project. Borehole LB-07A targeted thick melt/breccia thought to occur off the central uplift in the annular moat. The preliminary geophysical maps show some asymmetry with the main anomaly north of the crater center. These anomalies suggest the existence of a melt body centered 1 km north of the crater center.

The second site, LB-08A, is located at the shoulder of the central uplift and was expected to provide information about peak shock pressure and temperature to gain a better understanding of the principles of the formation of complex impact craters, a prerequisite for testing the validity of numerical models of the Bosumtwi structure. Besides the central uplift and the annular moat with a suggested thick breccia cover, drilling at the location of the geophysical anomalies and comparison of downrange and transversal locations provides insight about pre-impact and impact-induced asymmetries.

From a sedimentological point of view, the lake sediments above and away from the central uplift have to be compared for optimum stratigraphic resolution. Seismic data indicated that debris flows off the crater rim disturbed the stratigraphy further out in the ring basin around the central uplift, but that sediment thicknesses are greater in this zone, providing better resolution of interstratification. Disturbances of sediments on top of the central uplift, perhaps due to late collapse effects, are also possible. The drilling strategy for the paleoclimate studies envisaged a series of cores through the sedimentary fill of the structure to obtain a complete, continuous record. Thus, a series of cores, from the center to as close to the lake shore as possible (away from mass-wasting debris from the rim) were planned. The top parts of the two deep “impact” cores are part of this transect. Some of the cores needed to be duplicated because of possible loss of dating information and sedimentological record between core barrels.

Limnological Survey

As part of the conditions to obtain a drilling permit from the Environmental Protection Agency of Ghana, a pre-drilling baseline survey of the limnology of the lake was required to document any drilling-induced changes beyond normal seasonal variability. This was particularly important because earlier in the twentieth century the lake seems to have overturned on occasion. Rattray (1923, p. 67) described this as follows: “The colour of the water in the lake changes to almost black, and apparently quite suddenly, for they say this often happens at night, the air becomes full of a choking smell of what they describe as ‘gunpowder’….this smell comes from the black slime which rises on the water which, it is alleged, can be perceived some miles away…. Simultaneously, or soon after, the whole surface of the lake

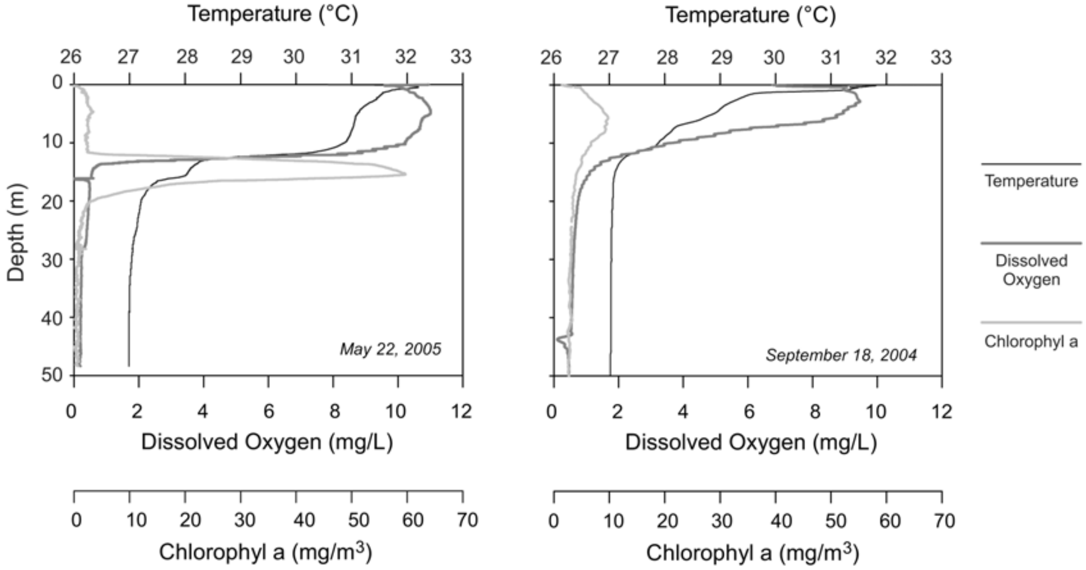

Fig. 8. Temperature, chlorophyl a, and dissolved oxygen profiles for the center of Lake Bosumtwi, measured in September 2004 (during drilling) and May 2005 (after drilling). Seasonal differences in the parameters of the water column are evident.

becomes covered with fish, either dead or flapping on the surface so that they can be readily caught." Rattray (1923) quotes an official from the British Geological Survey Office, who notes "what happens is that the organic matter which has been growing and collecting and putrefying on the bottom of the lake finally gets so buoyant with gases produced by the decomposition that it all rises to the surface and forms a black scum which has a terrific stench." It is not known to us if this phenomenon has occurred at Bosumtwi during the past decades, but certainly the drilling project did not want to be the cause for an overturn, killing a lot of fish. The gas concentrations in deep lake water were not known prior to the drilling program. In contrast, Turner et al. (1996a, 1996b) considered the water column to be well mixed, at least annually. As preliminary measurements in January 2000 determined that there was evidence for persistent stratification of the water column, ICDP funded a baseline survey that would document conditions before and after drilling to determine the possibility of any adverse effects of drilling. The level of pollution of the lake (mainly from anthropogenic sources) is still not well known (cf. Boamah and Koeberl 2007).

The lake was visited in May 2004 (before drilling began), September 2004 (during drilling), and in May 2005 (post-drilling). The lake has been warming over the last few decades, which may contribute to longer and more periods in which the water column is stable and stratified, and perhaps even to a lack of annual mixing (R. Hecky, unpublished data). The May 2004 pre-drilling survey revealed a highly structured water column. Similar observations were made in May 2005, after the drilling. In May (both 2004 and 2005) the water temperatures exceeded 31 °C down to 10 m depth, below which a steep thermocline paralleled a strong oxycline (Fig. 8). The lake was anoxic below 15 m, and a deep chlorophyll peak (from green sulfur bacteria) was also evident in May 2004 and 2005 in anoxic waters. The September 2004 profile was taken after the lake had cooled during July and August, and at that time the upper water column was cooler, with >29 °C water only extending to 4 m in depth (Fig. 8). The upper water column had less oxygen at 4–12 m than in May 2004 and 2005, but oxygen extended more deeply into the water column than in the May readings as a result of the mixing attendant with the cooling of the lake. The CO_2 and CH_4 gas concentrations in the deep waters were well below saturation and drilling posed no hazard of explosive gas release from the water column. The ICDP drilling program had no discernible effect on the lake's hydrographic structure and biogeochemistry. The lake is permanently anoxic at depth, but annual mixing does allow degassing of intermediate depths and prevents buildup of high gas concentrations. There is no evidence of significant sources of deep hydrothermal springs introducing CO_2 into the deep waters. The concentrations of CH_4 and CO_2 are likely entirely produced from biological anaerobic decomposition of organic matter produced within the lake. The unsuspected presence of a seasonal variation of anoxygenic photosynthetic green sulfur bacteria may provide a sensitive paleolimnological indicator of seasonal conditions within the Bosumtwi water column.

DRILLING OPERATIONS

Following the approval of the drilling project by ICDP, several site visits occurred in the two years preceding the drilling. This included a joint site visit in January 2003 (C. Koeberl for the project, D. Nielson for DOSECC, and

R. Oberhänsli as ICDP representative), to establish policy procedures, to survey the road conditions, to meet with the Ashanti king to obtain permission from the tribal leaders, as well as a large number of politicians to obtain all the necessary permits for the project. The main permits to be obtained included those from the Ghana Ministry of Mines, the Environmental Protection Agency of Ghana, Regional Government, and the Ashanti Kingdom.

Besides obtaining the permits, it was clear that the project would be logistically challenging. For example, the road leading to the town of Abono at the shores of Lake Bosumtwi (where the shipping containers had to be transported for offloading) was in bad shape in at least two locations; fortunately, repairs by the Ghana Road Authority were planned or in progress in 2003 and finished in 2004. A pier, necessary to dock the RV Kilindi (the support vessel operated by Syracuse University, a catamaran, which was necessary to go back and forth between the shore and the drill barge for shift changes and supplies) and to load and unload the parts of the GLAD800 drilling system, did not exist and had to be built (Fig. 9a). Figure 9b shows the RV Kilindi near the small town of Abono on the north side of the lake, having to negotiate numerous fishing nets. Construction was finished just in time for the planned start of the drilling operation in early July 2004. The drilling operations were divided into two main parts, the sediment drilling (first two months) and the hard-rock (impactite and bedrock) drilling, including some geophysical logging (last month). Two different science teams (one for sediment drilling and one for hard-rock drilling) were present, unfortunately with no overlap.

Drilling took place from the beginning of July to early October 2004 (see Koeberl et al. 2005 and Peck et al. 2005a for first drilling reports). Care was taken to situate all drill sites on seismic lines that were measured in the preparation phase of the drilling project (see previous section and Karp et al. 2002; Scholz et al. 2002). Figure 10 shows the locations from which the hard-rock and sediment cores were obtained in the summer of 2004, as well as the locations of the seismic profiles. Drilling was performed using the DOSECC/ICDP GLAD800 lake drilling system, which is a custom-built device specifically for lake scientific drilling (Figs. 11a–c).

