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Bosumtwi Impact Crater, Ghana (West Africa): An Updated and Revised Geological Map, with Explanations

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29 Text-Figures, 3 Tables and 1 Geological Map (in pocket)

Ghana
Lake Bosumtwi
Meteorit
Impaktkrater
Tektit
Impaktit
Strukturgeologie
Aerogeophysik
Petrographie

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Zusammenfassung

Die Bosumtwi-Impaktstruktur befindet sich in der Ashanti-Provinz (Ghana) und entstand in 2,1–2,2 Ga alten präkambrischen Metasedimenten und Metavulkaniten. Das Untersuchungsgebiet liegt in der bewaldeten Zone von Süd-Ghana (06°30'N und 01°25'W) in West-Afrika. Bosumtwi ist ein sehr gut erhaltener, nur 1,07 Ma alter komplexer Impaktkrater von ca. 10,5 km Durchmesser mit einem ausgeprägten Rand, und wird beinahe völlig vom Lake Bosumtwi mit ca. 8,5 km Durchmesser und bis zu 78 m Tiefe ausgefüllt. Bosumtwi ist einer von nur 19 derzeit nachgewiesenen afrikanischen Impaktkratern und steht im Zusammenhang mit einem von nur vier weltweit bekannten Tektit-Streufeldern (das Elfenbeinküsten-Tektitfeld).

Der Lake Bosumtwi ist aus verschiedenen Gründen sehr gut geeignet für eine detaiilierte Studie des Klimawandels in einer Äquatorialregion. Der See entwickelte sich in einem hydrogeologisch geschlossenen Becken; sein Tiefenwasser ist anoxisch. Dadurch kam es zur Erhaltung laminierter Warven in den Seesedimenten – ideale Voraussetzungen für eine hochauflösende paläoklimatische Jahr-für-Jahr-Rekonstruktion. Wegen seiner Bedeutung für Impaktgeologie und Paläoklimatologie war Bosumtwi in jüngster Zeit Gegenstand eines interdisziplinären und internationalen Bohrvorhabens des International Continental Scientific Drilling Program (ICDP). Ab der Mitte der 90er-Jahre wurden von multinationalen Teams geologische, geophysikalische, petrologische, geochemische und sedimentologische Untersuchungen im Impaktkrater und in den damit zusammenhängenden Brekzien und Strukturen und in den Seesedimenten durchgeführt. Methoden der Fernerkundung und geophysikalische Messungen (Gravimetrie, Magnetik, Reflexions- und Refraktions-Seismik) lieferten umfangreiches neues Datenmaterial über den Krater und seinen Untergrund.

Allerdings stammt die einzige Übersichtskartierung des Bosumtwi-Gebietes (zwei getrennte Kartenblätter der Umgebung des Sees) aus den 60er-Jahren. Die vorliegende Arbeit präsentiert eine zusammengefasste geologische Karte mit aktualisierten Informationen und widmet den impaktbezogenen Deformationen und der bisher bekannten Verteilung der Impaktbrekzien besondere Aufmerksamkeit.

Abstract

The Bosumtwi impact structure is located in the Ashanti Province of Ghana, and was formed in 2.1–2.2 Ga Precambrian metasedimentary and metavolcanic rocks. The location lies in the forest zone of southern Ghana, centered at 06°30'N and 01°25'W in West Africa. Bosumtwi is a very well-preserved, only 1.07 Ma old complex impact crater of ca. 10.5 km diameter. The crater displays a pronounced rim and is almost completely filled by the about 8.5 km diameter Lake Bosumtwi, which is up to 78 m deep in its central part. Bosumtwi is one of only 19 currently confirmed African impact craters and is associated with one of only four tektite strewn fields (the Ivory Coast tektite field) known wordwide.

Lake Bosumtwi has several important characteristics that make it well suited to provide a detailed record of climate change in an equatorial region. The lake developed in a hydrologically closed basin, and the deep water is anoxic, which has led to the preservation of laminated sediment varves in the lake sediments, providing a means for high resolution (annual) paleoclimate reconstruction. Because of its importance for impact geology and paleoclimatology, Bosumtwi was recently the subject of an interdisciplinary and international drilling effort of the International Continental Scientific Drilling Program (ICDP). From the mid 1990s, renewed interest in Bosumtwi led to geological, geophysical, petrological, geochemical, and sedimentological studies of this impact crater, the associated impact breccias and geological structure, and lake sediments, by several multinational teams. Remote sensing and geophysical measurements (gravity, magnetics, reflection and refraction seismics) provided abundant new data on the crater and its subsurface.

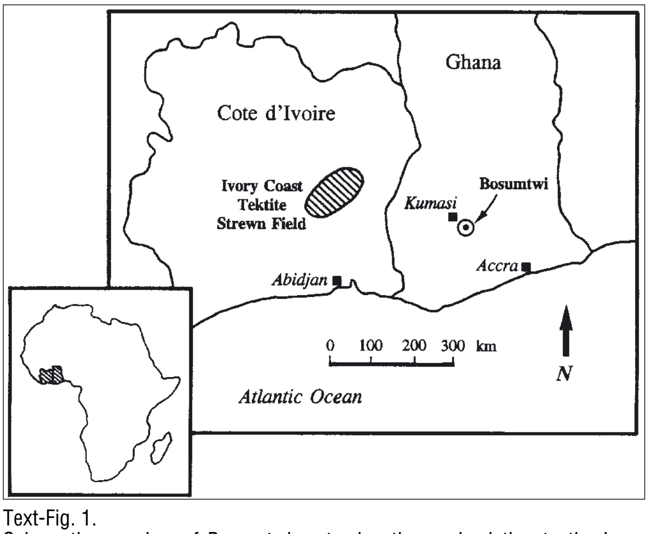
However, the only comprehensive regional mapping around Bosumtwi dates to the 1960s, when the geology of the environs of the lake was recorded on two separate map sheets. The purpose of the present work is to present a unified geological map that also includes new and updated information and emphasizes impact-induced deformation and known distribution of impact breccias.

1. Introduction

The Bosumtwi impact crater is located in the Ashanti Province of southern Ghana in West Africa. It is situated near the regional capital town of Kumasi, which is also the second largest city in Ghana as well as the capital of the Ashanti Kingdom. The Bosumtwi structure is centered at 06°32'N and 01°25'W (Text-Fig. 1). It is one of only 19 confirmed impact structures known in Africa, and is the youngest well-preserved complex impact crater known on Earth. The structure, which has an age of 1.07 million years, is almost completely filled by Lake Bosumtwi of roughly 8.5 km diameter, and has a rim-to-rim diameter of about 10.5 km. The following sections summarize important aspects of Bosumtwi, and additional details of some of these (with references) are given in the following chapters.

Since the 1930s, the origin of the Bosumtwi crater structure has been debated between geologists and geographers that either favored an origin by volcanism or, though very rarely, by meteorite impact. Only in the 1960s did this second hypothesis take hold, in particular because of the recognition that Bosumtwi could be the source crater for the Ivory Coast tektites. Ivory Coast tektites were first reported in 1934 from a geographically rather restricted area in the Ivory Coast (Côte d'Ivoire), West Africa (Text-Fig. 1). Microtektites occur in deep-sea sediments of corresponding age in the eastern equatorial Atlantic Ocean west of Africa. Ivory Coast tektites and the Bosumtwi crater have the same age, and there are close similarities between the isotopic and chemical compositions of the tektites and crater rocks.

Lake Bosumtwi is a closed-basin lake with strong paleoclimate significance and a detailed paleo-environmental record. The lake is at an ideal geographical location to provide data on climate variations, with time scales ranging from seasonal to very long-term (Milankovitch), for the West African monsoon and Sahel drought activity. Lake Bosumtwi has accumulated a detailed record of varved lake sediments that can be used to monitor both past local and Sahel rainfall variations. Rainfall over much of sub-Saharan Africa has been highly correlated on centennial



Text-Fig. 1.
Schematic overview of Bosumtwi crater location and relation to the Ivory Coast tektite strewn field.
From KOEBERL et al. (1998).

and longer time scales. A complex record of changes in lake level, lake chemistry, climate, and vegetation history has been documented since the 1970s by shallow piston core studies. Recent work has confirmed the potential of such paleoclimatic studies.

Petrographic and geochemical work during the past 10 years confirmed the presence of shock metamorphic effects and the presence of a meteoritic component in the Ivory Coast tektites as well as in the breccias at the crater. Insights into the deep structure of the crater and the distribution and nature of ejected material and post-impact sediments were obtained by geophysical work since 1998, which included aeromagnetic and airborne radiometric mapping, multi-channel seismic reflection and refraction profiles, and land- and barge-based gravity and magnetic studies. The seismic studies documented the existence of a central uplift underneath the lake sediments.

2. Purpose and Layout of this Work

Despite the renewed research activities at and around Bosumtwi, no update on the geology of the crater and its environs has been published since the 1970s. Geological fieldwork began early in the 20th century, and in the 1960s two geological maps of the region around Bosumtwi were published (see below, section 3.2.), without any attempt to combine these two works. As the Bosumtwi impact crater is clearly the most interesting geological feature in this region, which however also enjoys considerable geological interest because of known gold deposits in the wider region and strong gold exploration interest in the actual crater area, and Bosumtwi, as shown above, is a structure of world-class scientific importance, we decided to compile a single updated geological map of the Bosumtwi impact crater and its immediate environs. This map is based on the early geological maps by WOODFIELD (1966) and MOON & MASON (1967), with additional new and updated information added. The two topographic maps (Bosumtwi topography is also split into two sheets, No. 0602D1 for the southern part and No. 0602B3 for the northern part) of the Survey Department of Ghana of 1972 were used as a basis for this compilation. Where possible, road information within the vicinity of the crater was updated based on GPS measurements by the compilers and collaborators. A new overlay with geological information was created from the maps of MOON & MASON (1967) and WOODFIELD (1966), and newer information. Splicing the topographic maps and the previous geological maps together was difficult because of inconsistencies and color differences between the original maps. The scale of the map (all original maps of Ghana were produced at the scale of 1 : 62,500) was changed to 1 : 50,000. However, for consistency reasons, the coordinate and projection systems used in the previous maps had to be kept for the present map as well. The color scheme of the map was adapted as closely as possible to the new scheme used today by the Ghana Geological Survey Department (GSD) (D. BOAMAH, GSD, pers. comm., 2004).

New and updated geological information used for the present map was obtained from the following sources: A Ph.D. thesis by P. WATKINS (1994) (courtesy of E. SHARP, University of South Carolina, Columbia, USA), who mapped parts of the northeast quadrant of the crater rim and environs (see also information in WATKINS & ILIFFE [1990]; WATKINS et al. [1993] and BROMAN et al. [1997]); fieldwork around the whole crater by the compilers in 1997, which was aimed at documentation of the distribution of impact breccia and of impact-related structural deformation – this included detailed structural work along (then) extensive roadcuts across the northern part of the crater rim (cf. REIMOLD et al., 1998); fieldwork in the northern part of the structure by one of the compilers (CK) and D. BOAMAH (GSD) in 1999; subsequent fieldwork and shallow drilling by D. BOAMAH (GSD) as part of his Ph.D. thesis (BOAMAH, 2001); and field work and on-site editing in 2004 by the compilers and by A. DEUTSCH (University of Münster, Germany).

The following chapters summarize the current knowledge about the Bosumtwi crater, with particular emphasis on the description of the rock types found at the crater; this document constitutes the "Explanations" to the new geological map.

3. The Bosumtwi Impact Structure

3.1. Importance of Impact Cratering

This section provides a very short introduction to the importance and characteristics of impact structures (following mostly reviews by KOEBERL [2001 and 2002] and KOEBERL & MARTINEZ-RUIZ [2003]). These few paragraphs should introduce non-expert users of the Bosumtwi map to this topic, as Bosumtwi is an impact crater, and various terms that will be introduced later can only be understood in the context of its impact origin.

All bodies in the solar system – planets, moons, asteroids, etc. – that have solid surfaces are covered by craters. In contrast to many other planets and moons in the solar system, the recognition of impact craters on the Earth is difficult, because active geological and atmospheric processes on our planet tend to obscure or erase the impact record in geologically short times. Impact craters can only be recognized from the study of their rocks – remote sensing and geophysical investigations can only provide initial hints at the possible presence of an impact crater or supporting information. Petrographic studies of rocks at impact craters can lead to the confirmation of impact-characteristic shock metamorphic effects, and geochemical studies may yield information on the presence of meteoritic components in these rocks. Craters of any type and morphology are not an obvious and common landform. About 170 impact structures are currently (2005) known on Earth (updates are available on the internet, see the "Earth Impact Database", at: http://www.unb.ca/passc/ImpactDatabase/index.html). Considering that some impact events demonstrably affected the geological and biological evolution on Earth (e.g., papers in KOEBERL & MACLEOD [2002], BUFFETAUT & KOEBERL [2003]), and that even small impacts can disrupt the biosphere and lead to local and regional devastation (e.g., CHAPMAN & MORRISON, 1994), the understanding of impact structures and the processes by which they form should be of interest not only to earth scientists, but also to society in general.

When discussing morphological aspects, we need to mention the distinction between an impact crater, i.e., the feature that results from the impact, and an impact structure, which is what we observe today, i.e., long after formation and modification of the crater. Thus, unless a feature is fairly fresh and unaltered by erosion, it should rather be called an "impact structure" than an "impact crater". Impact craters (before post-impact modification by erosion and other processes) occur on Earth in two distinctly different morphological forms. They are known as simple craters (small bowl-shaped craters) with diameters up to about 2 to 4 km, and complex craters, which have larger diameters.

Complex craters are characterized by a central uplift (such as that found at Bosumtwi – see section 5.). Craters of both types have an outer rim and are filled by a mixture of fallback ejecta and material slumped in from the crater rim during the early phases of cratering. Such crater infill may include brecciated and/or fractured rocks, and impact melt rocks. Fresh simple craters have an apparent depth (crater rim to present-day crater floor) that is about one third of the crater diameter. For complex craters, this value is closer to one fifth or one sixth. The central structural uplift in complex craters commonly exposes rocks that are usually uplifted from considerable depth and thus contrast with the stratigraphic sequence of the environs around the impact structure. On average, the actual stratigraphic uplift amounts to about 0.1 of the crater diameter (e.g., MELOSH, 1989).

Remote sensing and morphological observations may yield important initial data regarding the recognition of a potential impact structure (such as annular drainage patterns or topographic ring structures), but cannot provide confirming evidence. Geological structures with a circular outline that are located in places with no other obvious mechanism for producing near-circular features may be of impact origin and at least deserve further attention. Geophysical methods are also useful in identifying candidate sites for further studies, especially for subsurface features. In complex craters the central uplift usually consists of dense basement rocks and usually contains severely shocked material. This uplift is often more resistant to erosion than the rest of the crater, and, thus, in old eroded structures the central uplift may be the only remnant of the crater that can still be identified.

Geophysical characteristics of impact craters include gravity and magnetic properties, distinct reflection and/or refraction seismic signatures, electrical resistivity anomalies, and others (see, e.g., GRIEVE & PILKINGTON [1996] for a review). In general, simple craters have negative gravity anomalies due to the lower density of the brecciated rocks compared to the unbrecciated target rocks outside of the structure, whereas complex craters often have a positive gravity anomaly associated with the central uplift of dense rocks originally located lower in the Earth's crust. This central positive gravity anomaly may be surrounded by an annular negative anomaly. Magnetic anomalies can be more varied than gravity anomalies (e.g., HENKEL & REIMOLD, 2002). The target rocks may have been magnetically diverse, but the impact event may also cause anomalies related to impact-induced remanence. Seismic investigations of impact structures often show the loss of seismic coherence due to structural disturbance, slumping, and brecciation. Such geophysical surveys are important for the recognition of anomalous subsurface structural features, which may be deeply eroded craters or impact structures entirely covered by post-impact sediments. In the past decades a large number of impact structures have been identified in the course of geophysical and drilling surveys related to hydrocarbon and other economic exploration (GRIEVE & MASAITIS, 1994; REIMOLD et al., 2005).

Only the petrographic and geochemical study of actual rocks from the potential impact structure will bring final confirmation of the presence of an impact structure. In case of a structure that is not exposed on the surface, drill core samples are essential. Good materials for the recognition of evidence for an impact origin are various types of breccia and melt rocks. These rocks often carry unambiguous evidence for the impact origin of a structure in the form of shocked mineral and lithic clasts or a contamination from the extraterrestrial projectile.