The locations of all coreholes, as well as detailed information on the drilling parameters, are given in Table 2. Details of the sediment drilling will be reported elsewhere. In terms of “hard-rock” drilling, two deep holes had been planned, one (later numbered LB-07A) in the deep crater moat, and the other (LB-08A) on the flank of the central uplift. Drilling depths of up to 800 m were planned. The interface between the fallback ejecta and the lake sediment was not collected in either of the two cores, because of difficulties in precisely locating this interface, and because of necessary drilling tool changes. In the case of the first hard-rock core, after about a week of coring the drill bit got stuck at a depth of 548 m below lake level. As fractured bedrock seemed to have been reached, the decision was made to abandon the hole. Thus the summary for the first hard-rock hole was: start coring (near top of impactite rocks) on September 10, 2004, at a depth of 333.38 m (after having rotary-drilled through the overlying lake sediment); core through lithic/suevitic breccia, and fractured bedrock; end coring (in fractured bedrock) on September 16–17, 2004, at a depth of 548.12 m. This worked out to about 33 m a day; the average rock recovery rate per core barrel was 64.1%. Drilling was followed by two days of logging, which was partly successful (due to logging through casing). Then the GLAD800 moved to the next location, and reaming through sediment resumed on September 23. Coring started at a depth of 230 m on September 25, 2004, at the second hard-rock site (LB-08A), and was completed on September 30, with good core recovery of, on average, about 90%, at a total depth of 451 m. The target depth at this location was ~600 m, but timing and scheduling problems prevented a continuation of the coring; also, once again fractured bedrock seemed to have been reached sooner than initially expected. Open hole logging was completed on October 2, 2004, and both the GLAD800 and the support vessel Kilindi arrived at the shore on October 3. The demobilization effort was successfully completed on October 14, 2004.

DOWNHOLE LOGGING OPERATIONS AND BOREHOLE GEOPHYSICAL SURVEYS

The long-term goal of the Lake Bosumtwi integrated drilling, rock property, and surface geophysical study was to probe and resolve the three-dimensional building blocks of a young impact crater (delineate key lithological units, image fault patterns, and define alteration zones). Results from the Lake Bosumtwi project are important for comparative studies and re-evaluation of existing geophysical data from older and larger impact sites (for example, Sudbury, Vredefort, Chicxulub, and Ries).

The drill holes had to be tied to the available potential field and seismic data that define the Lake Bosumtwi impact structure. Upon completion of drilling operations, a full suite of downhole geophysical measurements (including televiewer, full waveform sonic, and resistivity) was obtained in the two boreholes. All data are archived by the Operational Support Group of the ICDP and can be accessed via the ICDP website (www.icdp-online.org). In addition, zero- and multi-offset vertical seismic profiling (VSP) was conducted to establish a direct tie between the seismic reflection images and the borehole and core data (Schmitt et al. 2007). A vector magnetic study was conducted to provide crucial information about the distribution of magnetized formations within the breccia and help locate discontinuous melt units in the proximity of the scientific drill holes (Ugalde et al. 2007b). By documenting the distribution of magnetic susceptibility and the impact-related thermomagnetic remanance, the

Fig. 9. a) An aerial view of the town of Abono on the northern shore of Lake Bosumtwi, which served as the headquarters of the drilling project. This is where the only paved road that cuts through the crater rim reaches the lake. Visible in the front are the addition to the road leading to the pier and the pier, both of which were constructed by the ICDP project. Photo: C. Koeberl. b) The support vessel RV Kilindi, a catamaran, near Abono, operating in a narrow passage between the pier and the drilling barge in the center of the lake, through lots of fishing nets (tied to the bamboo poles that are visible in the lake). Photo: P. Claeys.

distribution of the thermal effects of the impact are outlined (Kontny et al. 2007). The offset vertical seismic (VSP) profiling calibrates the P-wave velocity model (Fig. 7), allows the conversion of reflection seismic images from time to depth, and provides the framework for the integration of conventional logs and the existing grid of multichannel seismic and refraction seismic data. The suite of downhole geophysical surveys is most suitable for the integration of core/laboratory data and logs (Elbra et al. 2007), and the conversion of reflection seismic images from time to depth.

Downhole measurements with wireline-operated instruments provide a continuous record of various

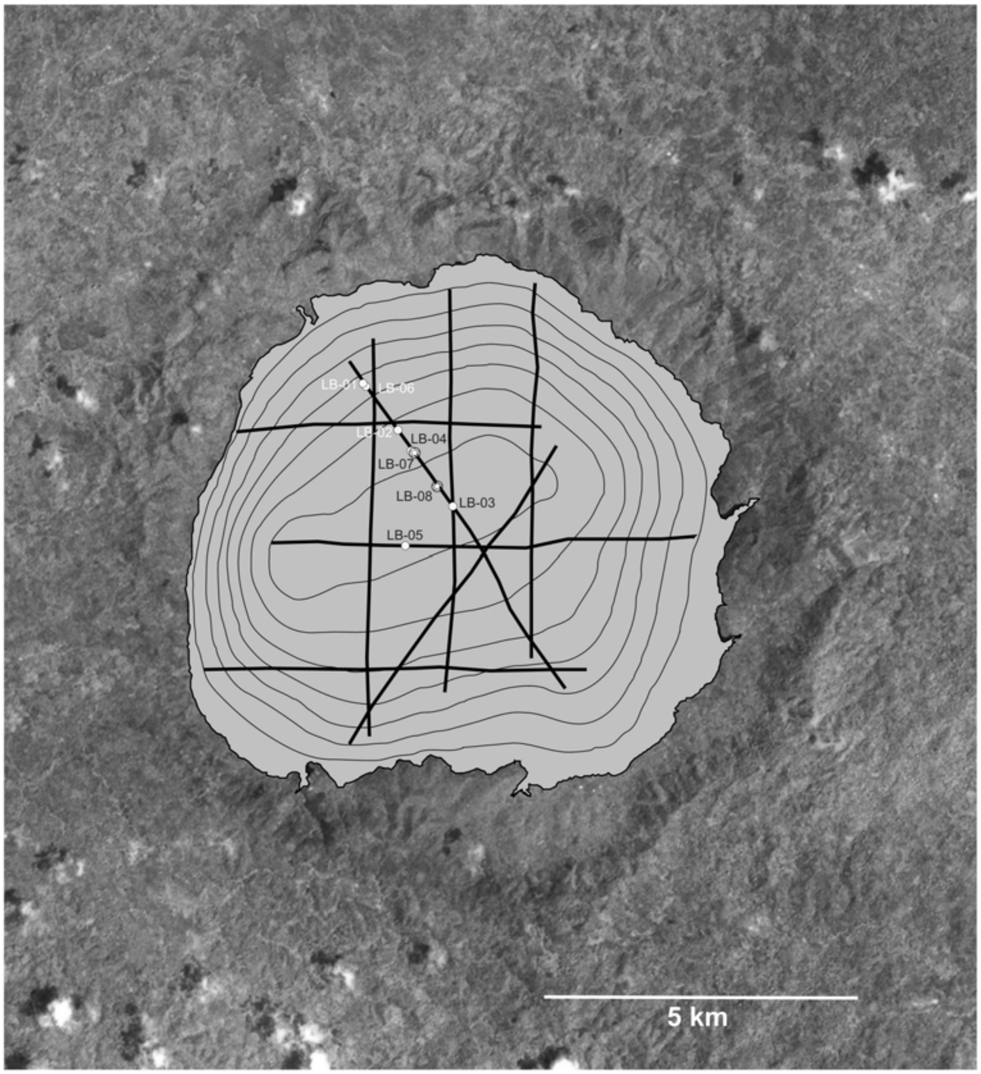

Fig. 10. A map showing the locations of seismic profiles as well as the positions of the drill cores that were obtained during the 2004 ICDP project, superimposed onto an Aster satellite image (band combination 7, 3, and 1, contrast-enhanced; gray-shaded) of the Bosumtwi area. Cores LB-01 through -06 are lake sediment cores, and LB-07 and LB-08 are the hard-rock (impactite and bedrock) cores.

petrophysical and structural borehole wall properties. They can be used to complement drill core investigations and allow calibration of geophysical surface data. The Operational Support Group of the International Continental Scientific Drilling Program (ICDP-OSG) performed geophysical downhole measurements with a set of ICDP-owned slimhole sondes in the two impact boreholes. The 150 °C and 80 MPa rated ICDP slimhole logging sondes produce best results in small-diameter holes (75–120 mm) and were, therefore, ideal in the drilled holes. The tool set delivers a primary set of 15 parameters comprising total natural gamma ray, contents of potassium, uranium, and thorium, three-component magnetic field, magnetic susceptibility, electrical resistivity for deep and shallow penetration, sonic compressional velocity and full "sonic waveforms," borehole 4-arm caliper, deviation and azimuth, and acoustic borehole wall images. Further processing derives other parameters: sonic shear wave velocity, total magnetic field, structural dipmeter data, and structural data from borehole wall images that are used by other investigators (Morris et al. 2007a, 2007b; Hunze and Wonik 2007).