The crater fill consists of a variety of breccia types. Fragmental impact breccia is a "monomict or polymict impact breccia with clastic matrix containing shocked and unshocked mineral and lithic clasts, but lacking cogenetic impact melt particles" (STÖFFLER & GRIEVE, 1994). These rocks have also been termed lithic breccia (FRENCH, 1998). Impact melt breccia has been defined by STÖFFLER & GRIEVE (1994) as an "impact melt rock containing lithic and mineral clasts displaying variable degrees of shock metamorphism in a crystalline, semihyaline or hyaline matrix (crystalline or glassy impact melt breccias)" (with an impact melt rock being a "crystalline, semihyaline or hyaline rock solidified from impact melt"). Suevite (or suevitic breccia) is defined as a "polymict breccia with clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism including cogenetic impact melt particles which are in a glassy or crystallized state". The distribution of the rock types is a function of their formation and the order in which they formed. For example, lithic breccias and suevite can occur not only inside (fallback breccia or injected into the crater floor), but also outside a crater (fallout breccia).

For the identification of meteorite impact structures, suevites and impact melt breccias (or impact melt rocks) are the most commonly studied units. It is easy to distinguish between the two impact formations, as suevites are polymict breccias that contain inclusions of melt rock (or impact glass) in a clastic groundmass, and impact melt breccias have a melt matrix with a variable amount of (often shocked) rock fragments as clasts (they are also referred in the literature as "melt-matrix breccias"). Whether these various breccia types are indeed present and/or preserved in a crater depends on factors including the size of the crater, the composition (e.g., crystalline rocks or sedimentary rocks), and the degree of porosity of the target, and the level of erosion of an impact structure. In cases of very deeply eroded structures, only remnants of injected impact breccias in the form of veins or dikes may have remained. Besides injections of suevite and impact melt rock, and local (in situ) formations of monomict or polymict clastic impact breccia, this may involve veins and pods of so-called "pseudotachylitic breccia" which is known from a number of impact structures. This material may closely resemble what is known as "pseudotachylite", the term for "friction melt", and indeed has been referred as this extensively in the literature. However, it has become clear in recent years that not all of the formations of such appearance actually represent friction melt, but also include impact melt rock and even tectonically produced fault breccias (friction melt, mylonite, or cataclasite). Thus, it is prudent to verify the nature of any such material before labeling it with a genetic lithological term (REIMOLD & GIBSON, 2005).

The rocks in the crater rim zone are usually only subjected to relatively low shock pressures (commonly <2 GPa), leading mostly to fracturing and brecciation, and often do not show shock-characteristic deformation. Even at craters of several kilometers in diameter, crater rim rocks that are in situ rarely show any evidence of shock deformation. However, there may be injections of impact breccias that may contain shock metamorphosed mineral and rock fragments. In well-preserved impact structures the area immediately outside the crater rim is covered by a sequence of different impactite deposits, which often allow the identification of these structures as being of impact origin.

The presence of shock metamorphic effects constitutes confirming evidence for impact processes. In nature, shock metamorphic effects are uniquely characteristic of shock levels associated with hypervelocity impact. Shock metamorphic effects are best studied in the various breccia types that are found within and around a crater structure, as well as in the formations exhumed in the central uplift area. During impact, shock pressures of >100 GPa and temperatures >3000°C are produced in large volumes of target rock. These conditions are significantly different from conditions for endogenic metamorphism of crustal rocks, with maximum temperatures of 1200°C and pressures of usually <2 GPa. Shock compression is not a thermodynamically reversible process, and most of the structural and phase changes in minerals and rocks are uniquely characteristic of the high pressures (diagnostic shock effects are known for the range from 8 to >50 GPa) and extreme strain rates (10^6–$10^8\,s^{-1}$) associated with impact. The products of static compression, as well as those of volcanic or tectonic processes, differ from those of shock metamorphism, because of lower peak pressures and strain rates that are different by many orders of magnitude.

A wide variety of shock metamorphic effects has been identified. The most common ones include planar microdeformation features, optic mosaicism, changes in refractive index, birefringence, and optic axis angle, isotropization (e.g., formation of diaplectic glasses), and phase changes (high pressure phases; melting). Kink bands (mainly in micas) have also been described as a result of shock metamorphism, but can also be the result of normal tectonic deformation (for reviews, refer to, for example, STÖFFLER & LANGENHORST [1994]; GRIEVE et al. [1996]; FRENCH [1998]).

Planar microstructures are the most characteristic expressions of shock metamorphism and occur as planar fractures (PFs) and planar deformation features (PDFs). The presence of PDFs in rock-forming minerals (e.g., quartz, feldspar, or olivine) provides diagnostic evidence for shock deformation, and, thus, for the impact origin of a geological structure or ejecta layer (see, e.g., STÖFFLER & LANGENHORST [1994]; MONTANARI & KOEBERL [2000] and references therein). PFs, in contrast to irregular, non-planar fractures, are thin fissures, spaced about 20 μm or more apart. While they are not considered shock diagnostic per se, should they be observed in significant abundance and particularly in relatively densely spaced sets of multiple orientations, they can provide a strong indication that shock pressures around 5–10 GPa were at play. To an inexperienced observer, it is not always easy to distinguish "true" PDFs from other lamellar features (fractures, fluid inclusion trails, tectonic deformation bands).

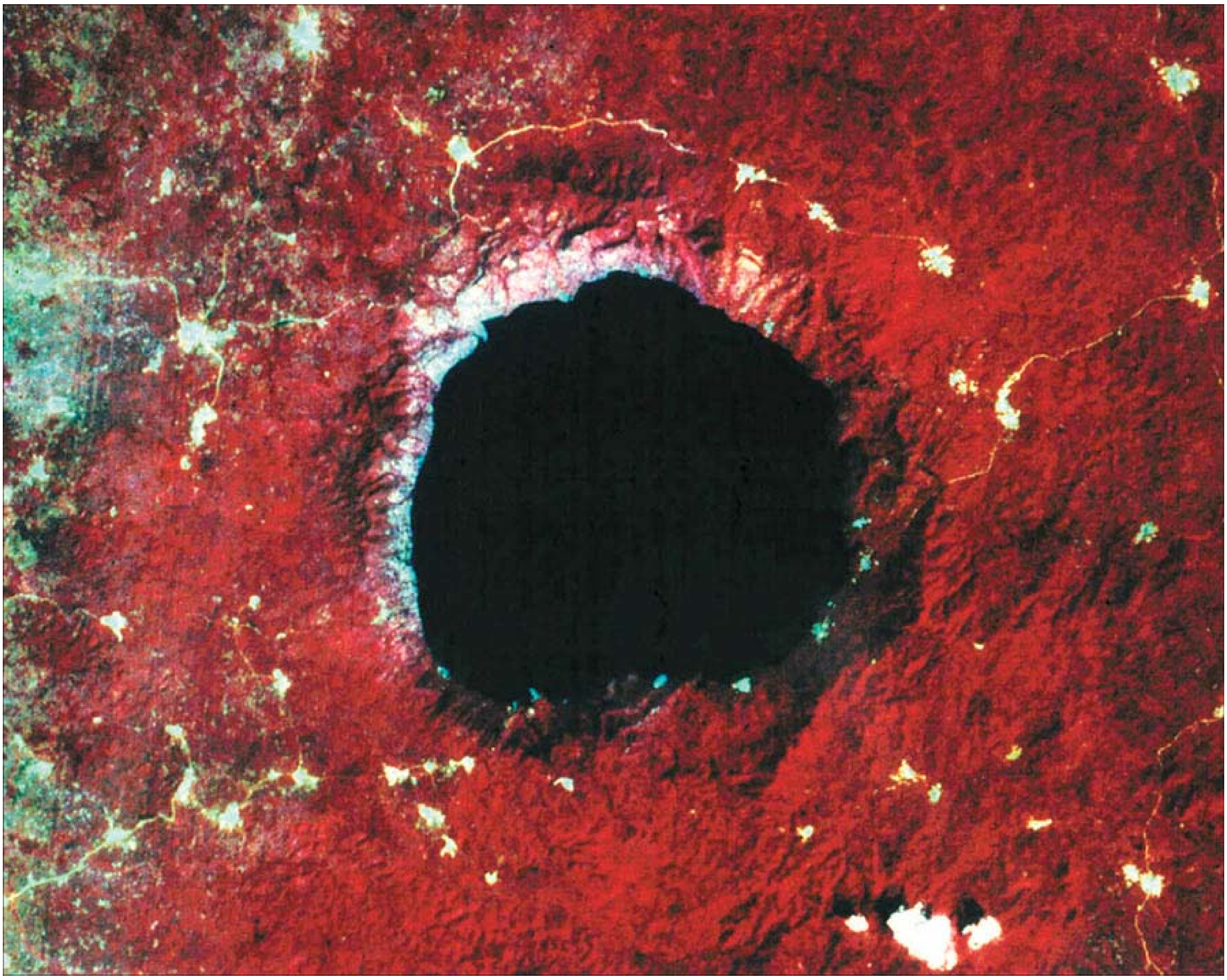
The most important characteristics of PDFs are: they are extremely narrow, closely and regularly spaced, completely straight, parallel, often extend (though not always) through a whole crystal, and at shock pressures above about 15 GPa occur in more than one set of specific crystallographic orientation per grain. This way, they can be distinguished from features that are produced at lower

Text-Fig. 2.
Panoramic views of the Bosumtwi impact crater.
a) View from the top of the north rim, looking south.
b) View from the southwestern part of the crater rim, looking towards the northeast. Both photographs taken (CK) in September 2004.
c) Aerial panoramic photos taken (C. KOEBERL) by helicopter in September 2004, view from the northeast towards the southwest.

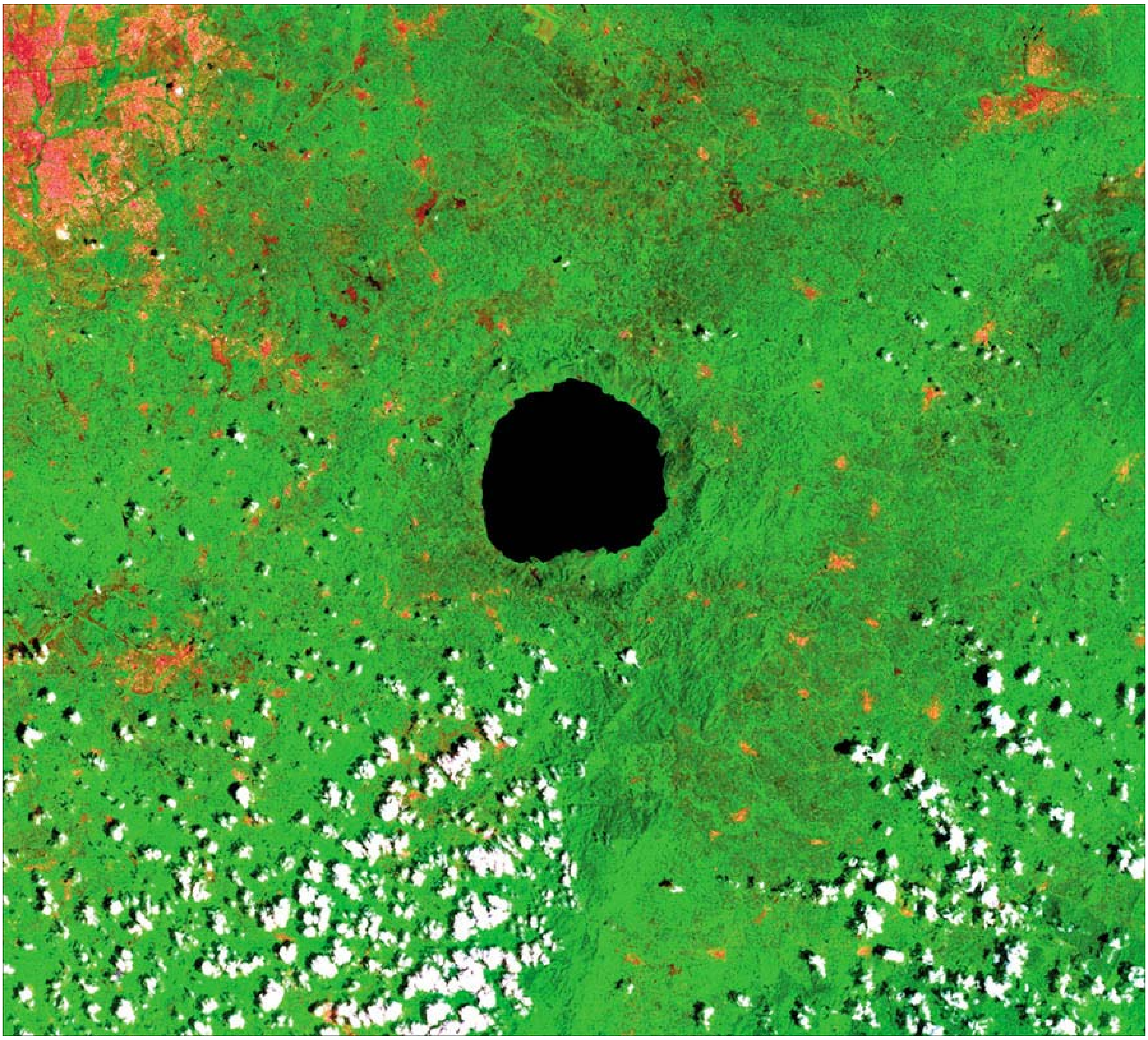
strain rates, such as the tectonically formed Böhm lamellae, which are not completely straight, occur only in one set, usually consist of bands >10 μm wide, and spaced at distances of >10 μm. It was demonstrated from Transmission Electron Microscopy (TEM) studies that PDFs originally consist of amorphous silica, i.e., they are planes of amorphous quartz that extend through the quartz crystal. This allows them to be preferentially etched by, e.g., hydrofluoric acid, emphasizing the planar deformation features (see, e.g., MONTANARI & KOEBERL, 2000). PDFs occur in planes that correspond to specific rational crystallographic orientations (for details, see, e.g., STÖFFLER & LANGENHORST [1994]). With increasing shock pressure, the distances between the planes decrease, and the PDFs become more closely spaced and more homogeneously distributed through the grain, until at about 30–35 GPa the grains show complete isotropization. Depending on the peak pressure, PDFs are observed in about 2 to 10 orientations per grain. To confirm the presence of PDFs, it is necessary to measure their crystallographic orientations by using either a universal stage or a spindle stage, or to characterize them by TEM. Because PDFs are well developed in quartz (STÖFFLER & LANGENHORST, 1994), a very widely observed rock-forming mineral, and because their crystallographic orientations are easy to measure in this mineral, most studies report only shock features in quartz. However, other rock-forming minerals, as well as accessory minerals, develop PDFs as well. If PDFs become annealed/metamophosed they evolve into planar fluid inclusion trails, or “decorated PDFs”.

The detection of small amounts of meteoritic matter in breccias and melt rocks can also provide confirming evidence of impact, but it is extremely difficult. Only elements that have high abundances in meteorites, but low ones in terrestrial crustal rocks, are useful – for example, the siderophile platinum-group elements (PGEs; Ru, Rh, Pd, Os, Ir, and Pt) and other siderophile elements (e.g., Co, Ni). Elevated siderophile element contents in impact melt rock or melt-rich suevite, compared to target rock abundances, can be indicative of the presence of either a chondritic or an iron meteoritic component. Achondritic projectiles (stony meteorites that underwent magmatic differentiation) are much more difficult to trace, because they have significantly lower abundances of the key siderophile elements. It is also necessary to sample all possible target rocks to determine the so-called indigenous component (i.e., the contribution to the siderophile element content of the impact melt rocks from the target), to ascertain that no possibly siderophile element rich mantle-derived target rock has remained undetected.

So far, meteoritic components have been identified for just over 40 impact structures out of the more than 170 impact structures currently identified on Earth. The situation at Bosumtwi is somewhat complicated because of high indigenous abundances of siderophile elements (see section 8.7.).



Text-Fig. 3.
Spot satellite image of the Bosumtwi impact structure. North is up; the lake is 8.5 km wide.
This false-color image (red shows vegetation) clearly indicates the densely vegetated area around the crater.



Text-Fig. 4.
Aster Satellite image of the Bosumtwi impact structure. North is up.
Band combination 7, 3, and 1, contrast-enhanced.