This logging parameter set provides detailed in situ information on variances in physical properties related to lithological differences, orientation of geological structures, elastic, electrical and magnetic properties, and borehole geometry. Figure 12 shows a section of a compilation of parameters logged in hole LB-08A. The logging data together with core data allow good differentiation of units in a continuous lithological profile. All logs were depth-corrected using the total gamma ray (GR) traces with respect to a master GR log. The only exception was the televiewer log, which does not include a GR measurement. It was depth-correlated

Fig. 11. Views of the GLAD800 drilling barge and rig. a) An aerial view of the drilling barge on Lake Bosumtwi. b) The GLAD800 on the lake, showing the floating containers on which the drill rig is mounted. c) A close-up of the modified Christensen CS-1500 diamond coring rig mounted on the barge. All images: C. Koeberl.

regarding the other logs using the total magnetic field in comparison to the total field measured with the dipmeter log. The sonic velocities were determined using a manual picking method and the semi-manual semblance velocity analysis. The sine structures were picked manually in the televiewer images. All data processing was done with either the data acquisition software Geobase or the processing software WellCAD. The depth-corrected logging data are integrated in and available at the ICDP Data and Information System (www.icdp-online.org).

In hole LB-07A, the spectrum gamma log was run inside the HQ drill pipes (cased-hole situation) because it was temporarily impossible to pull out the drill string. The other logs were run inside the open hole section (see Table 3). The GR log obtained in hole LB-07A is shown in Fig. 13 superimposed on the MCS reflection profile. The GR log covers both post-impact sediments and the contact between sediments and impactites. GR logs were obtained in all boreholes of the Lake Bosumtwi soft-rock drilling program and provide an important tool to correlate drill core and seismic images. In hole LB-08A logs were obtained over the entire open hole section (see Table 4).

SUMMARY OF RESULTS OF ICDP DRILLING OF LAKE BOSUMTWI

Lake Sediment Recovery

In order to gain greater insight into the role of the tropics in triggering, intensifying, and propagating climate changes, scientific drilling for the recovery of long sediment records from Lake Bosumtwi was undertaken. Five drill sites (Fig. 10) were chosen along a water-depth transect in order to facilitate the reconstruction of the lake level history. At these five sites, a total of 14 separate holes were drilled. Total sediment recovery was 1833 m. For the first time, the GLAD800 lake drilling system (Figs. 11a–c) cored an entire lacustrine sediment fill from lake floor to bedrock. The

Table 2. Names, locations, and core information for the cores obtained in the course of the 2004 ICDP drilling project at Lake Bosumtwi (see Koeberl et al. 2005; Peck et al. 2005a, 2005b). All cores obtained using the GLAD800 lake drilling system. Data compiled by H. Ugalde and B. Milkereit (University of Toronto).

Site	Water depth (m)	North latitude (degrees)	East longitude (degrees)	Total depth (m)[a]	Cored from (m)	Cored to (m)	Total core (m)
Sediment cores							
BOS04-1A	43.75	6.52227	1.42097	54.69	45.69	54.69	8.99
BOS04-1B	43.75	6.52227	1.42097	65.74	54.69	65.74	11.05
BOS04-1C	43.75	6.52226	1.42098	95.43	65.63	116.87	51.23
BOS04-1D	43.75	6.52226	1.42098	143.87	115.87	123.80	7.92
BOS04-1D							0.00
BOS04-1D					131.01	143.87	12.85
BOS04-1E	42.87	6.52266	1.42112	67.21	43.21	67.21	24.00
BOS04-2A	63	6.51635	1.41747	97.87	64.87	97.87	32.99
BOS04-2B	63.67	6.51600	1.41761	151.59	65.61	151.59	85.98
BOS04-2C	63.67	6.51600	1.41761				
BOS04-2D	63.08	6.51585	1.41770				0.00
BOS04-2D				150.60	80.77	150.60	69.82
BOS04-3A	73.5	6.50520	1.41065	207.57	75.46	207.57	132.11
BOS04-3B	74.15	6.50501	1.41039	208.79	77.11	208.79	131.67
BOS04-3C	73.25	6.50497	1.41030	80.16	74.14	80.16	6.02
BOS04-3D	73.25	6.50497	1.41030	200.96	74.14	200.96	126.82
BOS04-4A	68.95	6.51431	1.41508	138.48	70.84	138.48	67.64
BOS04-4B	68.41	6.51418	1.41489	135.05	69.32	135.31	65.99
BOS04-4C	69	6.51416	1.41484	89.64	71.91	89.89	17.98
BOS04-4D	69	6.51416	1.41484	188.24	89.89	188.24	98.35
BOS04-4E	69	6.51416	1.41484	315.57	188.24	214.53	26.29
BOS04-4E							0.00
BOS04-4E					215.37	315.57	100.20
BOS04-5A	74	6.50055	1.41593	224.33	74.93	224.33	149.40
BOS04-5B	74	6.50052	1.41595	370.56	75.90	370.56	294.67
BOS04-5C	74	6.50049	1.41594				
BOS04-6A	45.5	6.52184	1.42066	168.86			0.00
BOS04-6B	45.5	6.52184	1.42066				
Hard-rock cores (impactites)							
BOS04-7A	69	6.51385	1.41518	548.13	330.71	548.13	217.42
BOS04-8A	73	6.50908	1.41238	451.31	235.60	451.32	215.71

[a] Total depth of hole measured from water line.

shallow water drill sites consist of alternating laminated lacustrine mud (deepwater environment), moderately sorted sand (nearshore beach environment), and sandy gravel (fluvial or lake marginal environments). These sediment cores and seismic reflection profiles are being used to construct a basin-wide stratigraphic framework, in order to extend further back in time the present Bosumtwi lake level histories obtained from study of highstand terraces and short piston cores.

At site LB-05, the complete 1 Myr lacustrine stratigraphic section was recovered in three stacked cores that reached to a depth of 294 m; the final hole ended in impact-glass bearing, accretionary lapilli fallout (Koeberl et al. 2007a). This unit provides an important age constraint for the overlying sedimentary sequence. Also, it is highly important to complement the impact breccia sequences derived from holes LB-07A and LB-8A. The initial lacustrine sediment (overlying the fallback layer) is characterized by a bioturbated, light gray mud with abundant gastropod shells suggesting that a shallow-water oxic lake environment was established in the crater. Future study of the earliest lacustrine sediment will address important questions related to the initial formation of the lake and the establishment of biologic communities following the impact. Most of the overlying 294 m of mud is laminated; thus, these sediment cores will provide a unique 1-million-year record of tropical climate change in continental Africa at extremely high resolution. On precessional time scales, the Bosumtwi sedimentary property profiles are readily correlated with marine sediment and polar ice core records, thus allowing this equatorial African record

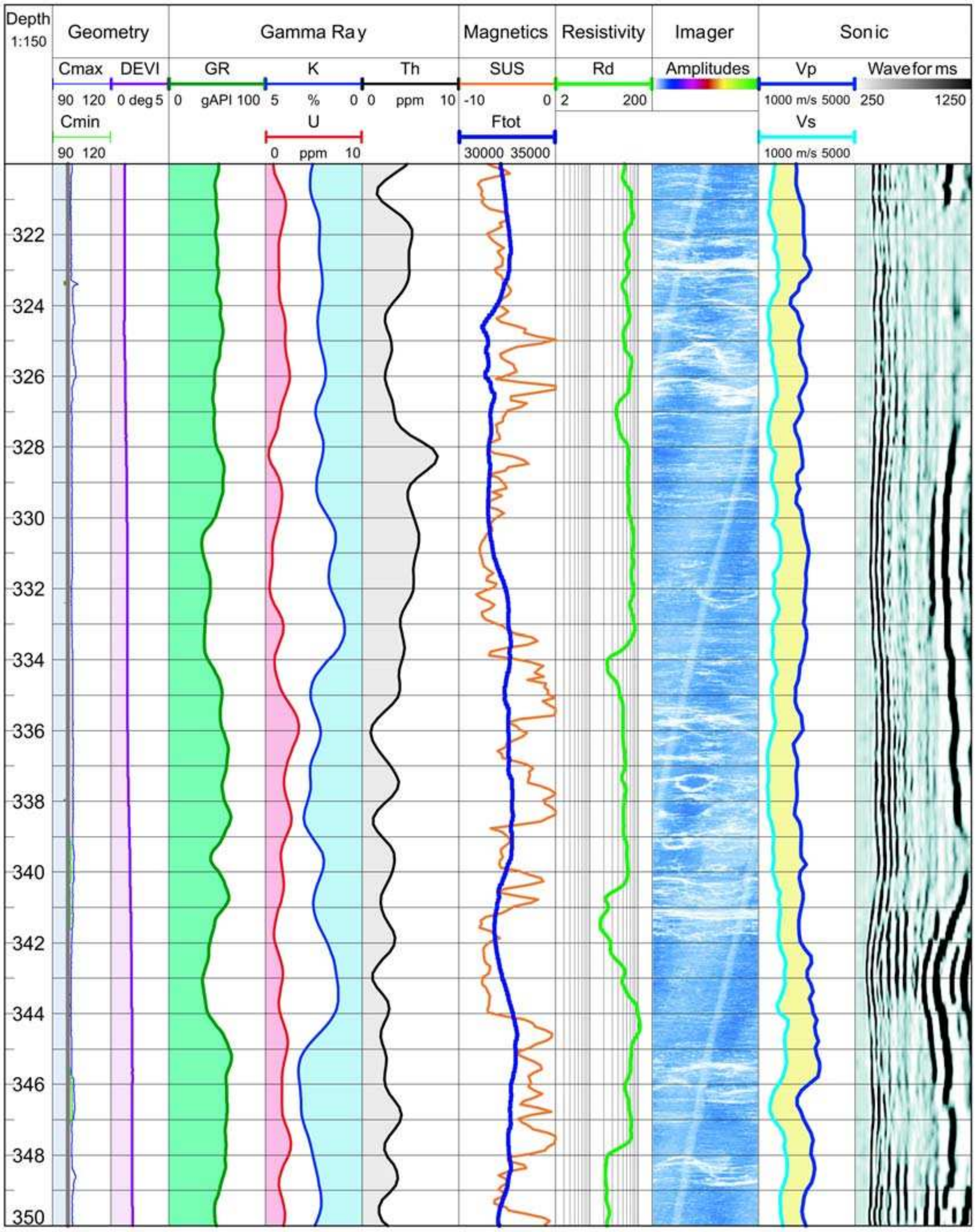

Fig. 12. A compilation of parameters logged in hole LB-08A. Borehole geometry: caliper (borehole diameter in two perpendicular directions, in mm) and deviation from vertical; natural gamma ray (GR): total GR, uranium, potassium, and thorium contents; magnetic data: susceptibility (SUS, 10^{-4} SI units) and total field amplitude (nT); electrical resistivity (Ohmm); borehole wall images (amplitudes); Sonic: Vp compressional, Vs shear wave velocity, and full waveforms.

to be placed within a global paleoclimate context. Strong eccentricity and obliquity periodicities in the Bosumtwi climate proxies reveal the response of tropical climate to higher latitude ice sheets and a connection between high- and low-latitude climate change. Ongoing work will utilize the varved sediment record to address the abruptness of environmental change in West Africa as well as connections between high- and low-latitude climate change (Peck et al. 2005). Some magnetic data on the cores were reported by Fox (2006). Early results suggest that a detailed record of both paleohydrologic and paleoenvironmental change are contained in the sediments from Lake Bosumtwi. Future work

Table 3. Logging program in hole LB-07A, 20–24 September 2004, 65–544 m, casing shoe at 332 m.

Sonde	Parameters	Log range (m)
SGR-TS	K, U, Th, GR (= gamma ray)	65–544
MS-TS	Magnetic susceptibility, GR	330–528
DLL-TS	Electrical resistivity deep and shallow, GR	330–528
DIP-TS	Hole orientation, oriented 4-arm caliper, magnetic field, dipmeter, GR	330–528
BS-TS	Acoustic velocities, sonic full waveforms, GR	330–476

on deep drill cores using these and other proxies can provide additional insights into the nature of West African climate and environmental variability. Detailed results on the lake sediment studies and their paleoenvironmental implications will be published elsewhere.

Results: Lithology and Composition of Core LB-07A

The lithologies of cores LB-07A and LB-08A, showing the most important units, are given in schematic form in Fig. 14. Lithostratigraphic and petrographic studies of drill core samples from the 545.08 m deep ICDP borehole LB-07A in the Bosumtwi impact structure revealed two sequences of impactites below the post-impact crater sediments and above coherent basement rock (Coney et al. 2007a; Morrow 2007). The upper impactites (333.38–415.67 m in depth) comprise an alternating sequence of suevite and lithic impact breccias. The lower impactite sequence (415.67–470.55 m in depth) consists essentially of monomict impact breccias, as well as two narrow injections of suevite, which differ from the suevites of the upper impactites in color and intensity of shock metamorphism (by showing a lower degree of peak shock pressure, but a higher abundance of melt particles compared to the upper suevites). The basement rock (470.55–545.08 m in depth) is composed of low-grade metapelites (shale and schist >> phyllite), meta-graywacke, and minor meta-sandstone, quartzite, and thin carbonate strata. The basement rock is transected by a number of suevite dikes. In addition, there is a single occurrence of a granophyric-textured rock, tentatively interpreted as a hydrothermally altered granitic intrusion likely related to the regional pre-impact granitoid complexes. Impact melt fragments are not as prevalent in LB-07A suevite as in the fallout suevite facies around the northern crater rim; on average, 3.6 vol% of melt fragments is seen in the upper suevites and up to 18 vol% in the lower suevite occurrences. Shock deformation features observed in the suevites and lithic breccias include planar deformation features in quartz (1 to 3 sets), rare diaplectic quartz glass, and very rare diaplectic feldspar glass. Notably, no ballen quartz, which is abundant in fallout suevite (e.g., Boamah and Koeberl 2006), has been recorded in the within-crater impact breccias.

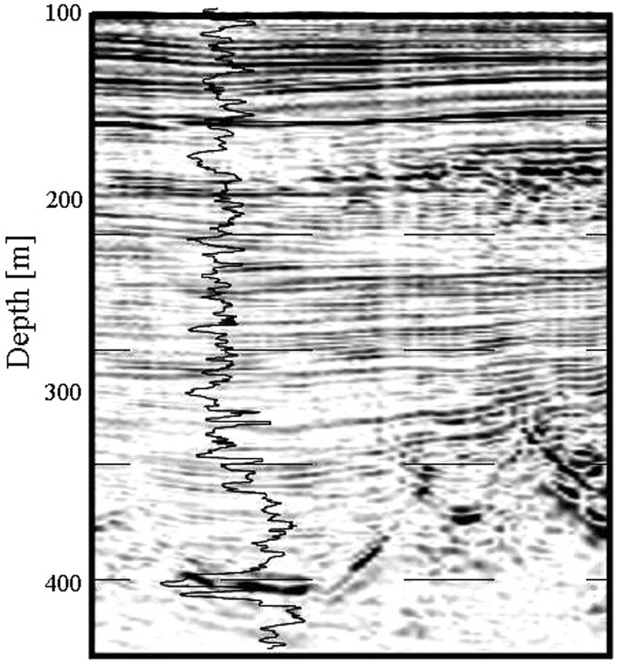

Fig. 13. At borehole LB-07A, the downhole total gamma ray (GR) log provides a link between the layered post-impact sediments and the impactite sequence, as imaged by the multichannel seismic reflection data (Scholz et al. 2002).

Morrow (2007) describes quartz shock-metamorphic features in suevite samples from core LB-07A that were produced by: a) deformation, such as abundant planar microstructures and grain mosaicism; b) phase transformations, such as rare diaplectic quartz glass, and possible coesite; c) melting, such as isolated, colorless to dark, glassy and devitrified vesicular melt grains; and d) post-impact transformations, such as abundant, variably decorated planar microstructures and patchy grain toasting. The quartz PDF orientations closely match those reported elsewhere from strongly shocked, crystalline-target impactites. Barometry estimates based on shock deformation in quartz in the upper impactite indicate that shock pressures in excess of 20 GPa were widely reached; more rarely, pressures exceeded 40 GPa. The relatively high abundances of decorated planar microstructures and toasting of shocked quartz, together with the nature and distribution of melt within suevite, suggest a volatile-rich target for the Bosumtwi impact event. Further details on the lithologies are given in Coney et al. (2007a) and Morrow (2007).

In terms of chemistry, no systematic difference was found between the composition of the polymict lithic and suevitic impact breccias (Coney et al. 2007b). Minor secondary carbonate due to hydrothermal alteration is observed on some samples from all lithologies (see also Petersen et al. 2007). The impactites of the borehole generally show intermediate compositions compared with the variety of compositions noted in the Bosumtwi country rocks (e.g., Koeberl et al. 1998; Karikari et al. 2007). The fallout suevites have comparable major element abundances except for MgO contents, which appear to be lower in the fallout suevites. The average composition of the Ivory Coast tektites is similar to that of the LB-07A suevites, except that wider ranges in MgO and CaO contents are observed for the LB-07A suevites.

Results: Lithology and Composition of Core LB-08A

Drill core LB-08A, into the outer flank of the central uplift (Fig. 6), consists of the following lithologies, in order of decreasing abundance: meta-graywacke, slate, phyllite, polymict impact breccia, and monomict lithic impact breccia. As shown in Fig. 14, the core can be divided into two main parts: the uppermost 25 m that are composed of polymict lithic impact breccia (clast supported) intercalated with suevite (containing melt fragments), and the other part of the core (between 262 to 451 m) which is dominated by fractured/brecciated metasediment, which is locally brecciated (monomict lithic breccia) and intersected by several suevite dikelets.

The upper part of the core, between 235.6 and 262 m, has been interpreted as a fallback impact breccia deposit (Ferrière et al. 2007a; Deutsch et al. 2007). Suevite has a fine-grained fragmental matrix (39–45 vol%) and contains a variety of lithic clasts and mineral fragments: meta-graywacke, phyllite, slate, quartzite, carbon-rich organic shale, and calcite, as well as impact melt particles, diaplectic quartz glass, unshocked quartz, fractured quartz, quartz with PDFs (up to 4 sets), phyllosilicate minerals, epidote, sphene, and opaque minerals (Ferrière et al. 2007a; Deutsch et al. 2007).

The lower part of the core represents an alternating sequence of metasediment comprised of (in order of decreasing abundance) meta-graywacke (dominant), phyllite, and slate, with locally occurring monomict lithic breccia, light greenish-gray medium-grained meta-graywacke (which contains some clasts of granophyric material), and suevite dikelets (likely injections into the metasediment, up to 80 cm thick; occur between 279.5 and 298 m, and between 418 and 440 m). The metasediment displays a large variation in lithology and grain size (Ferrière et al. 2007a). This second part of the core, between 262 to 451 m, represents the bedrock to the crater structure, which has been shocked and fractured in situ during the early phases of crater formation.

Samples from the central uplift (core LB-08A) display a variety of alteration effects: alteration of plagioclase to sericite, biotite to chlorite, fractures that are filled with iron oxides, secondary pyrite, and secondary calcite veinlets and flakes, and the matrices of polymict impact breccias are composed to a large degree of very fine-grained phyllosilicates. Calcite veinlets and flakes in suevite samples from the fallback deposit have been interpreted as the result of hydrothermal circulation in the rock after the impact event (Ferrière et al. 2007a; Petersen et al. 2007). No systematic change regarding the intensity of secondary alteration throughout the core has been identified in that detailed petrographic study.