3.2. Location and Background Information

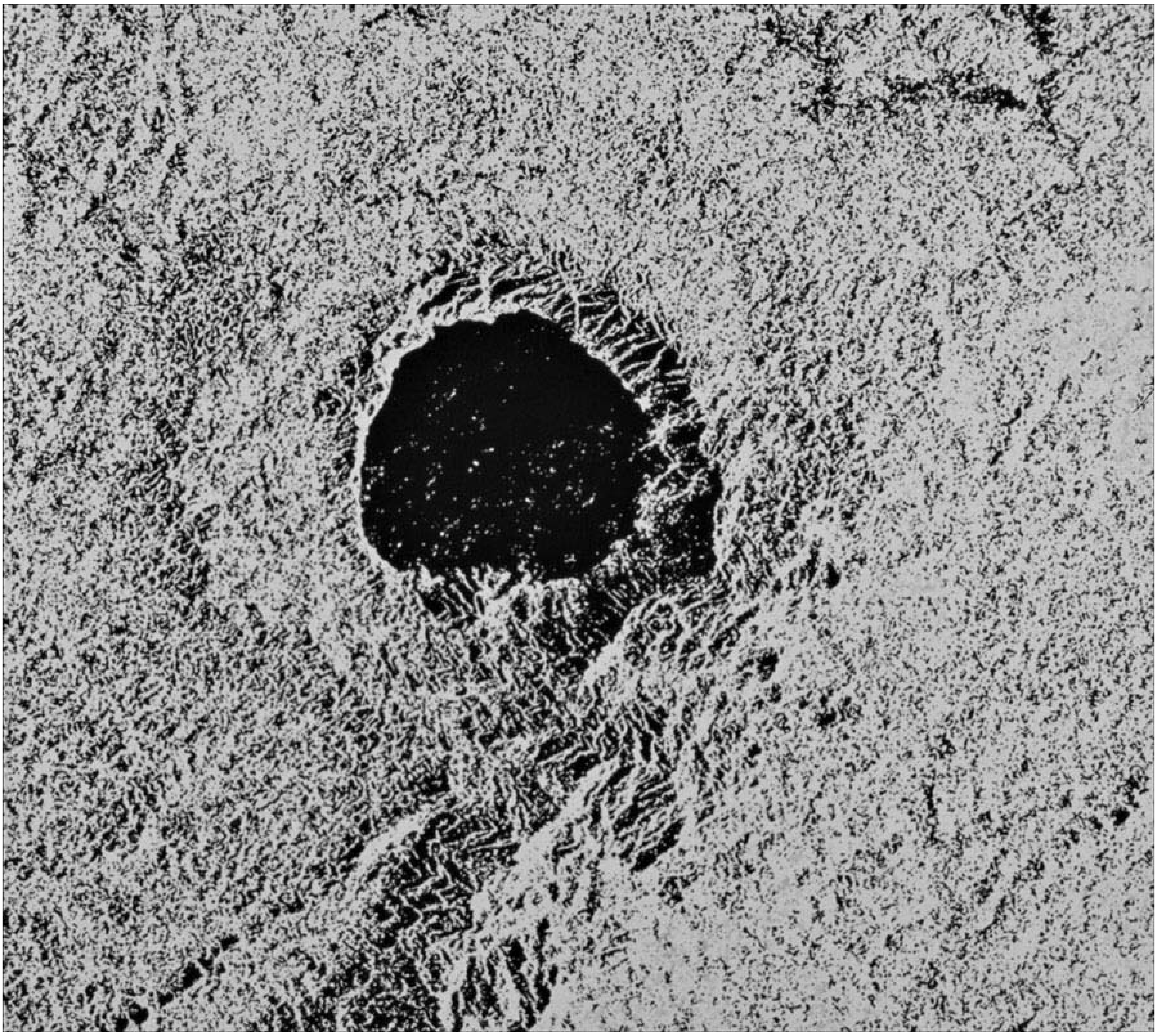
Bosumtwi is one of only 19 currently confirmed African impact craters (KOEBERL, 1994a; MASTER & REIMOLD, 2000), and one of only four known impact craters worldwide that are associated with tektite strewn fields (KOEBERL et al., 1997a).

The Bosumtwi location is shown in Text-Fig. 1. The 1.07 Ma Bosumtwi crater (centered at 06°30'N and 01°25'W) is situated in the Ashanti Region of Ghana, West Africa, and is centered about 32 km east of Kumasi, the regional capital. It is a well-preserved complex impact structure that displays a pronounced rim and is almost completely filled by the 8.5 km diameter Lake Bosumtwi (see the panoramic views in Text-Fig. 2a–c).

The crater was excavated in 2.1–2.2 Ga old metamorphosed supracrustal rocks of the Birimian Supergroup (JUNNER, 1937; WRIGHT et al., 1985; HIRDES et al., 1990; LEUBE et al., 1990; WATKINS et al., 1993) that are intruded by various, but mostly granitic, intrusive crystalline rocks. The crater structure has a rim-to-rim diameter of about 10.5 km. The prominent (i.e., well-preserved) crater rim is elevated by 210–350 m above the lake level; the lake level is about 80 to 100 m below the terrane outside of the rim. In satellite images the crater is a distinct feature of somewhat asymmetrical geometry, as discussed by WAGNER et al. (2002). The lake that fills the crater is also not completely circular, as is easily seen on satellite images (Text-Figs. 3, 4).

The region around Lake Bosumtwi is widely covered by very dense, tropical rainforest. Where less dense vegetation is observed, this frequently represents patches of agricultural activity. Cocoa plantations cover a significant area in the environs and on top of the rim of the structure.

Outcrop is generally scarce and mostly limited to exposure or suboutcrop along roads, some outcrop – often badly weathered – in stream beds, and occasional small exposures on steep slopes. Stream sections were the most important source of information during the extensive mapping of the 1960s (JUNNER, 1937; WOODFIELD, 1966; MOON & MASON, 1967) and for our own observations. Some shallow drilling has been carried out along the outer northern



Text-Fig. 5.
ERS1 radar satellite image of the Bosumtwi region, showing the steep crater rim, the Obuom range to the South, as well as the faint topographic annual feature at about 18–20 km diameter. North is up.

slope of the crater rim and into the surrounding shallow rim syncline (BOAMAH & KOEBERL, 1999, 2002, 2003).

The Bosumtwi impact crater is a well-preserved, ca. 10.5 km wide complex crater structure with a very pronounced rim (Text-Figs. 3–5). The interior is filled to a diameter of 8.5 km by Lake Bosumtwi, which has a maximum water depth of ca. 80 meters. Recent geophysical analysis has shown that there is a small (ca. 1.9 km wide and 130 m high) central uplift in the central part of the structure (KARP et al., 2002; SCHOLZ et al., 2002). The crater itself is surrounded by a shallow, near-circular, but very slight depression at ca. 7 to 8.5 km from the structural center, and a shallow outer topographic ring feature at 18–20 km diameter (JONES et al., 1981; GARVIN & SCHNETZLER, 1994; REIMOLD et al., 1998; WAGNER et al., 2002). This topography is also evident in radar satellite images (e.g., Text-Figs. 5–7a), as well as in the regional drainage pattern (Text-Fig. 7b) (see also MOON & MASON [1967]; WAGNER et al. [2002]), and the latter authors have discussed that preferential removal of ejecta within the area just outside of the crater rim could be the reason for this shallow depression. To the southeast of the crater and actually extending into the southeastern sector of the crater structure, is the Obuom Hill range of up to about 700 m elevation within a few kilometers south of the crater rim. It appears that the pre-impact existence of this range could be a reason for the non-circular appearance of the southern part of the impact structure (WAGNER et al., 2002).

Our knowledge of the Bosumtwi impact structure is still fairly limited. The only detailed structural evaluation of a cross section through the crater rim and detailed petrographic studies of rocks found along the crater rim and of ejecta (suevitic breccias) have been carried out very recently (REIMOLD et al., 1998; KOEBERL et al., 1998; BOAMAH & KOEBERL, 1999, 2002, 2003) and refer only to rocks available at surface exposures (see below) and in shallow boreholes through the ejecta blanket. No comprehensive petrographic and geochemical studies are available yet for basement rocks and impact breccias, with exception of the work by KOEBERL et al. (1998), but analysis of the recently obtained drill cores from the crater interior will address that need. The detailed structural aspects of the central part of the crater are unknown. Until a few years ago only some very general geophysical studies of the area have been available (JONES et al., 1981), but recently the work of PLADO et al. (2000), KARP et al. (2002), SCHOLZ et al. (2002), and PESONEN et al. (2003) provided much needed geophysical assessment of the crater and its surroundings (see below, section 5). Understanding the subsurface crater structure is important for determining the connection between the various country rocks and impact breccias, as well as for constraining numerical models of the formation of this structure.

The Bosumtwi impact crater was excavated in lower greenschist facies metasediments of the 2.1–2.2 Ga Birimian Supergroup (cf. WRIGHT et al., 1985; LEUBE et al., 1990; WATKINS et al., 1993). These supracrustals comprise interbedded phyllites/mica and quartz-feldspar schists and meta-tuffs, together with meta-graywackes, quartzitic graywackes, shales and slates. Birimian metavolcanic rocks (altered basic intrusives with some intercalated metasediments) occur to the southeast of the crater. Clastic sedimentary rocks of the Tarkwaian Group, which are regarded as the detritus after erosion of Birimian rocks (LEUBE et al., 1990), occur to the east and southeast of the crater. The late Proterozoic supracrustal strata are locally intruded by a series of granitic-dioritic bodies that have been related by regional geologists to the Pepiakese and Kumasi intrusions (WOODFIELD, 1966; MOON & MASON, 1967). A range of mafic intrusions, mostly in the form of local dike and sill developments, are known from the entire region.

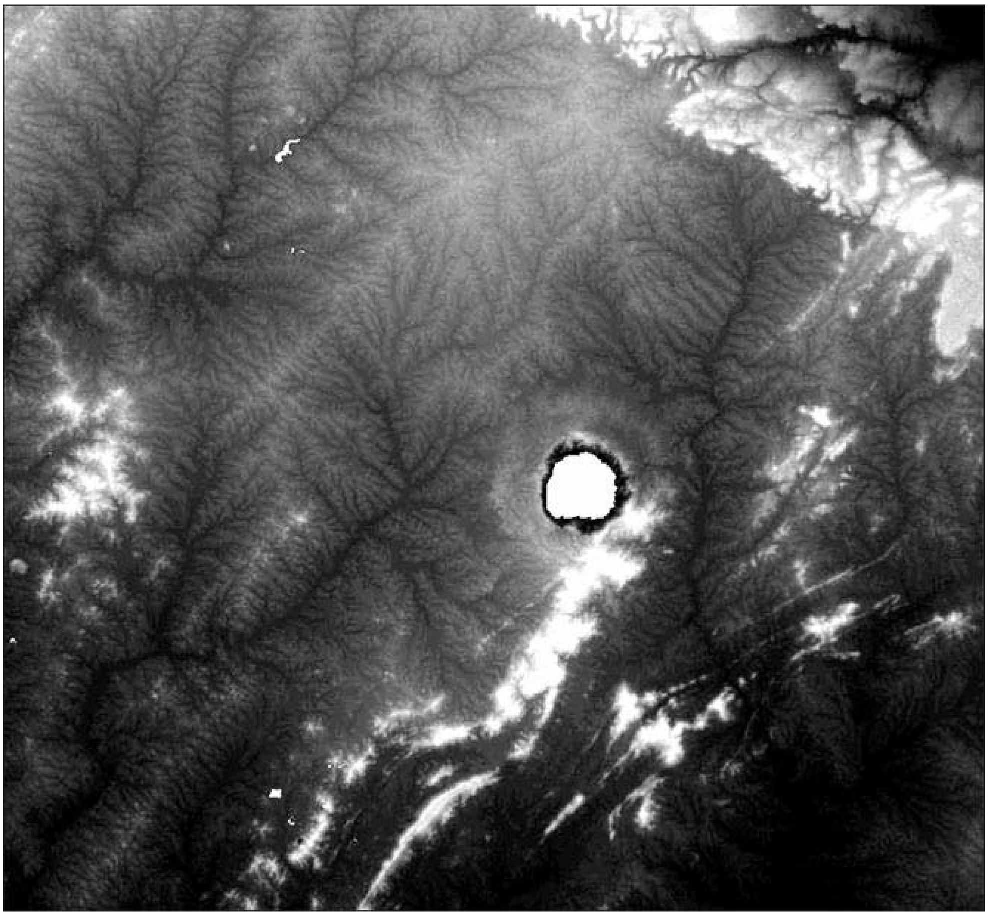
Rock formations younger than about 1.1 Ma include the Bosumtwi lake beds, as well as soils and breccias associated with the formation of the crater (JUNNER, 1937; KOLBE et al., 1967; WOODFIELD, 1966; MOON & MASON, 1967; JONES et al., 1981; JONES, 1985b; KOEBERL et al., 1997b, and REIMOLD et al., 1998). Massive suevite (impact breccia of fine-grained clastic groundmass and mineral and lithic clasts derived from the various target rocks, as well as a distinct clast component of impact melt/glass particles – see below, section 8.4.) deposits have been observed just outside the northern and southwestern crater rim.

3.3. Bosumtwi History

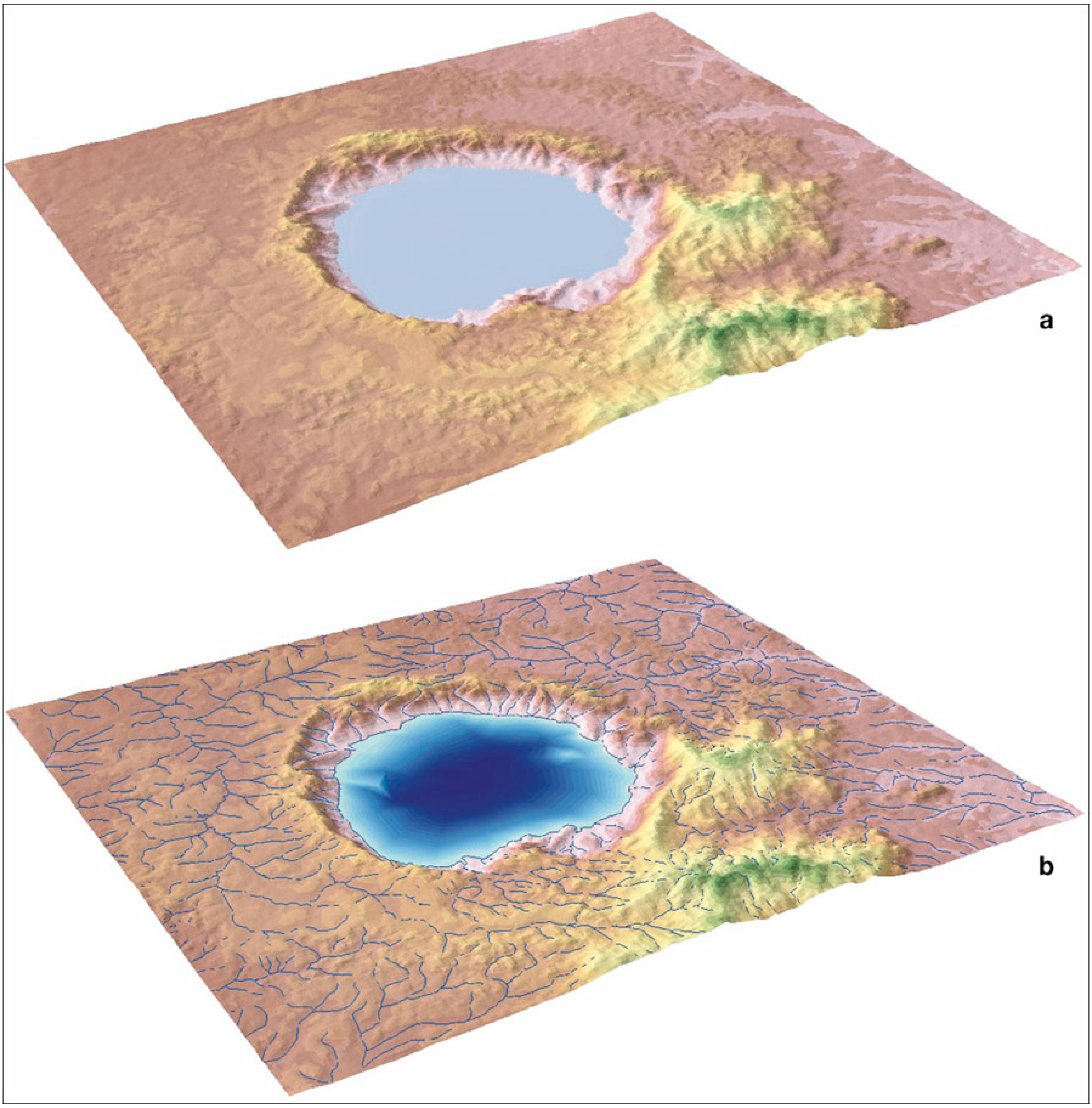
Europeans must have first seen Bosumtwi in the mid to late 19th century, as described by RATTRAY (1923). Bosumtwi was known to the local people, who belong to the Kingdom of the Ashanti, as a sacred lake. RATTRAY (1923) explains that the name "Bosomtwe" (the old spelling of Bosumtwi) is derived from obosom (god) and Twe, with the latter being the name for the supposed anthropomorphic lake spirit. He also noted that the name had nothing to do with otwe, a duyker (a small antelope), as has been sometimes stated (and as is still mentioned occasionally today by locals at the Lake). Oral traditions seem to go back not more than a few hundred years (RATTRAY, 1923).

The traditional beliefs of the Ashanti indicate that Bosumtwi is the resting place of souls of the deceased. RATTRAY (1923) explains this in some detail. The full name of the lake, at least in 1921 when he visited the area, was said to be "Akwasi Bosomtwe Akowuakra". Akwasi, if used with a person, signifies that it is a male born on a Sunday; if used with a god (obosom), it indicates the day that is sacred to that deity; in this case, Sunday. Akowuakra is a compound word, that can be translated as "when you die, you bid farewell"; the explanation of this name is found in the Ashanti belief that just before death, the sunsum or ntoro or spirit, about to quit the body for ever, flits – from wherever the dying man or woman may be – to this lake and says "good bye" (RATTRAY, 1923, p. 55). Rattray thus translates "Bosomtwe" as "The Lake of the Last Farewell".

RATTRAY (1923, pp. 56ff) also gives details of the myths, customs, and traditions associated with the lake. The "discovery" (or re-discovery) of the lake supposedly dates back to the middle of the 17th century, when a hunter followed an antelope to the lake, which was not yet known to his people; there he discovered that the lake contained fish, and this was supposedly the beginning of the settlements



Text-Fig. 6.
Shuttle Radar topography mission (SRTM) gray-shaded image of the Bosumtwi environs, also clearly showing the outer ring feature.
North is up.



Text-Fig. 7.
a) Projection of the SRTM data close to Bosumtwi (north points towards the upper left), showing the crater rim, the elevation of the Obuoum Range, and the faint outer ring feature.
b) Same as (a) but with the drainage pattern (creeks from the Survey of Ghana topography regional maps; cf. also WAGNER et al., 2002) superimposed; the drainage pattern emphasizes the circular drainage in the slightly depressed annular zone outside the crater rim.

around the lake. RATTRAY (1923) also described local traditions, in which white fowl (as well as cows and dogs) are sacrificed and presented to the spirit of the lake (these traditions do not seem to be followed anymore today). RATTRAY (1923, p. 61–62) also lists a number of things that are forbidden at the lake:

1) iron hooks (or line fishing),
2) cast nets,
3) seine nets,
4) the use of canoes, sails, paddles, poles, and anything hollowed out (not even logs),
5) brass or metal pans; it is also forbidden to fish on Sundays, and menstruating women are not allowed on the lake either.

Clearly these traditions (some of which were still observed in the late 1950s; K. BURKE, pers. communication, 1990) today are no longer observed to the same degree as earlier. More recently, it was said that supposedly no metal objects are allowed onto the lake (which is contradicted by the use of a small metall motorboat that is currently used for transport across the lake).

This, and the rule that nothing "hollowed-out" is allowed, is the reason why the local people still use flotation devices made from trees for their fishing activities (Text-Fig. 8). These trees (Corkwood or *Musanga Smithii*) are very light and float; the logs are roughly hewn into a rectangular shape. WHYTE (1975) described 11 species of fish from Bosumtwi, of which four are cichlids and one of these is endemic. In fact, fishing provides the only noteworthy means of income for the local communities, and it is noted with grave concern that the lake seems to be all but fished out.

Lake Bosumtwi has been known to the scientific community since the late last century. The origin of the crater was the subject of a controversy, as described by JUNNER (1937) and JONES (1985b): Already FERGUSSON (1902) discussed that the crater was not of volcanic origin, KITSON (1916) interpreted it as a subsidence feature, MACLAREN (1931) thought the crater was of impact origin, and ROHLEDER (1936) preferred an explosive (endogenic) explanation. This latter conclusion consitutes an interesting turn, because around the same time ROHLEDER had suggested that the Steinheim Becken in southern Germany, a smaller structure (ca. 4 km in diameter), and the much smaller Pretoria Saltpan (1.13 km diameter, now known as Tswaing) Crater in South Africa could be impact-generated structures, due to the occurrence of shatter cones at Steinheim and topographic similarities between Steinheim and Tswaing; but when he could not find similar features at Bosumtwi, ROHLEDER concluded that it was not of impact origin.

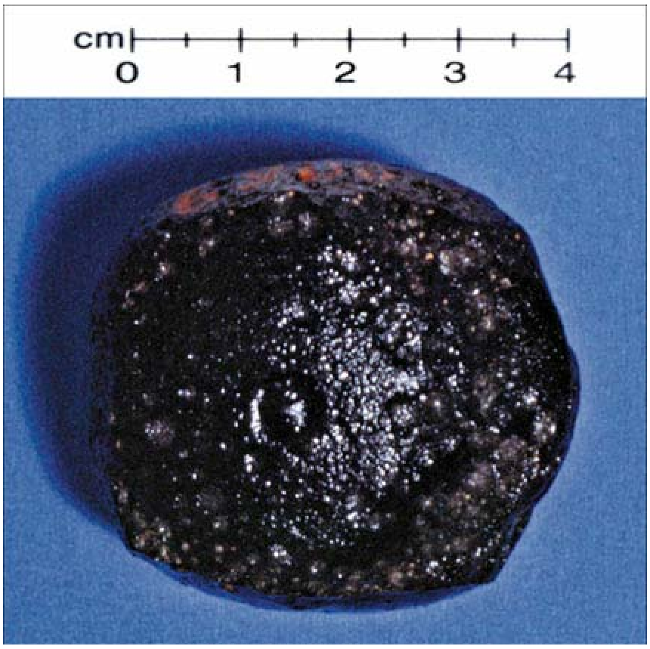
In the early 1960s, renewed interest led to additional studies and continuing controversy, caused partly by then incomplete understanding of impact processes (BAMPO, 1963; SMIT, 1964). An early geological summary was compiled by BLINOV (1964) in a rather inaccessible report; he described the various rock types, with some emphasis on auriferous rocks (as Bosumtwi is located close to the Ashanti gold belt), and followed JUNNER (1937) in concluding that the crater structure was a volcanic caldera. Subsequently, outcrops of suevitic breccia, similar to the type breccia found at the Ries impact structure in Germany, were found around the crater (e.g., CHAO, 1968; JONES et al., 1981), and the high-pressure quartz modification coesite (LITTLER et al., 1961), as well as Ni-rich iron spherules and baddeleyite, the high-temperature decomposition product of zircon, were discovered in vesicular glass in samples from the crater rim (EL GORESY, 1966; EL GORESY et al., 1968). All these lines of evidence supported an impact origin for the structure. However, the occurrence of shocked minerals has only recently been demonstrated (see below, section 8.5).

4. Bosumtwi and the Ivory Coast Tektites

4.1. History

The Bosumtwi crater is of special interest as the likely source crater for the Ivory Coast tektites, which were first reported in 1934 (LACROIX, 1934) from an area of about 40

Text-Fig. 8.
Local people who live in villages around the crater lake use carved tree trunks for fishing activities (all photos taken in 2004 by C. KOEBERL).
a) Overview of lake with (in foreground) a roughly hewn wood log used for fishing; a submerged tree (indicating rising waterlevels on a centennial scale) in the background.
b) Use of "fishing log" by local fisherman near drilling barge in September 2004.
c) Use of fishnet by local fisherman.
d) Collapsed tree in foreground (near Abono), submerged tree in background in lake, indicating rising water levels, and floating fishnets (indicated by floating bamboo rods in water), which are set throughout the lake by local fishermen.



Text-Fig. 9.
Image of an Ivory Coast tektite.
Sample IVC-2069; see KOEBERL et al. (1997a) for details.

km radius in the Ivory Coast (Côte d'Ivoire) territory (Text-Fig. 1). These tektites are centimeter-sized, spherically-symmetric glass objects that macroscopically are black in color (Text-Fig. 9), but in translucent light appear gray. Later, more samples were recovered by, e.g., GENTNER (1966) and SAUL (1969). Microtektites were found in deep-sea cores off the coast of West Africa (GLASS, 1968, 1969), and related to the tektites found on land. The geographical distribution of microtektite-bearing deep-sea cores has been used to determine the extent of the strewn field (GLASS & ZWART, 1979; GLASS et al., 1979, 1991) shown in Text-Fig. 10. These microtektites are up to one millimeter in size and show a variety of shapes, mostly spherical shapes, droplets, tear-drops, dumbbells, ropes, and fragments of particles with these respective shapes (Text-Fig. 11). The variation of the density number with distance can be used to deduce the location and size of the source crater (Text-Fig. 12), as demonstrated by GLASS & PIZZUTO (1994) and GLASS et al. (1991). SCHNEIDER & KENT (1990) and GLASS et al. (1979, 1991) studied the relationship of the Ivory Coast microtektites with the Jaramillo geomagnetic reversal, and found that while the ages of the two events agree somewhat, they are not identical.

As tektites are formed during hypervelocity impacts on Earth and represent melts of surficial, predominantly sedimentary, precursor rocks of upper crustal composition (see, e.g., KOEBERL [1994b]; MONTANARI & KOEBERL [2000], and references therein), a suitable source crater needed to be identified. A variety of arguments was used to conclude that Bosumtwi is most likely this source crater, including similar chemical compositions (SCHNETZLER et al., 1967; JONES, 1985a) and similar isotopic characteristics of the tektites and rocks found at the crater (e.g., SCHNETZLER et al., 1966; LIPPOLT & WASSERBURG, 1966; SHAW & WASSERBURG, 1982), as well as the similar ages of tektites and Bosumtwi impact glasses (e.g., GENTNER et al., 1964, 1967; DURRANI & KHAN, 1971; STORZER & WAGNER, 1977). While early published ages ranged from 0.71 to 1.2 Ma for Ivory Coast tektites, recent precise fission track and ^{40}Ar-^{39}Ar step-heating dating on both Ivory Coast tektites and Bosumtwi impact glass established a reliable age of 1.07±0.05 Ma for the Bosumtwi impact event and the tektites (KOEBERL et al., 1997a), providing a firm basis for the link between the Bosumtwi impact and the tektite-forming event.

4.2. Tektite Geochemistry

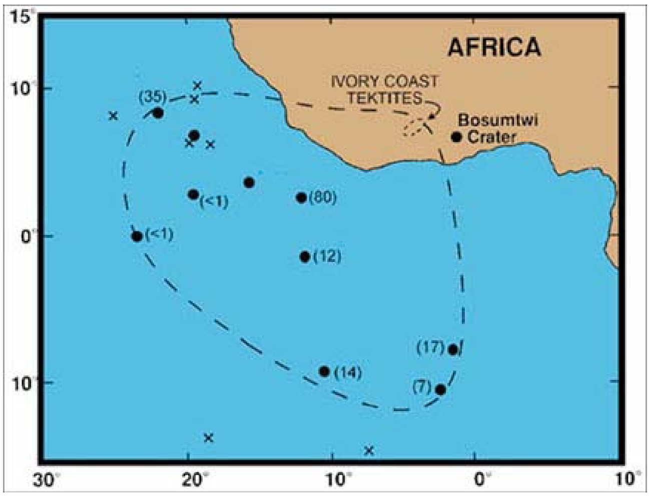
Tektites are known on Earth to occur in just four geographically extended (but well-defined) strewn fields – the North American strewn field of 35.5 Ma age (associated with the Chesapeake Bay impact structure; cf. POAG et al., 2004), the Central European strewn field of 14.4 Ma age (associated with the Ries crater in southern Germany), the Ivory Coast tektite strewn field, and the 0.8 Ma Australasian strewn field (for which no source crater has been identified so far). For details on these strewn fields and the chemistry and origin of the tektites, see the review in MONTANARI & KOEBERL (2000).

It is well established that the chemical and isotopic composition of tektites in general is identical to the composition of the upper terrestrial continental crust (e.g., KOEBERL, 1994b). For the Ivory Coast tektites, these considerations helped to establish the link to the Bosumtwi crater.

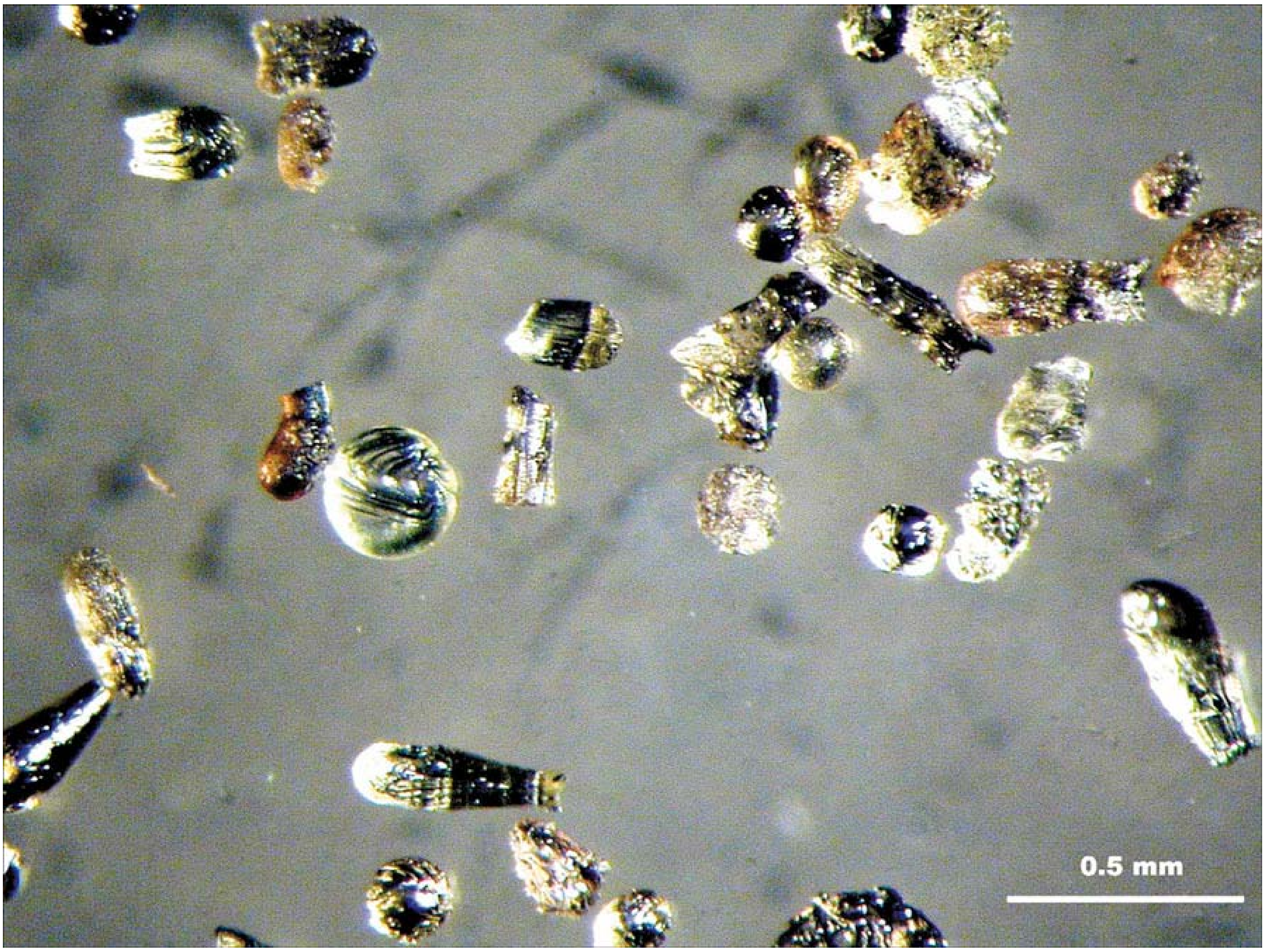
KOEBERL et al. (1998) found that the oxygen isotopic composition of the metasedimentary rocks and granite dikes ($\delta^{18}O$ = 11.3–3.6 ‰) from the Bosumtwi area, and that of the tektites ($\delta^{18}O$ = 11.7–12.9 ‰), agree fairly well, whereas the Pepiakese granites (sampled to the northeast of the crater structure) have lower values ($\delta^{18}O$ = 8.6–9.0 ‰), indicating that these rocks were not a major component in the formation of the Ivory Coast tektites. Furthermore, these authors determined the Sr and Nd isotopic characteristics of a selected number of Bosumtwi target rocks and Ivory Coast tektites, for comparison.