Table 4. Logging program in hole LB-08A, 1 and 2 October 2004; 75–452 m, casing shoe at 237 m.

Sonde	Parameters	Log range (m)
SGR-TS	K, U, Th, GR (= gamma ray)	229–447
MS-TS	Magnetic susceptibility, GR	240–452
DLL-TS	Electrical resistivity deep and shallow, GR	240–452
DIP-TS	Hole orientation, oriented 4-arm caliper, magnetic field, dipmeter, GR	240–449
BS-TS	Acoustic velocities, sonic full waveforms, GR	238–448
FAC40	Acoustic borehole wall images	239–450

Complementary observations were made by Deutsch et al. (2007). These authors confirmed that the dominant shock effects in the uplifted target rocks are planar fractures and planar deformation features in quartz, and polysynthetic twinning in carbonate minerals, with a maximum shock pressure recorded in quartz of up to 26 GPa. Deutsch et al. (2007) note that the shock levels observed in the uplifted target rocks are lower than expected from numerical modeling (e.g., Artemieva et al. 2004). Deutsch et al. (2007) performed shock recovery experiments with typical graywackes at 34 and 39.5 GPa, which resulted in almost complete transformation of quartz into diaplectic glass. Deutsch and co-workers note that these observations make it difficult to explain the low amount of melt and lower than expected shock levels in these rocks from a specific shock behavior of the soft, fluid-rich target material (graywackes, shales, slates) in core LB-08A as the prime or only reason.

The chemical composition of samples from core LB-08A is described by Ferrière et al. (2007b). Major variations of the abundances of major and trace elements in the different lithologies result from the initial compositional variations of the various rock types, as well as from aqueous alteration processes, which have undeniably affected the different rocks. Suevite from core LB-08A (fallback suevite) and fallout suevite samples (from outside the northern crater rim) display some differences in major (mainly in MgO, CaO, and Na_2O contents—higher in fallback suevite) and minor (mainly Cr and Ni—higher in fallout suevite) element abundances that could be related to different degrees of post-impact alteration, or result from differences in the clast populations of the two suevite populations. For example, granite clasts are present in fallout suevite and not in fallback breccia, and calcite clasts are present in fallback breccia and not in fallout suevite. Chondrite-normalized abundances of rare earth elements for polymict impact breccia and bedrock samples are very similar.

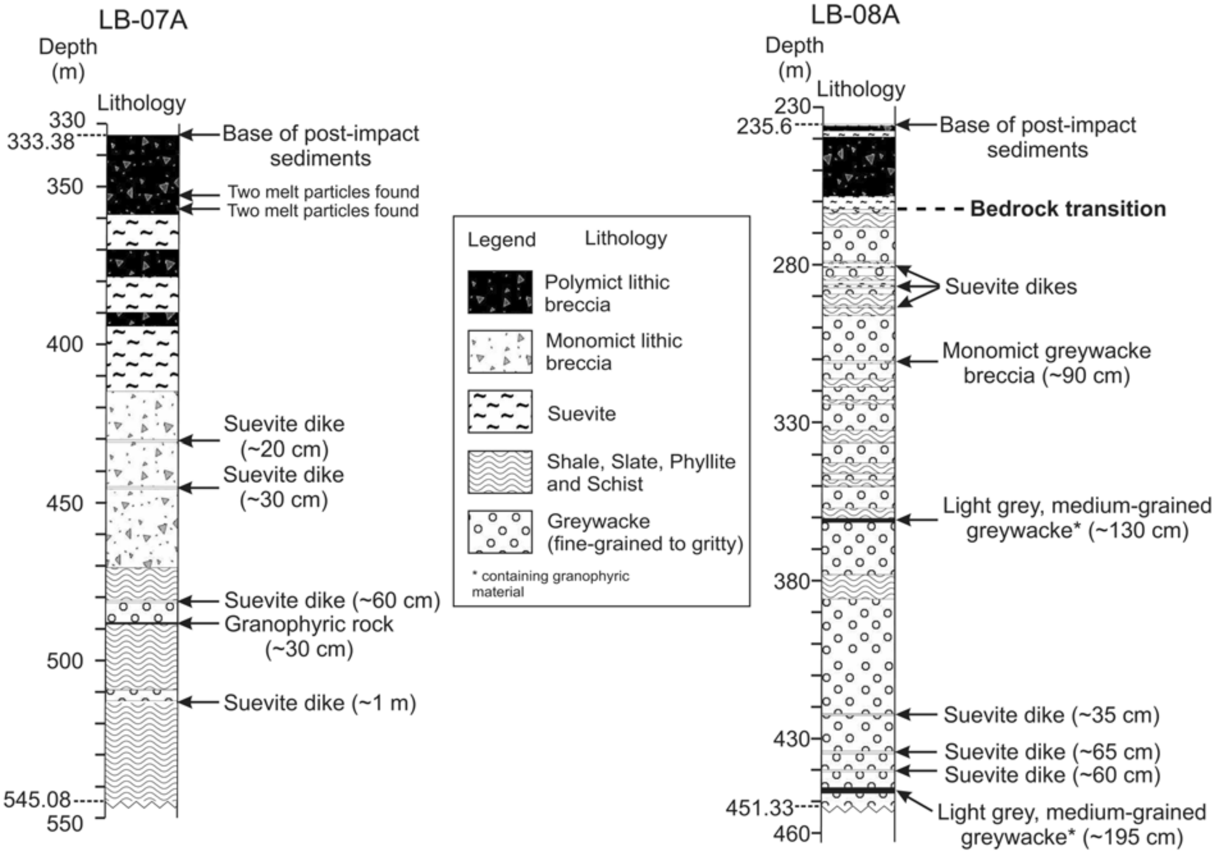

Fig. 14. Schematic lithostratigraphic columns of drill cores LB-07A and LB-08A. For details, see Coney et al. (2007a), Deutsch et al. (2007), and Ferrière et al. (2007a).

An Immediate Post-Impact Fallback Layer in Core LB-05B

As mentioned above, in core LB-05B, one of the 16 cores drilled into the lake sediments, the zone between the impact breccias and the post-impact sediments was penetrated, preserving the final, fine-grained impact fallback layer. According to Koeberl et al. (2007a), this ~30 cm thick layer contains in the top 10 cm accretionary lapilli, microtektite-like glass spherules, and shocked quartz grains. Glass particles—mostly of splash form with less than 1 mm maximum size—make up the bulk of the grains (~70 to 78% by number) in the coarser size fraction (>125 μm) of the top of the fallback layer. About one third of all quartz grains in the uppermost part of the layer are shocked, with planar deformation features (PDFs); almost half of these grains are highly shocked, with 3 or more sets of PDFs. K-feldspars also occur and some show shock deformation. The abundance of shocked quartz grains and the average shock level, as indicated by the number of sets of PDFs for both quartz and K-feldspar, decrease with depth into the layer. The well-preserved glass spherules and fragments are chemically rather homogeneous within each particle, and also show relatively small variations between the various particles. On average, the composition of the fallback spherules from core LB-5B is very similar to the composition of Ivory Coast tektites and microtektites, with the exception of CaO contents that are about 1.5 to 2 times higher in the fallback spherules. This is a rare case in which an immediate post-impact fallback layer has been preserved in an impact structure; its presence indicates that the impactite sequence at Bosumtwi is complete and that Bosumtwi is a well-preserved impact crater.

Search for a Meteoritic Component

Several different studies were made to detect and quantify the presence of an extraterrestrial component in the suevites at Bosumtwi. Earlier work by Palme et al. (1978) and Jones (1985) on Ivory Coast tektites led to a debate about the meaning of high platinum group element (PGE) abundances in the tektites. Koeberl and Shirey (1993) showed from osmium isotopic studies that both the tektites and, to a lesser degree, impact glasses from the suevites contain a small (<0.6 wt%) extraterrestrial component (either chondritic or iron meteoritic). A study by Dai et al. (2005) on suevites from outside the crater rim came up negative—high indigenous PGE abundances seemingly obscure any extraterrestrial signature. It was hoped that the drill cores would preserve some material that was enriched in extraterrestrial components. Goderis et al. (2007) and McDonald et al. (2007) attempted such a search, using PGE abundances. In both cases it was found that the siderophile element contents in the impact breccias are not significantly different from those of the metasediments, i.e., the target rocks exposed outside the crater rim. A minor enrichment, and a slightly different PGE abundance pattern in the fallback layer of core LB-05B, might be projectile-related, but the signal is not very strong. In addition, McDonald et al. (2007) used Os isotopic compositions to search for an extraterrestrial signature in the suevites of both cores LB-07A and 08A, and the result was also negative. So far, no evidence for a meteoritic component has been detected in polymict impact breccias during this study, in agreement with previous work. The reason seems to be the high PGE contents of the target rocks, possibly related to early regional ore mineralization. Thus tektites provide, so far, the only way to obtain information on the composition of the Bosumtwi impactor. Recent work reported by Koeberl et al. (2007b), based on the tektite Cr isotopic composition, indicates an ordinary chondritic composition of the impactor.

Geophysical Results from Drilling and Logging

Drilling results confirmed the gross structure of the crater as imaged by the pre-drilling seismic surveys including multichannel reflection seismic and refraction seismic studies (Fig. 6). Complete downhole logs (including logging through casing) provide an important link between the soft-rock and hard-rock drilling results. Figure 13 shows the gamma ray log with the high-resolution seismic section at site LB-07A. Borehole geophysical studies conducted in the two boreholes (including downhole logging and VSP) confirmed the low seismic velocities for the post-impact sediments (less than 1800 m/s) and the impactites (less than 3300 m/s). These velocities are important for the conversion of reflection times to reflector depth.

The zero-offset VSP data (Schmitt et al. 2007) confirm the low velocities in the post-impact sediments, the higher compressional velocities (>2800 m/s) and pronounced velocity gradients in the impactite sequence. The offset VSP (receiver located at 450 m depth and airgun seismic sources along a 1 km long profile centered above borehole LB-08A) data confirm the topography of the sediment-bedrock interface. Figure 15 shows that borehole LB-08A was drilled into the sloping shoulder of the central uplift. The depth-to-bedrock increases to the NW towards LB-07A.

The televiewer images reveal a high number (>3 structures/m) of planar structures intersecting the well (sine structures) with a random distribution of dip directions within 50 m long hole intervals (Figs. 16 and 17). It was not possible to orient and depth-match cores according to the televiewer images using semi-automatic software because of too-short continuous core sequences. Nevertheless, the visual comparison of both the core and log image can deliver core orientation of at least some cores in future processing. Another method to match core depth to logging depth is to correlate the magnetic susceptibility data (SUS) from downhole logs and from the core. The parameter SUS is very suitable because it has characteristic variations with high dynamic and high vertical resolution but without any statistical disturbance, such as a gamma ray log has, and is much easier to measure on cores than the gamma ray log is. Hunze and Wonik (2007) note that the physical properties (e.g., resistivity, P-wave velocity, magnetic susceptibility) of the breccia differ significantly from those of the meta-graywackes and slate/phyllites. Fractures observed in the televiewer images indicate steep dip angles (50–70°) and the two main dip directions are southeast and southwest. Most fractures observed in the borehole are open. The indicated main stress direction is north-south. The analysis of the reflection seismic pattern beneath the central uplift provides further evidence for random distribution of physical rock properties (L'Heureux and Milkereit 2007).

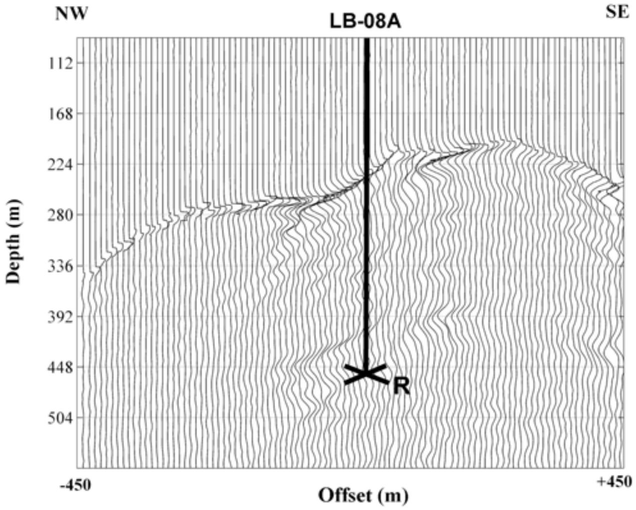

Fig. 15. Offset VSP records in borehole LB-08A (receiver located at bottom of hole). Air gun sources for offsets up to 450 m provide an image of the contact between the low-velocity post-impact sediments and the higher-velocity impactites (Vp > 2800 m/s). The wave front image confirms that hole LB-08A was drilled into the central uplift. The receiver location is marked by the X.

The resistivity of the impactite sequence was measured with a dual laterolog type resistivity tool in borehole LB-07A and LB-08A. The resistivities are measured with two different, strongly focused currents. The more sharply focused current is able to penetrate deeper into the rock giving the reading Rd. The hardly focused current stays close to the borehole wall and it gives the shallow reading Rs. How deep the currents can penetrate depends on the resistivity of the

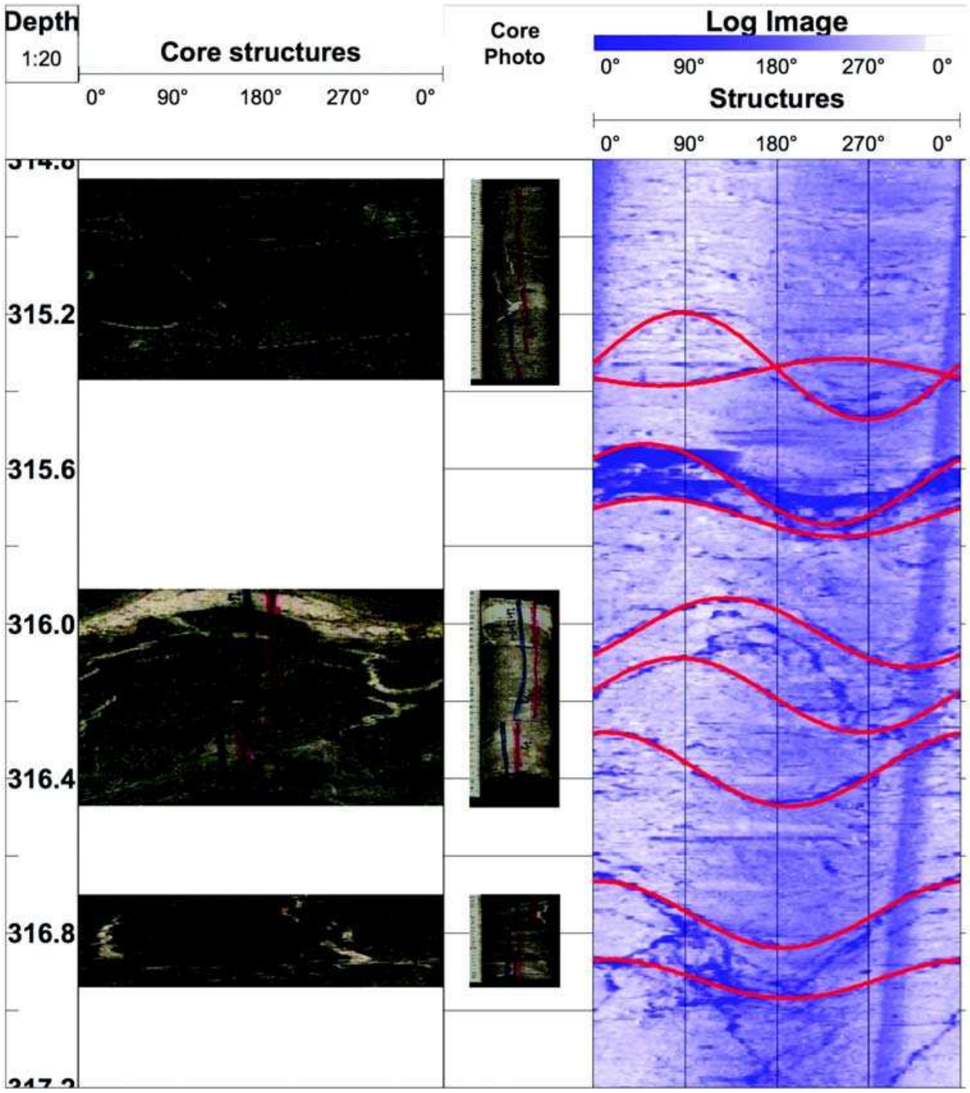

Fig. 16. Visual comparison of the core scan (portion of LB-08A) with the log image provides core orientation. An analysis of the log image is shown in Fig. 17.

rocks. The shallow resistivity can be a good indication of resistivities of the flushed (by drilling mud) zone around the borehole and deep resistivity infers that of a more or less undisturbed rock more far away from the hole. If mud with a different resistivity from the host rock invades the rock on "permeabilities" (micropermeability or fracs), it will change the total resistivity reading. The difference between Rd and Rs is an indicator for "flushed" rock around the borehole. Here, the Rs values parallel the trends in Rd values fairly well, indicating that even Rs has penetrated deep into the rock formation. The offset between Rd and Rs varies according to the difference in flushing of the rocks close and far from the borehole.

The resistivity data show poor correlation with lithologies as discriminated from core samples. Thus, the resistivity variations can be interpreted in terms of fracture porosity within the impactite sequence encountered in boreholes LB-07A and LB-08A. Using Archie's law with certain assumptions about pore fluid resistivity and rock matrix structure, we can calculate the porosity from the resistivity logging data. The absolute value of the porosity obtained is, however, dependent on these assumptions, but the relative change of the porosity in the impactite sequence is certain.

Figure 18 shows the porosity derived from resistivity measurements for boreholes LB-08A and LB-07A. The porosity changes from about 10 to 20 vol%. This preliminary result is in good agreement with porosity measurements obtained from melt-rich suevite (ejecta) from the lake Bosumtwi area and laboratory measurements on drill cores from the 2004 drilling (Elbra et al. 2007; Ugalde et al. 2007a, 2007b). The relative porosity highs seem to correlate with fracture zones seen in the televiewer images.

In summary, the analysis of full waveform sonic and resistivity logs, in conjunction with the petrophysical studies of selected core retrieved during drilling, revealed some surprising results: the impactites exhibit very high porosities (up to 30 vol%). These high porosities (close to the critical porosity) have important implications for mechanical rock stability.