The large variation in target rock compositions did not allow the unambiguous determination of distinct end-member compositions, but in both a $^{87}Sr/^{86}Sr$ vs. 1/Sr plot and an εSr vs. εNd diagram the tektites plot within the field defined by the metasedimentary and granitic Bosumtwi country rocks that were the likely target rocks for the Bosumtwi impact.

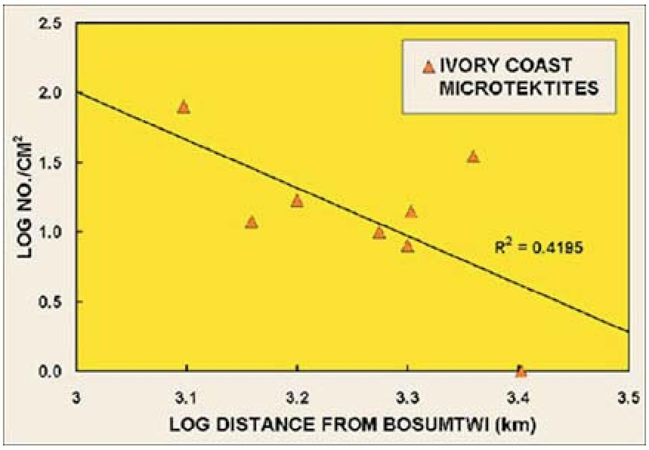
Despite the spread in rock type and chemical and isotopic compositions of the presently available, somewhat limited, set of Bosumtwi crater and country rocks, the available geochemical data (KOEBERL et al., 1997a, 1998) support the conclusion that the Ivory Coast tektites were formed from the same rocks that are currently exposed at the Bosumtwi crater, and during the same impact event that formed the Bosumtwi crater. The compositions of indi-



Text-Fig. 10.
Geographic distribution of deep-sea cores that were found to contain Ivory Coast microtektites (after GLASS et al., 1991).
Full circles indicate location with microtektites, whereas X marks locations where no microtektites were found. The numbers indicate the integrated numbers of microtektites per cm².



Text-Fig. 11.
Microtektites from deep-sea sediments within the Ivory Coast tektite strewn field.
Photo courtesy B.P. GLASS.



Text-Fig. 12.
Variation of number density of Ivory Coast microtektites with distance.
The regression of the data can be used to determine the location and size of the source crater, which fits very well with Bosumtwi.
After GLASS & PIZZUTO (1994).

vidual glasses from impact breccia (suevite) show a much wider range in composition than the tektites and seemingly have preserved the compositions of the variety of country rocks in much more detail than the extensively homogenized tektites.

Harmonic least-squares (HMX) mixing calculations (KOEBERL et al., 1998) were able to reproduce the composition of Ivory Coast tektites from a mixture of Bosumtwi country rocks that includes about 70 % phyllite/schist/graywacke, 16 % granite dike, and 14 % Pepiakese granite. However, the data set is incomplete, as until 2004 there was no information at all about the deep crater structure, the rock types present there (i.e., the basement as well as glass in fallback suevite within the crater) and their compositions. This will change soon with the study of the recently obtained deep drill cores (see below, section 7).

Studies of Australasian tektites used measurements of the concentrations of the cosmogenic radionuclide ^{10}Be, which forms by interaction of cosmic rays with nitrogen in the atmosphere and is concentrated in the top of any sediment column, to constrain the location and characteristics of the source material. The average value of ^{10}Be (corrected to time of formation at 0.77 Ma) in Australasian tektites is $143 \pm 50 \cdot 10^6$ atoms/g. Such a value is comparable to those measured in near-surface source materials, such as soils (terrestrial) or sediments (marine and terrestrial). The Ivory Coast tektites are regular (splash-form, see e.g., KOEBERL et al., 1997a) tektites related to the Bosumtwi Crater formed 1.07 Ma ago, and if Ivory Coast tektites also formed from surficial materials as did the Australasian tektites, then they are expected to contain similar concentrations of ^{10}Be. Measurements by SEREFIDDIN et al. (2005) show that ^{10}Be concentrations of Ivory Coast tektites are consistent with formation from mostly near-surface sediments or soils. These authors found that Ivory Coast tektites have ^{10}Be values on average 77 % lower than the

Australasian tektites and concluded that several factors may have contributed to the variability in tektite ^{10}Be concentration:

1) age of tektites,
2) nature and age of source materials,
3) depth of sample in soil column, and
4) environmental conditions at time of formation.

Individually these different factors seem unlikely to account for the full difference in ^{10}Be concentrations between the Ivory Coast and Australasian tektites. However, a combination of these factors can readily explain up to 80 % of this difference. Mixing of sediments and soils with low ^{10}Be materials such as deposits eroded from bedrock may also explain the lower values in the Ivory Coast tektites.

4.3. Tektite Origin

Geochemical studies have shown tektites in general (at all strewn fields) must have been derived from near-surface sedimentary rocks (as indicated by ^{10}Be data) that were generated from the terrestrial upper continental crust (see, e.g., KOEBERL [1994B]; MONTANARI & KOEBERL [2000]). The exact conditions that led to tektite production (as opposed to the formation of only impact melt rocks contained within or nearby the crater) are not well known.

To better constrain these conditions, numerical modeling of the initial stage of growth of a Bosumtwi-size crater was performed by ARTEMIEVA (2002) and ARTEMIEVA et al. (2004) to reproduce the formation of impact melt from the upper 50 m of the target surface, as well as total melt volume. Such melt, fragmented into centimeter-sized particles, could produce the Ivory Coast tektite strewn field. Melt production from the surface layer of the target due to an asteroidal impact was studied with 3D numerical simulations for various impact angles (15°–60° to the horizon) and velocities (11–40 km/s). For this range in impact angles and velocities, projectile sizes are within the range of 400 to 1100 m, according to the scaling law, and produce the same transient cavity of 9 km in diameter (final crater diameter is 10.5 km).

The mass of the near-surface melt (tektite material) is almost constant for all impact velocities, but high velocity impact (>20 km/s) accelerates the melted ejecta, whereas in the case of low-velocity impact (11 km/s) all the melt is contained within the crater. The amount of tektite material increases with decreasing impact angle, but low-angle impacts produce melt which is strongly contaminated by projectile material. Pure (that is barely contaminated with projectile matter) target melt is formed during an impact with an “intermediate” impact angle of 30°–50°. This melt is ejected from the growing crater with high velocity and may produce tektites after disruption into cm-sized particles. Such solid particles may be transported to distances of hundreds of km in the post-impact atmospheric flow. ARTEMIEVA et al. (2004) calculated that with oblique impacts of 45 to 30°, as required for tektite production, very little projectile material remains within the crater fill. This prediction will be tested by analyses of the newly acquired drill cores.

Table 1.
Averages of compositions of Ivory Coast tektites and microtektites.
Major element data in wt-%, trace element data in ppm, except as noted. All Fe as Fe_2O_3.
Data from KOEBERL et al. (1997a).

	Tektites	Microtektites
	Average	Average
SiO_2	67.58	67.37
TiO_2	0.56	0.59
Al_2O_3	16.74	17.07
Fe_2O_3	6.16	6.40
MnO	0.06	0.07
MgO	3.46	3.70
CaO	1.38	1.22
Na_2O	1.90	1.63
K_2O	1.95	1.86
H_2O	0.002	
Total	99.79	99.89
Sc	14.7	17.9
Cr	244	292
Co	26.7	32.7
Ni	157	224
Zn	23	12
Ga	21	17
As	0.45	0.42
Br	0.79	0.4
Rb	66	66.7
Sr	260	325
Zr	134	215
Sb	0.23	0.21
Cs	3.67	3.2
Ba	327	620
La	20.7	25.9
Ce	41.9	55.1
Nd	21.8	27.3
Sm	3.95	5.10
Eu	1.2	1.43
Gd	3.43	4.40
Tb	0.56	0.74
Tm	0.30	0.31
Yb	1.79	2.07
Lu	0.24	0.31
Hf	3.38	4.28
Ta	0.34	0.42
Ir (ppb)	0.4	0.9
Au (ppb)	41	0.8
Th	3.54	3.99
U	0.94	0.64
K/U	17287	21343
Th/U	3.77	6.52
La/Th	5.85	6.48
Zr/Hf	39.6	50.3
Hf/Ta	9.94	10.3
La_N/Yb_N	7.81	8.44
Eu/Eu^*	1.01	0.92

5. Geophysical Studies at Bosumtwi

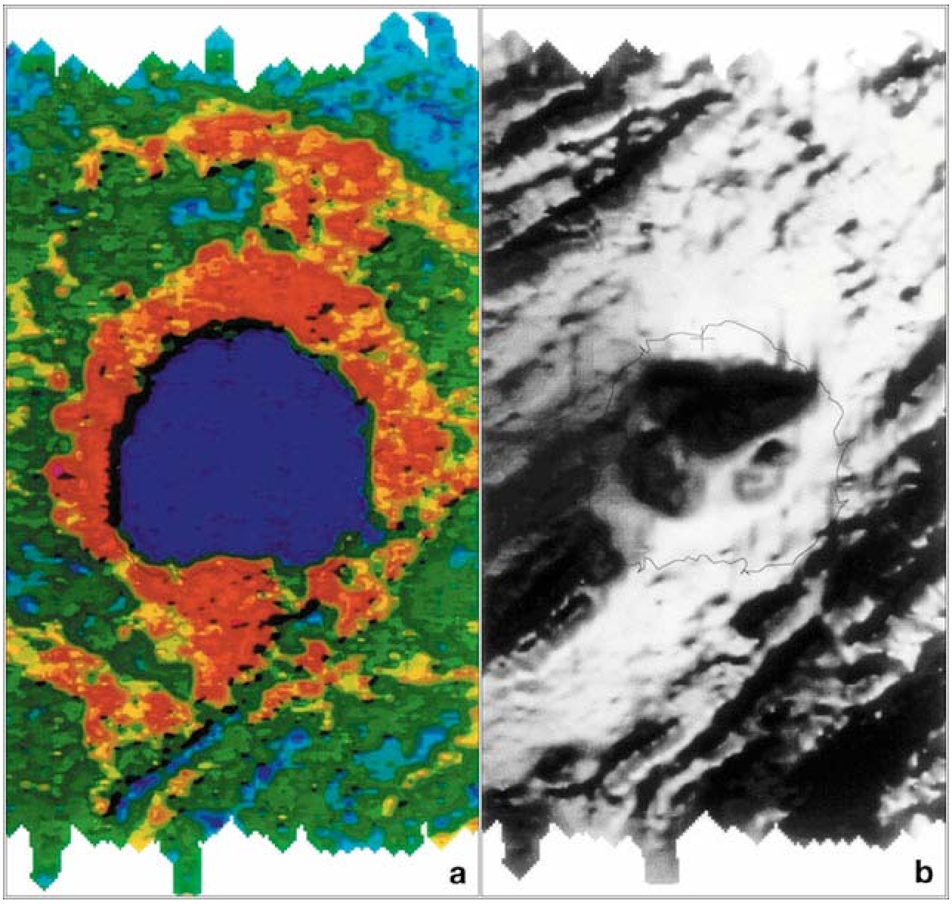
The first magnetic field studies of the structure were conducted in 1960, and revealed a central negative anomaly of ~40 nT, attributed to a lens of low-density crater-fill breccia below the lake sediments (JONES et al., 1981). Gravity measurements, collected around the lake at this time, reflected only the regional trends (see JONES et al., 1981). It was not until the late 1990s that new geophysical studies of the Bosumtwi crater were undertaken.

5.1. Aerogeophysical Survey

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, 1999a). Examples of the results, which were presented in detail by PESONEN et al. (2003), are shown in Text-Fig. 13.

PLADO et al. (2000) produced a magnetic model for the Bosumtwi structure. They used data from the Finnish-Austrian high-resolution, low altitude (~70 m) airborne geophysical survey, which included measurements of the total magnetic field, electromagnetic data, and gamma radiation. 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 N and S of it, 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. Together with the northern anomaly they seem to encircle a possible central uplift. The model by PLADO et al. (2000) shows that the magnetic anomaly of the structure is presumably produced by one or several relatively strongly remanently magnetized impact melt rock or melt-rich suevite bodies in the crater.

The paper by PLADO et al. (2000) gives also petrophysical data of Bosumtwi impactites and country rocks. The petrophysical measurements of PLADO et al. (2000) 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. In suevites, the remanent magnetization dominates over induced magneti-



Text-Fig. 13.
a) Airborne radiometric map (equivalent concentrations of potassium) of the Bosumtwi impact structure.
b) Total intensity [nT] aeromagnetic map.
The data are from a high-resolution aerogeophysical survey conducted by the GSF (OJAMO et al., 1997; PESONEN et al., 1998, 1999; 2003). North is up,

zation. Preliminary palaeomagnetic results of PLADO et al. (2000) indicate that the normally magnetized remanence component in suevites was acquired during the Jaramillo (starting at about 1.07 Ma) normal polarity epoch (e.g., CHANNELL et al., 2002). GLASS et al., 1991) noted that the Ivory Coast microtektites were deposited a few thousand years after the onset of the Jaramillo normal polarity epoch. This interpretation is consistent with the modelling results that also require a normal polarity magnetization for the magnetic body beneath the lake. The reverse polarity remanence component, superimposed onto the normal component, is probably a secondary remanence acquired during subsequent reverse polarity events.

5.2. Seismic Studies of the Bosumtwi Impact Structure

In 1999 and 2000 several geophysical expeditions to Lake Bosumtwi were undertaken by a team from Syracuse University (USA), the University of Kiel (Germany), the Ghana Geological Survey, and the University of Science and Technology in Kumasi. The “marine” seismic work was undertaken using the portable research catamaran Kilindi and included the acquisition of multichannel reflection seismic profiles using an airgun array and a 600 m-long streamer, a reflection and wide angle refraction seismic study using ocean bottom seismometers, and a high-resolution seismic survey using a CHIRP sub-bottom profiling system. Eight profiles of marine-type multichannel seismic reflection (MCS) data were acquired from the lake that fills much of the crater. These data were supplemented by wide-angle seismic measurements acquired using ocean-bottom hydrophones. MCS data reveal a well-defined central uplift near the NW-central part of the lake. The seismic data and their interpretations were published by KARP et al. (2002) and SCHOLZ et al. (2002).

The central uplift structure has a diameter (at its base) of 1.9 km and a maximum height of 130 m above the annular moat inside the crater. It apparently has undergone faulting, probably during the later stages of transient crater collapse and during the subsequent lacustrine phase of the structure (some of the faulting extends into overlying sediment). An intermediate velocity layer (3200 m/s) beneath the lacustrine sediment was interpreted as fall-back breccia or a breccia-melt horizon. The internal seismic velocity structure for the crater was determined from the wide-angle refraction seismic experiment. Fracturing may be responsible for the relatively low velocity of 3.8 km/s in the crater floor. The post-impact sediments covering the crater structure are 180–300 m thick. The apparent crater depth, defined as the difference between the original target surface and the top of the breccia layer, is ca. 550 m, slightly deeper than several other complex impact structures on Earth of larger diameter (e.g., GRIEVE, 1991). In this aspect, the Bosumtwi impact structure is a small complex crater that deviates slightly from trends predicted from classical scaling laws.

5.3. Gravity Studies

Gravity studies on land and over the lake were performed in 2000–2002 within the framework of the geophysics studies of several German teams (Universities of Kiel, Munich, and Frankfurt), in collaboration with the University of Science and Technology at Kumasi, Ghana. The combination with previously obtained gravity measurements on land in the environs of the lake has been finished recently and was subject of a Ph.D. thesis by S.K. DANUOR (DANUOR, 2004). These data indicate a free-air anomaly in the gravity field of Lake Bosumtwi. There is a general gravity low over the structure caused by the lower-density breccia, as is typical for impact structures (cf. GRIEVE & PILKINGTON, 1996). Gravity modeling by DANUOR (2004) shows that the gravity field of the Bosumtwi area is characterized by a negative Bouguer anomaly with an amplitude of about –18 mgal and a diameter of about 13 km. Within the central low there is a small relative maximum of about 2 mgal in the central region, which could be caused by the central uplift that was inferred from the seismic studies. The effect cannot be the result of lake floor topography, which is known to be smooth.