Besides porosity, Fig. 18 also shows a compilation of compressional wave velocities and resistivities. The statistical analysis of the velocities and densities (L'Heureux and Milkereit 2007) reveals a seismically transparent (free of prominent internal reflections) impactite sequence—an observation consistent with results from the pre-drilling seismic surveys across the center of the impact structure. The densities obtained from the physical rock property studies on core material provided the basis for a 3-D gravity model for the Bosumtwi structure (Ugalde et al. 2007a). The central gravity anomaly is controlled by laterally varying densities (and porosities). In addition, the downhole borehole vector-magnetic data point to a patchy distribution of highly magnetic rocks within the sampled impactite sequence (Ugalde et al. 2007b).

DISCUSSION AND UNRESOLVED PROBLEMS

Lithology and Geochemistry

One of the most interesting problems for which the studies are not yet finished concerns the detailed shock barometry of the uplifted country rocks in the central peak area. First work by Ferrière et al. (2007b) indicates that there is a difference with depth, but so far this is based on only two levels; more work is necessary. If no clear evidence for a decrease of the shock levels with depth is found, this has implications for the interpretation of structure and formation of the central uplift (maybe in terms of juxtaposed megablocks). Another important aspect concerns the lack of coherent melt rocks (see below), and the observation that both the clast populations and the abundance of glass and melt fragments in fallback suevite (inside the crater) and fallout suevite (outside the crater rim) are quite different. Lastly, the source of the high indigenous contents of the siderophile elements (including the PGEs) is puzzling, and the resulting problems in determining the presence of a meteoritic component in these rocks remain unresolved. The lack of abundant melt rocks and glasses in the drill cores makes it difficult to fulfill one of the stated goals of the drilling project—refine the crater age—by radiometric dating.

Geophysical Models

The magnetic and gravity data (Danuor and Menyeh 2007) were modeled in 3-D (Ugalde et al. 2007a). This model, which was calibrated with the data available from the two ICDP deep boreholes, matches the previously collected seismic data for the sediment thickness and size of the central uplift; it allows lateral density variations and updates the results from previous 2.5-D modeling of the structure. The model succeeded in generating a three-dimensional sediment thickness grid across the crater, which correlates well with the available seismic and borehole data. For the first time it was recognized that the different pressure conditions induced by the impact, and the post-impact differential pore-space filling across the structure, have an effect on the density distribution. Lateral density variations inside and outside of the central uplift are supported by a previous velocity-depth model, porosity-depth analysis, petrophysical data, and by this new 3-D model of the structure. The thickness of the impactite unit (impact breccia, impact melt and fractured basement combined) is much smaller than predicted by numerical modeling (Artemieva et al. 2004).

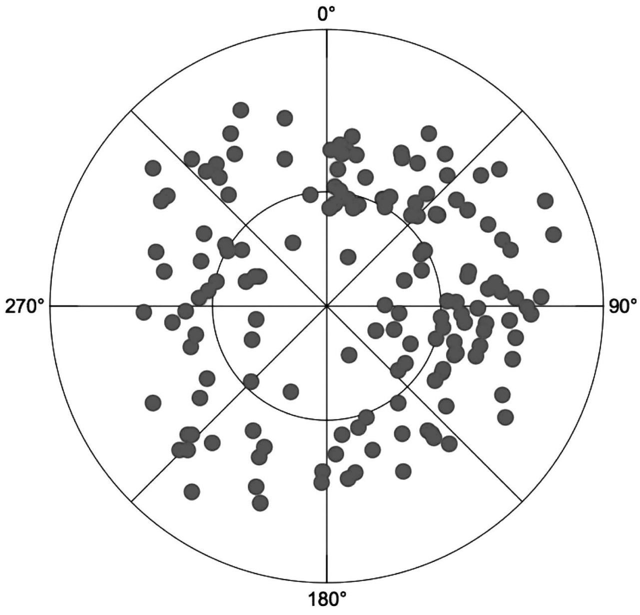

Fig. 17. Wulff stereonet plot (lower hemisphere), showing a random distribution of the dip direction of the structures determined from televiewer images in borehole LB-08A from 290 to 343 m depth.

Magnetic susceptibility and density measurements (Ugalde et al. 2007a, 2007b; Schell et al. 2007; Elbra et al. 2007) made on cores LB-07A and LB-08A from the Bosumtwi meteorite impact crater contain no evidence for a highly magnetic and dense melt sheet. Both density and magnetic susceptibility exhibit low amplitude contrasts between the uppermost polymict lithic breccia and suevite, the intermediate monomict lithic breccia and the lowermost bedrock. The depth extent of fracturing-related density reduction is much greater at LB-08A than at LB-07A. A total magnetic intensity log from borehole LB-08A supports the suggestion that magnetic anomalies over Lake Bosumtwi are mainly sourced in bedrock intrusions.

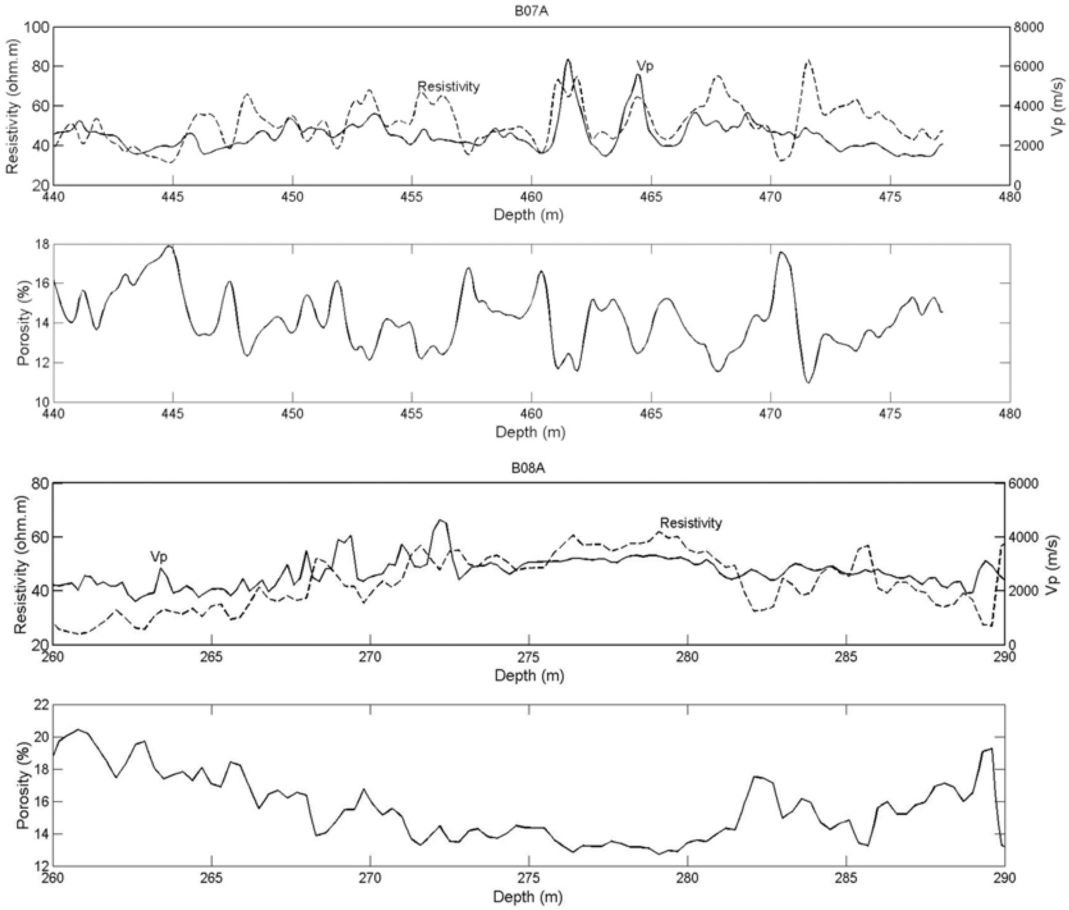

Fig. 18. Resistivity (dashed) and compressional wave velocity logs (solid lines) from boreholes LB-07A (top) and LB-08A (bottom) show comparable trends. Patterns of low P-wave velocity and associated low resistivity provide compelling evidence for high in situ porosities.

A revised 3-D magnetic model for the structure (Ugalde et al. 2007a) was constructed based on a newly acquired (on the lake) higher-resolution magnetic data set, which takes into account the observed gravity data on the lake, previous seismic models, and the magnetic properties and lithology mapped from the two deep boreholes into the structure. The new model, which reproduces the lake magnetic data within ±1 nT, contains highly magnetic bodies located in the northeast of the structure, beyond the drilling sites. As in previous models, higher magnetization than those measured in outcropping impactites had to be assigned for the non-outcropping source bodies. Integration of the new model with the borehole petrophysics and published geology indicates that these bodies correspond to an extension to the south of the Kumasi batholith, which outcrops to the northeast of the structure. On the other hand, this needs to be reconciled with the lack of granitoid clasts in the fallback suevite. The possibility that these source bodies are related to the seismically detected central uplift or to an unmapped impact melt sheet predicted by previous models of the crater is not supported. In the future, detailed magnetic mapping of the Kumasi batholith to the north, and the Bansu intrusion to the south, should provide better insights into this interpretation.

At this stage, it is difficult to reconcile some of the drilling results with predictions from geophysical modeling studies (such as the proposed thick homogeneous magnetic breccia melt layer) and numerical impact process simulations (melt breccia volume at the center of the structure).

Melt Production in the Bosumtwi Impact Event and Melt Content in Bosumtwi Drill Cores

Numerical modeling of the Bosumtwi impact event (Artemieva et al. 2004) was published prior to the start of the ICDP drilling project. Prior to drilling, correlation of the impact model and geophysical observations resulted in the following observations: a) the calculated crater size and its shape were comparable with the Bosumtwi topography (Scholz et. al. 2002; Karp et. al. 2002); b) the calculated distribution of tektites and microtektites agreed broadly with the actual distribution (e.g., Glass et. al. 1991); and c) predictions of melt volume within the crater were comparable with the magnetic model by Plado et al. (2000). It

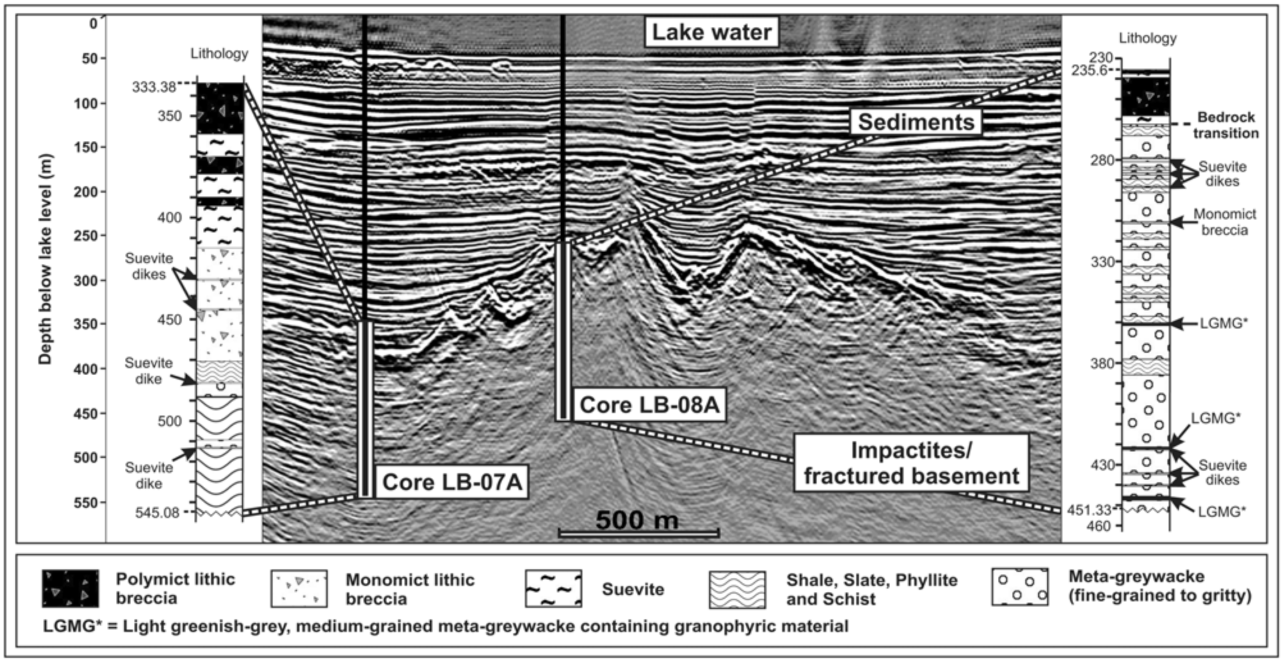

Fig. 19. Lithologies of the two hard-rock drill cores superimposed on the seismic profile, showing the clear connection between the two data sets and giving a summary of the lithological observations.

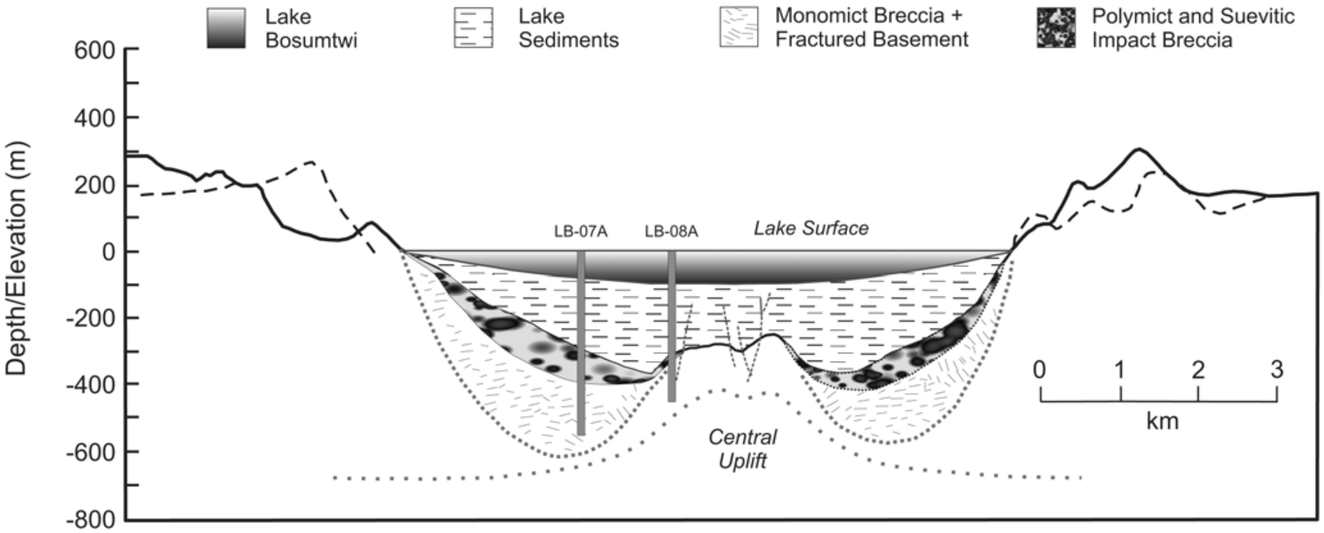

Fig. 20. An interpreted cross section of the Bosumtwi crater, based on the first results from the ICDP drilling project. The dashed line underneath the monomict breccia/fractured bedrock marks the zone in which a change to unfractured bedrock is expected. The dotted line indicates the approximate amount of central uplift underneath the structure.

was expected that the numerical study would provide predictions of the physical properties of the rocks in the drill cores: the value of maximum shock compression could be connected with shock metamorphic features in the target rocks; the presence of the projectile material could be confirmed by geochemical analysis of brecciated materials and melts; the temperature distribution would constrain the region of natural remanent magnetization, and in combination with predicted fracture distribution, it would define the zone of intensive post-impact hydrothermal activity. However, the now-available core material is very different from the predictions, because of the absence of a coherent melt sheet and very low melt content in core suevite, high porosity of impactites, and absence of clear trends regarding changes of shock metamorphism with depth, at least in core LB-07A. It is possible that the core did not reach a sufficient depth—

drilling to 1000 m might have shown a clearer development of the shock barometry.

An increase of melt volume with crater diameter increase is a well-known trend (see Fig. 3 in Grieve and Cintala 1992). Exceptions occur for the craters in sedimentary targets or with substantial sedimentary cover (e.g., Meteor Crater, Logoisk, Ries). Craters with mixed targets with diameters similar to Bosumtwi, from the database by Grieve and Cintala (1992), are Ilyinets (8 km in diameter) and Kaluga (15 km) with 0.7 and 8 km^3 of impact melt, respectively. Bosumtwi might be an anomaly in this trend.

Future research will investigate possible reasons of the low amount of melt and highly shock-compressed minerals. A decrease in impact velocity leads to a decrease of impact melt production. However, this dependence is not strong: it is easy to show that for a given crater size melt volume is approximately proportional to the cubic root of impact velocity, i.e., melt volume at the lowest velocity of 11.2 km/s is only 20% lower than at an average for the Earth impact velocity of 18 km/s. For the smallest craters (<3 km in diameter) final impact velocity may be substantially less than pre-atmospheric velocity because of strong disruption and deceleration of the projectile in atmosphere (Melosh and Collins 2005). This is a very special case in which a lot of projectile fragments and smaller secondary craters (strewn field) can be identified near the crater rim. The low-velocity low-angle scenario does not appear to be applicable for the Bosumtwi structure. The effects of several different target properties (e.g., lithology, or the influence of wet porosity) are explored by Artemieva (2007).

SUMMARY

Within the framework of an international and multidisciplinary, ICDP-led drilling project, 16 drill cores were obtained at six locations within Lake Bosumtwi (8.5 km in diameter) using the GLAD800 lake drilling system from June to October 2004. The 14 sediment cores are currently being investigated for paleoenvironmental indicators. The two impactite cores, LB-07A and LB-08A, were drilled into the deepest section of the annular moat (540 m) and the flank of the central uplift (450 m), respectively. The locations of these drill cores, and their schematic lithologies, are shown in Fig. 19 superimposed on the seismic profile. The first results from multidisciplinary studies of these drill cores—in terms of lithology, petrography, shock stages, petrophysics, chemical composition, geophysics, tied to detailed geological and geophysical studies of the crater, are described in 26 papers in this issue. A preliminary interpretation of the cross section of Bosumtwi, derived from some of these studies, is shown in Fig. 20. Despite some technical and logistic difficulties (e.g., getting stuck during drilling, supply problems; see above) the drilling project was highly successful and delivered information with unprecedented detail on the youngest large impact structure on Earth. Further work will be done to refine numerical modeling of the formation of this crater and of impact craters in general, and to evaluate the effects that this impact event had on the local and regional eco- and biosphere (building on work by Rampino and Koeberl 2006).

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