6. The Importance of Bosumtwi for Paleoenvironmental Studies

Lake Bosumtwi is a closed-basin lake with a present-day area of 52 km^2 and a maximum depth of 78 m. The lake is ideally configured and situated to monitor interannual local to long-term (orbital)-scale variations in the West African monsoon and Sahel drought activity. Lake Bosumtwi is hydrologically closed at the present time, with its water balance being dominated by rainfall on the lake surface and direct evaporation. Groundwater sources are thought to be negligible.

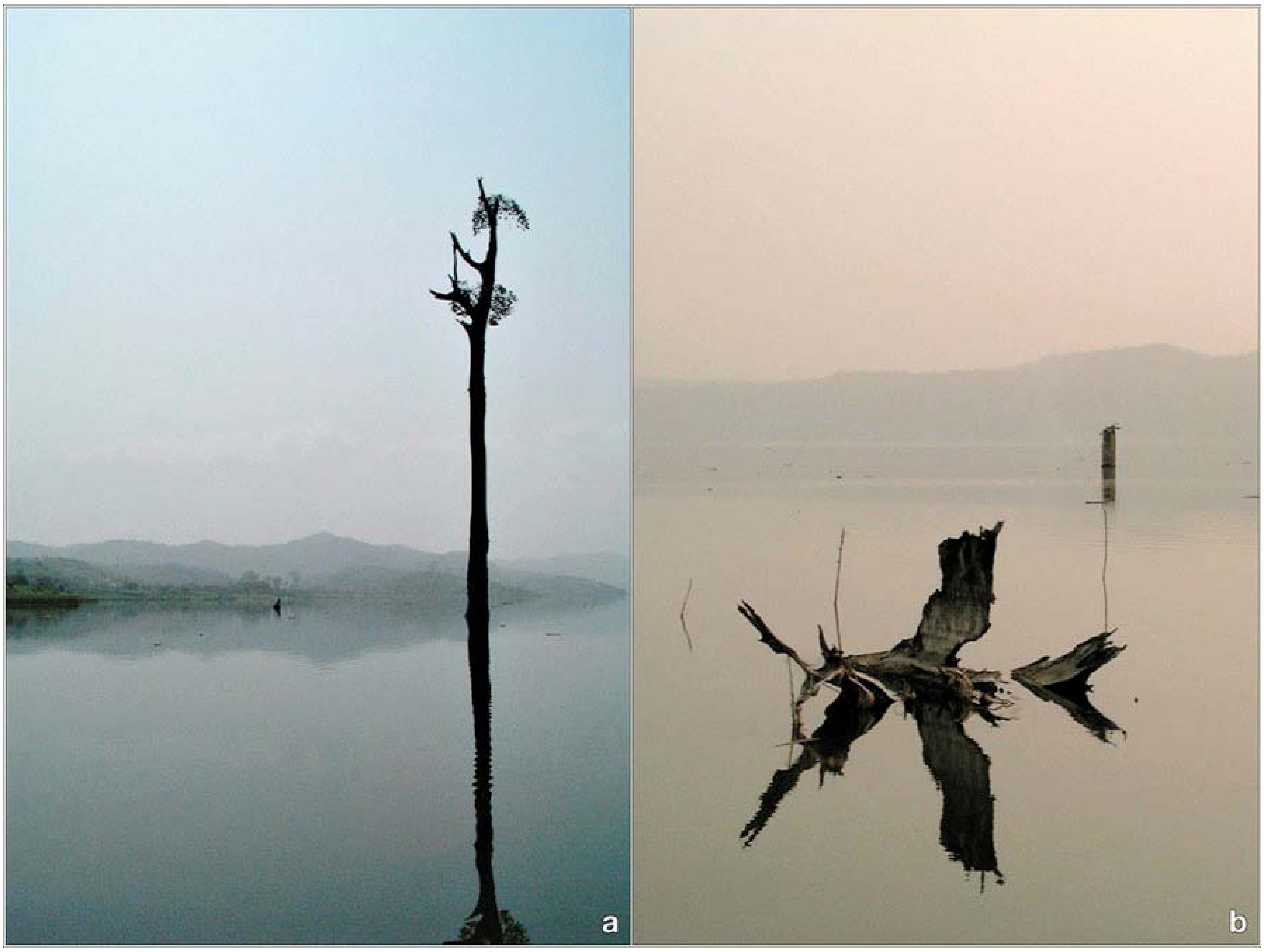
However, the highest position where lake sediments occur along the inner crater rim is located about 110 m above the present lake level. The lowest topographic point on the crater rim has an elevation of 210 m, about 110 m above the present lake level, which is the elevation at which the lake will overflow (TURNER et al., 1996a,b). 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.

Low salinity of about 1 per mil 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. Although interannual variations in rainfall in the area of Bosumtwi are not highly correlated with those of the Sahel Zone that starts several hundred kilometers to the north of Bosumtwi (OPOKU-ANKOMAH & CORDERY, 1994), the Bosumtwi sediments can be used to monitor both local and Sahel rainfall variations (cf. also STREET-PERROTT & PERROTT, 1990).

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 Ma) and its location in West Africa, the lake sediments can provide a long record of change in North African monsoon strength. 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. During the summer months, the ITCZ migrates to the north of Lake Bosumtwi and moisture-laden winds bring heavy, monsoonal precipitation to western Africa. The reverse occurs during the winter months, as the ITCZ is displaced towards the south of Lake Bosumtwi, and dry, aerosol-rich northeasterly continental trade winds (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



Text-Fig. 14.
Drowned trees at Bosumtwi, indicating lower lake levels within the past few hundred years (photos by C. KOEBERL).
a) Tall submerged tree near the eastern shore of Lake Bosumtwi, near the village of Ankasi.
b) Collapsed tree in water near eastern shore, and, in distance, trunk of submerged tree, indicating lake level rise on a centennial scale.

limit wind wave mixing of the water column. As a result, the deep water is anoxic, thereby limiting bioturbation and allowing for the preservation of laminated sediment varves – and, thus, providing the potential for high resolution (annual) paleoclimate reconstruction.

The paleoclimatic significance of Lake Bosumtwi was recognized early (see SMIT [1964] for a review), but only in the 1970s M. TALBOT and D. LIVINGSTONE began the first detailed paleoenvironmental studies of Bosumtwi. These researchers and their collaborators used a suite of sediment cores (up to 16.9 m in length) and analytical methods (e.g., stratigraphy, sedimentology, geochemistry, and palynology) to document critical aspects of the Bosumtwi record, including a complex record of lake level, lake chemistry, climate, and vegetation history stretching back 27,500 years (e.g., TALBOT & DELIBRIAS, 1977; HALL et al., 1978; TALBOT & KELTS, 1986). These records helped to put aside the concept of tropical climate and vegetation stability (e.g., TALBOT et al., 1984), and now include some of the best records of low-latitude environmental change produced to date. Perhaps the most widely used result of this pioneering work is the often-cited Bosumtwi record of lake level fluctuations spanning the last 13,500 years (TALBOT & DELIBRIAS, 1980; TALBOT et al., 1984).

TALBOT & DELIBRIAS (1977) and TALBOT & JOHANNESSEN (1992) showed that lake-level variations correlate well with rainfall in the Sahel region. The short drill cores show that sediments in the deep basin of the lake are typically varved and contain sapropels. TURNER et al. (1996a,b) suggested that rapid increases in lake level might trigger episodes of sapropel deposition as a result of the rapid drowning of forests and introduction of lignin-rich biomass to the deep lake basin.

PECK et al. (2004) reported results of a study of magnetic parameters of minerals extracted from an 11-m-long core, taken within the lake basin, that spans 26,000 years. They found that the dust flux to Lake Bosumtwi, which is inferred to be very low during the African humid period due to the strengthening of the summer monsoon, is characterized by abrupt shifts in magnetic parameters between 12,000 and 3200 years B.P. More recent data suggest increased aridity as compared to the earlier humid period.

BROOKS et al. (2005) reported results from a high-resolution, single-channel seismic-reflection survey of Bosumtwi, Ghana, and sedimentological data from a ^{14}C-dated sediment piston core. These data were used to revise and extend the basin's late-Quaternary lake level history.

Four seismic sequence boundaries and an exposure surface from a sediment core were found and interpreted by BROOKS et al. (2005) as erosional surfaces formed at times of drastic low lake level. The youngest erosional surface occurs as much as 31 m below present lake level (bpll) and up to 0.7 m below the present sediment-water interface. This most recent unconformity observed in the seismic data was interpreted to be coeval with the late-Holocene dry period between 0.5 and 1 cal ky BP (thousand calendar years before present). 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 to other observed continent-wide shifts in African climate over the past 100 ky. More recent fluctuations in lake level are also documented by a number of near-shore large flooded trees located in a few meters water depth (Text-Fig. 14). Data by TALBOT & DELIBRIAS (1977) indicate that the lake level could have risen by as much as 50 m during the past 250 years.

7. The 2004 ICDP Drilling Project

These 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.

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 was intended to bring the various research communities interested in Bosumtwi (impact research, geophysics, paleoenvironment research) together. The workshop was highly successful and resulted in the definition of the goals for a deep drilling project. There are several reasons for deep drilling from each of the two main driving research topics, but the two most important goals can be summarized as

1) to obtain a complete 1 million year paleoenvironmental record in an area for which so far only limited data exist;
2) to study the subsurface structure and crater fill of one of the best preserved, large and young impact structures.

More specifically, in terms of paleoenvironmental studies, a deep drilling project at Bosumtwi would allow to obtain information on:

1) long- and short-term changes in the West African monsoon;
2) hydrologic variation of the Sahel region;
3) dust export from various African deserts to West Africa; and
4) sea-surface temperature variations in the tropical East Atlantic.

Understanding the full range of climate variability in this region over the last 1 Ma will fill a major gap in our understanding of global climate dynamics, and thus also lead to an enhanced climate prediction capability over a broad part of the earth.

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 diameter, is twice as large). Zhamanshin (Kazakhstan) is of similar dimensions and age as Bosumtwi, but poorly preserved (e.g., GARVIN & SCHNETZLER, 1994). Drilling allows to correlate all the geophysical studies and will provide material for geochemical and petrographic correlation studies between basement rocks and crater fill in comparison with tektites and ejected material.

As a result of the successful workshop in 2001, a full proposal was submitted to ICDP in January 2002. It was proposed to obtain drill cores at nine locations in the crater lake, with core lengths ranging from 50 to 1035 meters. This would provide a total core length of 3 km sediments and 1 km impact-related rocks. The proposal was accepted by ICDP in mid 2002 and logistical work to organize and plan the drilling started in late 2002. Additional funding from various other national funding agencies in the US, Austria, and Canada was obtained as well. A variety of permits had to be obtained, 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 work was completed in the early summer of 2004.

Drilling was then undertaken from the beginning of July to early October 2004 (see KOEBERL et al. [2005] and PECK et al. [2005] for some first reports). Care was taken to situate all core locations on seismic lines that were measured

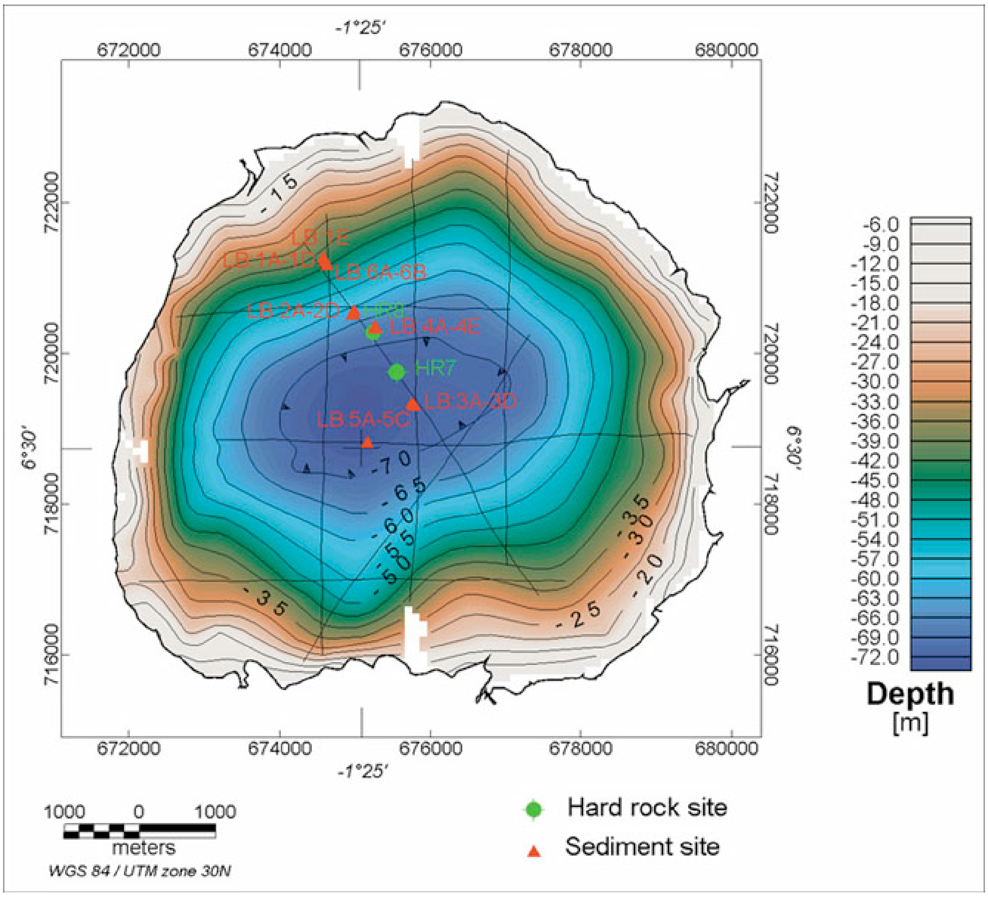
Table 2.
Names, locations, and core information for the cores obtained in the course of the 2004 ICDP drilling project at Lake Bosumtwi .
See KOEBERL et al. (2005); PECK et al. (2005).
All cores obtained using the GLAD800 lake drilling system. Data compiled (and courtesy of) H. UGALDE and B. MILKEREIT (University of Toronto).
* = total depth of hole measured from water line.

site	water depth (m)	North Latitude (Degrees)	East Longitude (Degrees)	Total Depth (m)*	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

*Total depth of hole measured from water line

in the preparation phase of the drilling project (KARP et al., 2002; SCHOLZ et al., 2002). Text-Fig. 15 shows the locations of the hard rock and sediment cores that were obtained in the summer of 2004. Drilling was performed using the DOSECC/ICDP GLAD 800 lake drilling system, which is a custom-built device specifically for lake scientific drilling (Text-Fig. 16). Funding for about $^2/_3$ of the total cost was provided by ICDP (the International Continental Scientific Drilling Program). Table 2 lists the drilling locations.

Text-Fig. 15.
Location map of the 2004 drill cores in relation to the seismic profiles.
Courtesy H. UGALDE and B. MILKEREIT (Univ. of Toronto).



7.1. ICDP Drilling of Lake Bosumtwi – 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 (Text-Fig. 15) 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 1,833 m.

For the first time the GLAD lake drilling system (a system specifically constructed for drilling at lakes, see www.dosecc.org) cored an entire lacustrine sediment fill from lakefloor to bedrock (Text-Fig. 16). The complete ca. 1 Ma lacustrine sediment fill was recovered from the crater ending in a narrow, possibly impact-glass (accretionary lapilli-like particle) bearing layer. This accretionary lapilli unit likely represents the initial post-impact sedimentation and provides an important age constraint for the overlying sedimentary sequence. The initial lacustrine sediment 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 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.

7.2. Geophysics and Impact Results

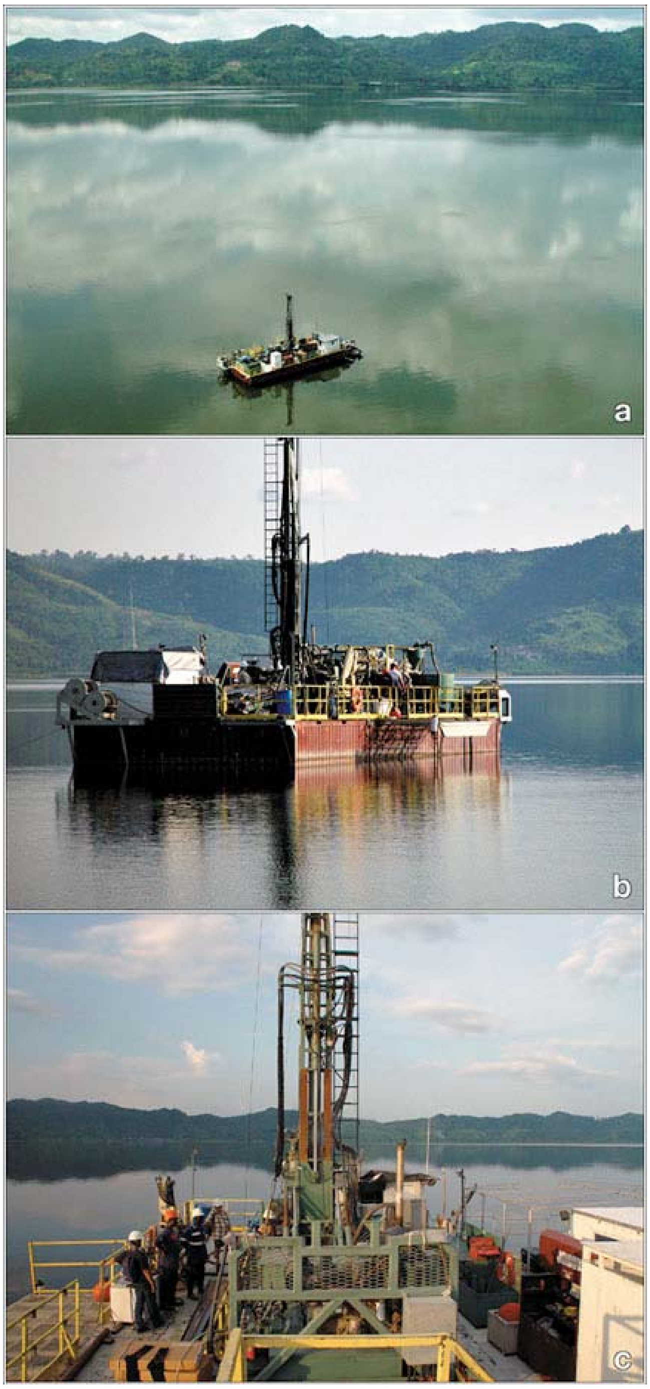
Two additional deep boreholes (LB07A and LB08A) were obtained from a specific impact point of view, and their drilling was tied to detailed investigations of the potential field and seismic sub-structure that define the Lake Bosumtwi impact structure (Text-Fig. 15). Acquisition of zero-offset and multi-offset VSP data in deep hardrock holes LB07A and LB08A (Text-Fig. 15) established a link with existing seismic data. Slim-hole borehole geophysical studies provided crucial information about the distribution of magnetized formations within the crater fill and could potentially help locate discontinuous melt units in the proximity of the scientific drill hole(s). Information about the distribution of magnetic susceptibility and remanence of breccias and possible impact melt units holds the key to an improved three-dimensional model for the Bosumtwi crater and its thermal history. Multi-offset vertical seismic (VSP) profiling supports the integration of conventional logs and an existing grid of multi-channel seismic and refraction seismic data. The offset VSP experiments are also important for the integration of core/laboratory data, logs, and conversion of reflection seismic images from time to depth. By documenting the distribution of magnetic susceptibility and the impact related thermo-magnetic remanence, the distribution of the thermal effects of the impact might be outlined. Combining the horizontal resolution of the seismic surveys with the enhanced vertical resolution of the borehole magnetic surveys provides an ideal set-up for 3D modeling through data integration.

The hard rock drilling phase, as well as borehole logging and geophysical studies, was completed on October 2nd, 2004. During that phase two boreholes, to depths of 540 and 450 m, respectively, were drilled in the deep crater moat, and on the outer flank of the central uplift. In both cases, casing was set through the lake sediment part of the section, and drilling, using diamond coring tools, started at the sediment/impactite (fallback suevite) interface. Drilling progressed in both cases through the impact breccia layer into fractured bedrock. Text-Fig. 17 shows a few images of the cores retrieved from the crater fill breccia. After completion of the drilling operations, the hard rock cores (122 core boxes) were shipped to the Geo-Forschungs-Zentrum in Potsdam, Germany, for scanning and documentation. A sampling party took place in January 2005, samples were distributed in February of 2005, and first research results are expected in late 2005/early 2006.

8. Geology of the Crater Area

8.1. General

This section provides an explanation of previous geological work at Bosumtwi, as well as some information on the rocks represented in the area and shown on the map.



Text-Fig. 16.
The GLAD800 drilling barge on Bosumtwi duringthe ICDP drilling project in 2004.
a) Aerial view of the GLAD800 barge, looking towards the northeast.
b) Close-up of the GLAD800, showing how the barge is made up of eight shipping containers (with floatation devices inside), with a moon-pool at the center.
c) View of the modified Christensen CS-1500 diamond coring rig that is mounted on the barge.
All photos by C. KOEBERL, September 2004.

Detailed geological studies of the region around Lake Bosumtwi have been carried out since the 1930s (JUNNER, 1937; WOODFIELD, 1966; MOON & MASON, 1967; JONES et al., 1981). More recent geological studies were carried out along a section across the western crater rim and on exposures in the sector 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. Text-Fig. 18 presents the general geology around the Lake Bosumtwi.

The regional stratigraphy comprises a series of supracrustal rock types, including both meta-sedimentary and meta-volcanic material, belonging to the 2.1–2.2 Ga Birimian Supergroup. Detritus from this sequence is believed to have formed the overlying Tarkwaian Supergroup. Both these sequences are intruded by mostly granitic-granodioritic bodies and dikes belonging to the Pepiakese and Kumasi intrusions. In addition, a variety of mafic to ultramafic intrusives occur locally. Crater formations (i.e., impact breccia), other breccias of unresolved origin (i.e., either impact produced or related to surface processes such as erosion and weathering in the tropical environment), lake beds around Lake Bosumtwi, and weathering soils have been formed since the impact event at 1.07 Ma ago.

8.2. Paleoproterozoic Supracrustals

8.2.1 Birimian Rocks

The Bosumtwi impact event excavated lower greenschist facies metasediments of the 2.1–2.2 Ga (WRIGHT et al., 1985; LEUBE et al., 1990) Birimian Supergroup (previously separated into a Lower Birimian comprising dominantly meta-sediments and an Upper Birimian comprising dominantly "greenstone" meta-volcanics; JUNNER, 1937). This subdivision has recently been abandoned (staff of the Geological Survey Department of Ghana – pers. communication, 2004).

The Birimian Supergroup in Ghana comprises five parallel, evenly spaced, volcanic belts several hundred kilometers in length, which are separated by basins containing dacitic volcaniclastics as well as a range of metasedimentary lithologies (WRIGHT et al., 1985; LEUBE et al., 1990). Geochronological data available (LEUBE et al., 1990; TAYLOR et al., 1992; DAVIS et al., 1994; HIRDES et al., 1996) have shown that there is no evidence that would support the temporal division of a Lower and Upper Birimian. Instead, on the basis of a Sm-Nd isochron for rocks from both groups, corresponding to an age of 2.17±0.07 Ga, these authors argued for contemporaneous emplacement of both volcanic and sedimentary rocks of the Birimian Supergroup. A variety of granitoids intruded synorogenically (the sedimentary-basin granitoids of the Cape Coast type) or late-orogenically (the volcanic-belt granitoids of the Dixcove type) with the folding of the basins following the termination of the volcanic activity (LEUBE et al., 1990).

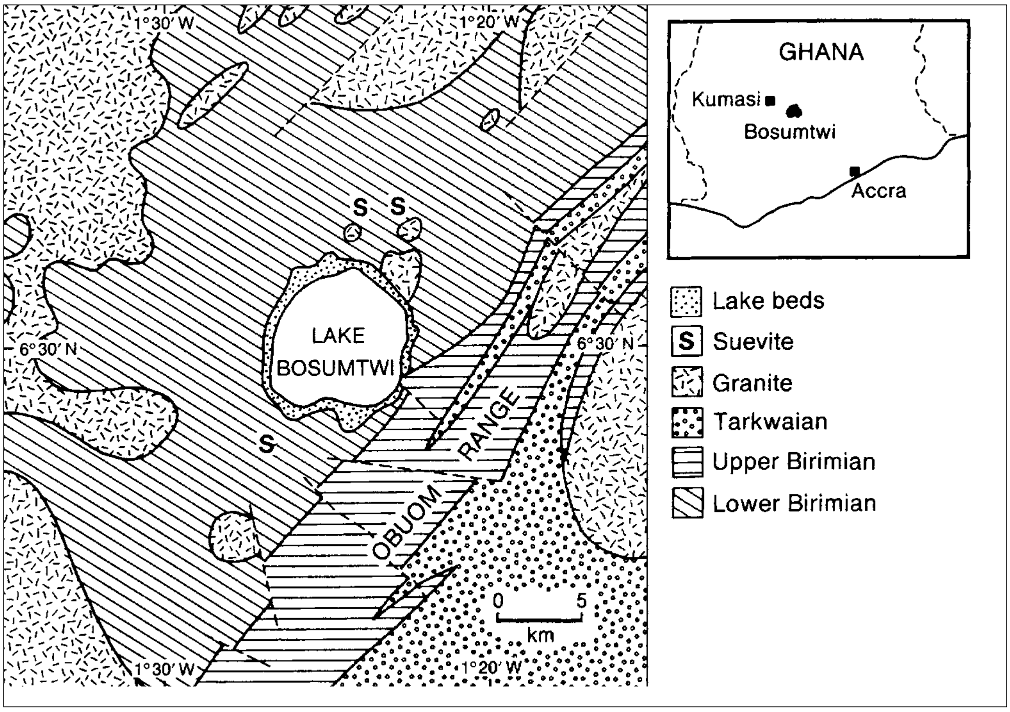
Traditionally the Birimian target rocks have been summarised as including complexly interbedded phyllite, meta-greywacke, quartzite and sandstone, schist, shale and slate, as well as meta-tuffs. Our studies of such rocks from the crater area and as inclusions in suevites from the crater environs have shown that mica schists and banded schists with both micaceous and quartz-feldspathic bands are seemingly more important in this area than phyllites.

Birimian meta-volcanic rocks (altered basic intrusives intercalated with some metasediments) occur in the south-eastern sector of the Bosumtwi area.

Graywackes predominate the surface exposures and are the most important clast type in many suevite samples. They appear in many lithological variations ranging from silty, tuffaceous phyllite and tuffaceous grits to medium- and even coarse-grained arenitic rocks. They are mostly fine- to coarse-grained, light to dark gray, impure fragmental arenaceous rocks containing a mixture of clastic and tuffaceous material. The finer varieties exhibit good cleavage, but coarser types are more massive and cleavage is often difficult to determine. The coarse-grained types grade into pebbly grits and conglomerates containing sub-angular to rounded pebbles of quartz and deformed (squeezed)

Text-Fig. 17.
Photos of drill core obtained from Bosumtwi hole LB-7 into the deep crater moat in September 2004 during the ICDP drilling project.
a) Core from run 3, about 10 meters below the sediment/breccia interface, shown as it was released from the core barrel.
b) Box with core from run 9, showing breccia, starting (lower right) at 356 m below lake level.
c) Core box 16 with slightly different looking breccia, starting at run 18 (upper left) at a depth of about 383 m below lake level.
d) Close-up of a breccia with a possible impact glass fragment (dark gray frothy fragment directly at the bottom center of image, from run 3).
All photos by C. KOEBERL.

pebbles of phyllite and lava, and the fine-grained types grade into phyllites. It is typical of the coarser types that they contain a high proportion of feldspar (feldspathic graywacke). Quartz veining and silicification are common in the graywacke. The graywackes observed in road cuts are highly fractured



Text-Fig. 18.
Schematic geological map of the Bosumtwi impact structure and surroundings, after JONES et al. (1981).
The distinction between Upper and Lower Birimian has recently been questioned (cf. LEUBE et al., 1990; HIRDES et al., 1996), but is kept to allow comparison with older maps and to indicate the slightly different rock types involved.
From KOEBERL et al. (1998)

Table 3.
Average and range of compositions of target rocks and impactites from the Bosumtwi impact structure (data from KOEBERL et al. [1997a, 1998] and DAI et al. [2005]). Major element data in wt %; trace element data in ppm, excepted as noted; all Fe as Fe_2O_3; blank space: no data available.

	Schist	Shale	Graywacke-phyllite	Granite dike	Pepiakese granite	Locally melted graywacke		Suevite		Impact glass	
	Average	Average	Average	Average	Average	Average	Range	Average	Range	Average	Range
SiO_2	70.17±0.65	55.56	66.75	68.74	57.81	64.64±1.41	62.52-66.09	64.10±0.49	63.17-64.74	63.32±2.06	58.17-64.94
TiO_2	0.47±0.08	0.84	0.66	0.50	0.46	0.76±0.05	0.69-0.81	0.64±0.03	0.61-0.67	0.66±0.07	0.6-0.83
Al_2O_3	13.39±0.73	19.56	15.27	15.91	16.45	13.96±0.36	13.41-14.32	15.71±0.53	14.64-16.20	16.66±1.44	15.5-20.25
Fe_2O_3	5.43±0.69	8.54	6.37	3.97	6.09	6.75±0.15	6.52-6.87	6.08±0.40	5.59-6.88	5.55±0.89	4.67-7.78
MnO	0.04±0.00	0.046	0.028	0.014	0.067	0.1±0.02	0.07-0.13	0.12±0.05	0.06-0.19	0.05±0.01	0.04-0.07
MgO	1.14±0.02	2.90	2.12	1.44	6.63	5.09±1.47	3.69-7.29	1.43±0.32	0.95-1.87	0.96±0.34	0.7-1.82
CaO	0.18±0.02	0.09	0.19	0.31	4.36	0.58±0.25	0.21-0.8	1.79±0.30	1.19-2.24	1.23±0.16	0.86-1.48
Na_2O	2.21±0.74	1.00	2.26	4.14	6.04	2.27±0.36	1.74-2.68	1.98±0.22	1.62-2.28	2.31±0.1	2.18-2.48
K_2O	1.66±0.33	2.89	1.80	1.92	0.67	0.72±0.57	0.23-1.57	1.40±0.34	0.97-1.89	1.85±0.28	1.57-2.55
P_2O_5	0.07±0.03	0.08	0.06	0.06	0.10	0.14±0.01	0.13-0.15	0.10±0.02	0.08-0.12	0.08±0.01	0.07-0.1
L.O.I.	5.19±1.33	7.91	4.25	2.98	1.48	4.94±0.44	4.27-5.3	6.74±1.43	4.86-9.21	7.19±0.55	5.99-8.19
Total	99.94±0.23	99.41	99.76	99.98	100.15	99.94±0.38	99.63-100.51	100.09±0.40	99.54-100.51	99.86±0.38	99.17-100.59
Sc	12.3±1.9	23.4	15.5	9.76	17.5	14.0±0.6	13-14.5	14.2±0.4	13.7-14.9	15.4±1.6	13.9-19.3
V	107±2	184	134	91	110	116±10	101-127	104±8	96-118	102±17	89-145
Cr	84.4	194	165	127	517	373±17	360-398	195±17	175-213	133±23	115-190
Co	9.31±0.44	22.6	12.1	9.66	30.4	22.4±2.8	18.2-24.6	17.1±2.0	14.6-19.8	22.2±1.0	20.7-24
Ni	44±21	79	48	49	172	219±34	191-270	70±5	64-79	70±6	56-81
Cu	19	52	15.5	10.7	24.3	<2	<2	19±2	17-22	28±5	15-33
Zn	58.4±2.8	143	104	82	90	92.2±7.2	84.2-103	70.5±5.5	61-76	93.7±13.7	79-128
Ga	9.4±1.6	24	67	37	73	6.8±4.4	0.13-11.2			14.9±4.2	5.8-21
As	1.81	8.61	7.00	14.9	12.7	7.9±8.0	1.7-19.8	3.2±0.8	2.3-4.8	3.8±1.3	0.66-5.1
Br	0.85±0.75	0.23	0.18	0.15	0.16	0.6±0.03	0.56-0.62	0.20±0.03	0.16-0.23	0.53±0.07	0.42-<1.3
Rb	32.4±16.8	104	65.2	69.9	22.4	32.3±19.5	6.55-61.5	56.0±11.7	43.5-71.2	83.2±11.1	71.8-100
Sr	243±103	118	152	342	377	227±16	203-239	323±13	297-338	298±16	260-320
Y	28±15	23.8	19	11	11	12±2	<3-13	16.0±1.5	15-19	16±2	14-19
Zr	122±8	153	143	129	82	108±12	90-120	129.0±4.5	121-136	153±7	135-163
Nb	7.5±0.5	6.1	5.7	3.7	1.8	8±1	7-9	8.5±0.5	8-9	9.6±0.7	9-11
Sb	0.14±0.02	0.38	0.20	0.18	0.42	0.09±0.01	0.08-0.11	0.38±0.05	0.33-0.44	0.3±0.08	0.18-0.45
Cs	1.88±0.52	5.57	3.27	4.22	0.87	1.54±0.64	0.78-2.49	2.87±0.26	2.51-3.39	4.13±0.35	3.59-5.01
Ba	663±238	765	454	605	226	251±116	136-424	591±60	521-684	695±120	573-986
La	26.0±6.2	30.9	23.4	18.8	15.6	11.4±3.2	6.53-15.8	19.6±1.8	16.70-22.00	31.9±3.2	27.9-38.2
Ce	48.3±17.7	38.4	34.8	39.4	32.0	20.5±8.9	9.95-33.8	41.4±2.7	36.00-45.80	50.0±4.1	44.1-57.9
Nd	26.0±6.0	28.2	26.5	19.8	17.5	11±2	7-13	18.8±2.8	15-23	26±1.3	24-29
Sm	4.83±1.42	5.48	5.06	3.74	3.58	2.64±0.54	1.83-3.29	3.71±0.42	3.10-4.55	4.84±0.5	4.26-5.62
Eu	1.51±0.45	1.37	1.29	1.03	1.19	0.89±0.13	0.7-1.04	1.17±0.11	1.02-1.30	1.32±0.11	1.18-1.52
Gd	4.1±1.3	6.55	4.80	3.40	3.07	2.57±0.44	1.9-3	3.39±0.19	3.1-3.7	3.54±0.45	3.1-4.4
Tb	0.67±0.25	1.06	0.73	0.59	0.47	0.41±0.06	0.33-0.46	0.51±0.08	0.44-0.67	0.59±0.06	0.5-0.69
Tm	0.31±0.13	0.47	0.35	0.22	0.20	0.17±0.01	0.16-0.19	0.25±0.04	0.20-0.31	0.23±0.02	0.2-0.27
Yb	2.18±0.97	2.70	2.14	1.13	1.18	1.17±0.12	1.05-1.36	1.52±0.20	1.35-1.92	1.52±0.2	1.3-1.96
Lu	0.32±0.14	0.38	0.29	0.16	0.14	0.18±0.02	0.16-0.22	0.22±0.01	0.20-0.24	0.22±0.03	0.17-0.3
Hf	2.44±1.12	4.12	4.04	3.66	1.88	2.94±0.17	2.74-3.2	3.32±0.24	2.85-3.61	3.66±0.28	3.17-4.02
Ta	0.22±0.13	0.53	0.42	0.28	0.19	0.27±0.03	0.23-0.31	0.32±0.02	0.30-0.35	0.4±0.06	0.31-0.55
Ir (ppb)	1.4±0.4					0.42±0.05	0.35-0.50	0.91	0.91	0.80±0.27	0.42-1.12
Au (ppb)	6.2±2.0	11.8	10.3	21.5	18.3	5.2±2.0	3.2-8.2	13.2±13.4	2.2-39.9	13.3±8.9	4.1-27.4
Th	2.64±0.37	4.36	3.94	3.10	2.21	2.18±0.14	2.07-2.38	3.26±0.16	2.94-3.44	3.55±0.18	3.32-3.92
U	1.30±0.82	1.69	1.35	1.75	0.74	0.64±0.18	0.36-0.86	1.09±0.25	0.84-1.43	0.81±0.12	0.65-0.99
K/U	15416±7586	14406	11389	9245	10800	9222±6444	3475-18889	11638±2842	8049-15683	19560±4082	14322-28225
Th/U	3.67±2.59	2.60	35.5	1.79	2.67	3.85±1.29	2.77-5.78	3.14±0.56	2.41-3.90	4.53±0.81	3.39-5.42
La/Th	10.39±3.82	7.10	6.15	6.00	10.9	5.35±1.74	2.74-7.63	6.01±0.44	5.46-6.71	9.04±0.84	7.12-10.9
Zr/Hf	61.5±24.9	37.1	10.11	35.4	51.9	37.03±5.96	28.1-43.8	39.1±2.1	35.5-42.5	42.1±4.4	36.5-50.8
Hf/Ta	12.56±2.12	8.28	2.95	14.55	12.71	10.97±0.63	10.32-11.91	10.54±0.64	9.50-11.33	9.44±1.46	7.22-11.94
La_N/Yb_N	8.72±1.99	7.75	7.30	11.21	13.72	6.65±2.32	3.17-9.37	8.8±0.8	7.7-10.4	14.2±1.9	9.37-17.2
Eu/Eu^*	1.01±0.01	0.73	0.83	0.88	1.16	1.04±0.06	0.99-1.13	1.02±0.08	0.95-1.18	0.94±0.07	0.82-1.1

and shattered. In a number of places in the crater environs graphitic schist has been observed, and this lithology is also an important clast component in impact breccia from both outside of the crater rim and from the recently drilled crater fill.

Metamorphic grade of the lower Birimian strata involves assemblages with kyanite, andalusite, and staurolite, indicative of amphibolite grade, but their occurrence seems to be limited to the surroundings of larger granitoid intrusions. Regionally, upper greenschist facies metamorphic grade seems to be widespread, with assemblages of biotite and chlorite, and also involving cordierite as cited by MOON & MASON (1967). The strata of the upper part of the Birimian Supergroup have generally only attained low to medium grade metamorphism (greenschist facies, also involving some actinolite), but locally (presumably in shear zones) higher grade is indicated by garnetiferous quartz-sericite and garnet-chlorite schists, as well as occurrence of actinolite-hornblende schist and even amphibolite (MOON & MASON, 1967).

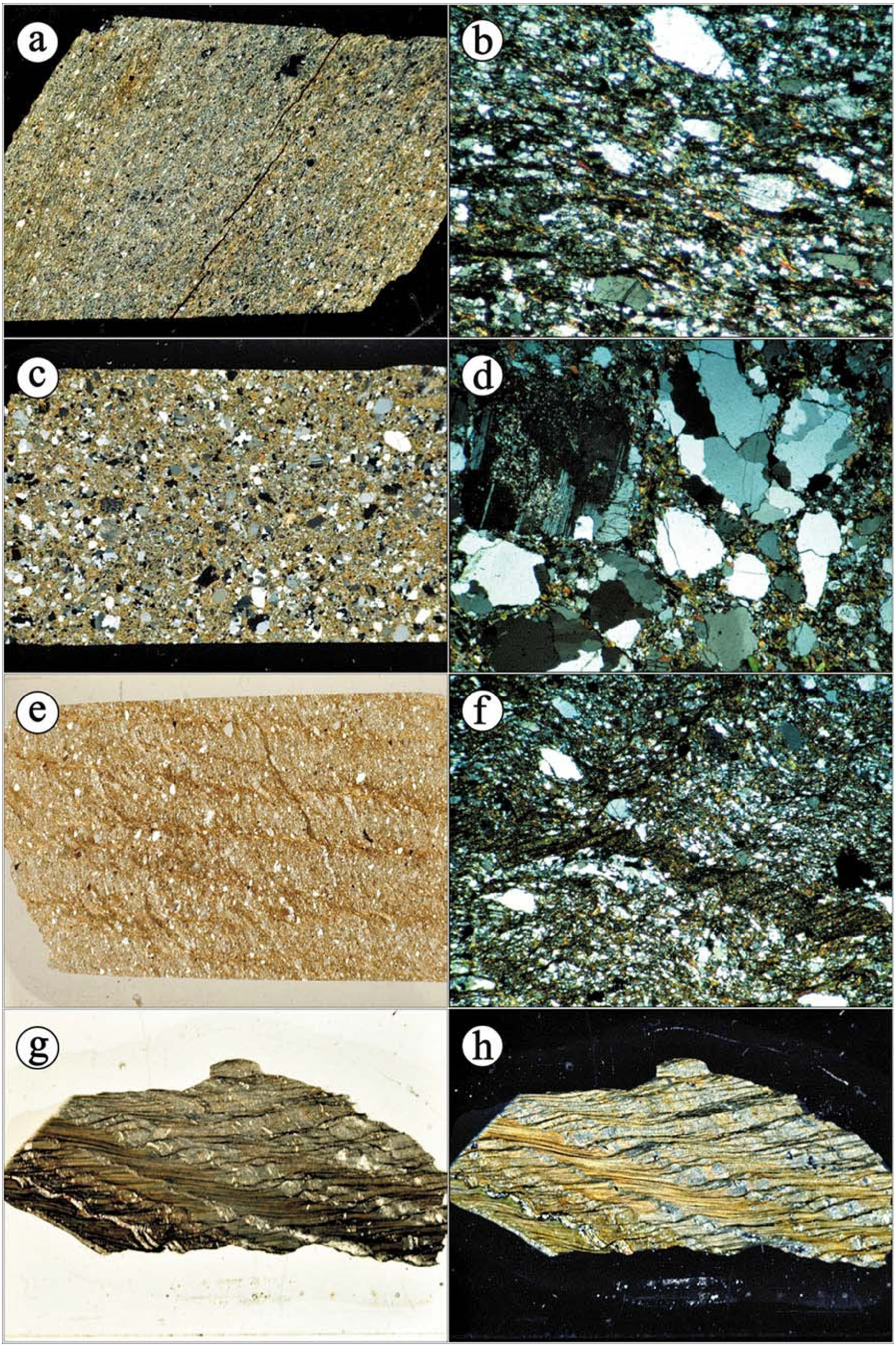
Brecciated greywacke and phyllite dominate the geology immediately around the crater. They are locally intruded by small dikes and pods of granitic intrusive (JUNNER, 1937; MOON & MASON, 1967; REIMOLD et al., 1998). In the investigations of the northern and northwestern sectors around the crater rim and of the crater rim itself, greywacke appeared dominant, however, recent drilling into the crater floor revealed that shales did indeed represent a major component of the target geology. Intercalated with these greywacke meta-sediments are silty, probably tuff-derived phyllites, fine-grained schists, and tuffaceous grits of variable (fine- to medium) grain size. These metasediments have variable appearance from fine-grained and then often laminated to more coarse-grained and often more massive varieties. Locally pebbly grits and even conglomerate have been described. Greywackes are characterized by very variable feldspar content. Quartz veining and local silicification are often observed in the Birimian metasediments – both in the crater rim as well as in the crater environs. Thus, this hydrothermal activity is likely of regional geological importance and not limited to the crater system.

The phyllitic rocks are grey to black and generally fine-grained rocks. They are frequently crumpled or folded and often exhibit evidence of local shearing. Many samples collected from the crater environs display distinct mylonitic fabrics (including very well developed S-C fabrics). The phyllitic and schistose lithologies are also frequently mylonitised, with quartz-rich bands having been dismembered into quartz ribbons. Lenses and stringers of vein quartz are also typical between laminae or bands. In places, it has been observed that such veining crosscuts already silicified phyllite, this giving evidence of two stages of hydrothermal activity.

Generally, the Birimian metasediments are characterised by a well defined, though locally folding-obscured, northeast–southwest fabric, with variable though generally steep dip in either northwest of southeast direction.

The immediate crater rim area is strongly deformed, as detailed by REIMOLD et al. (1998), based on detailed mapping of extensive roadcuts along the then new road to Abono (since then reclaimed by the rainforest); Text-Fig. 19 shows a variety of views of the extensive faulting along

Text-Fig. 19.
Rock exposures at roadcuts along the road from Kuntenase to Abono, cutting through the crater rim.
a) Overview of the lower portion of the road from the crater rim to Abono (outside of image at right); village at lake front center right of image is Obo.
b) Intense block faulting at roadcut about 200 m below rim crest along road towards Abono.
c) Complex low-angle faulting in lower part of crater rim, about 1/3 of the way from rim crest to lake level.
d) Steep aplitic dike (a likely pre-impact intrusion) cutting across extensively faulted and fractured metasediments of the lower part of the crater rim.
All photos taken in 1997 by C. KOEBERL.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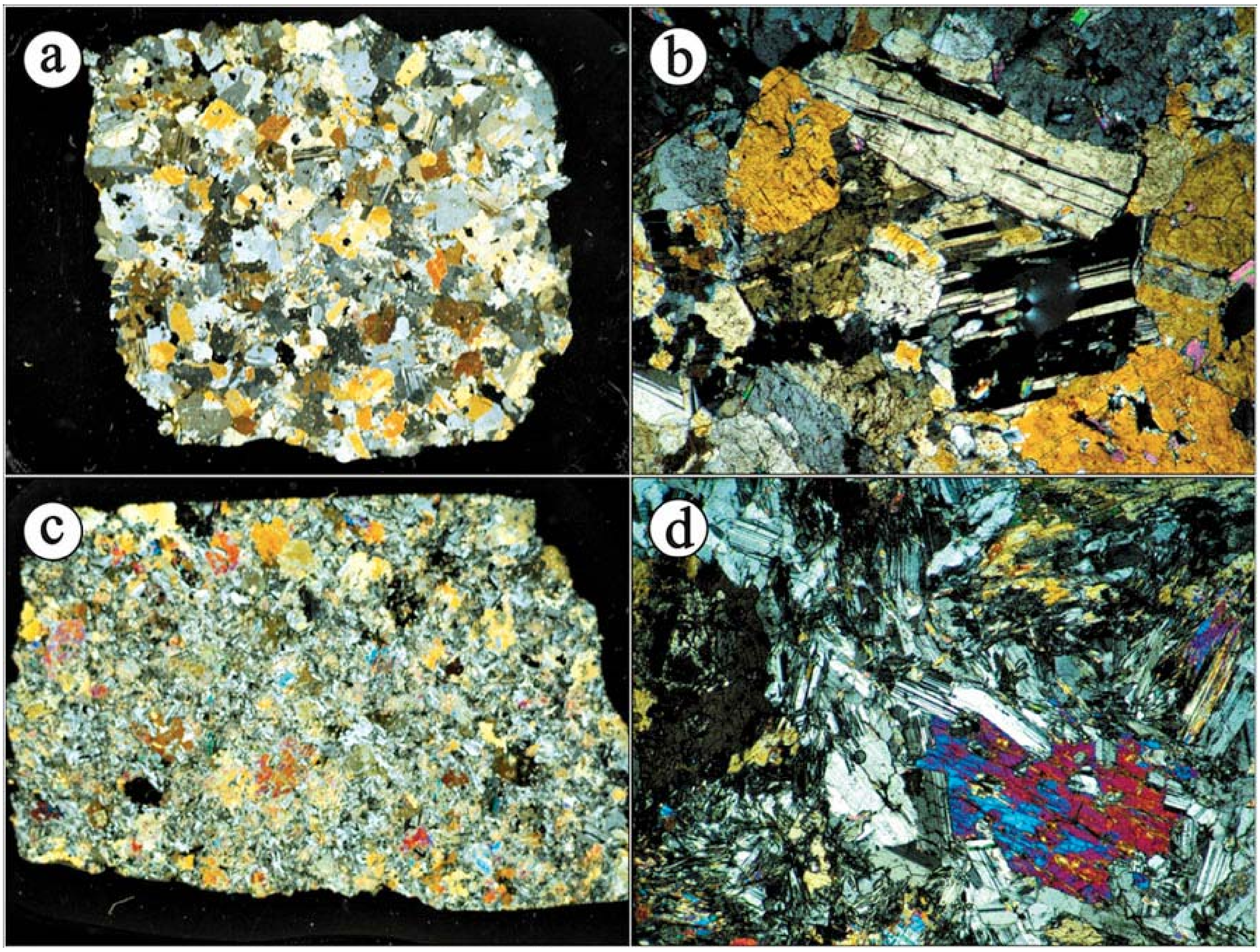


Text-Fig. 20.
Examples of Birimian meta-greywacke and shale samples from the environs of the Bosumtwi crater.
Note that sample numbers Jxyz in this and subsequent text-figures correspond to the analytical work reported by KOEBERL et al. (1998). LB-xy and Bxyz sample numbers referred pertain to samples collected by the authors in 1997.

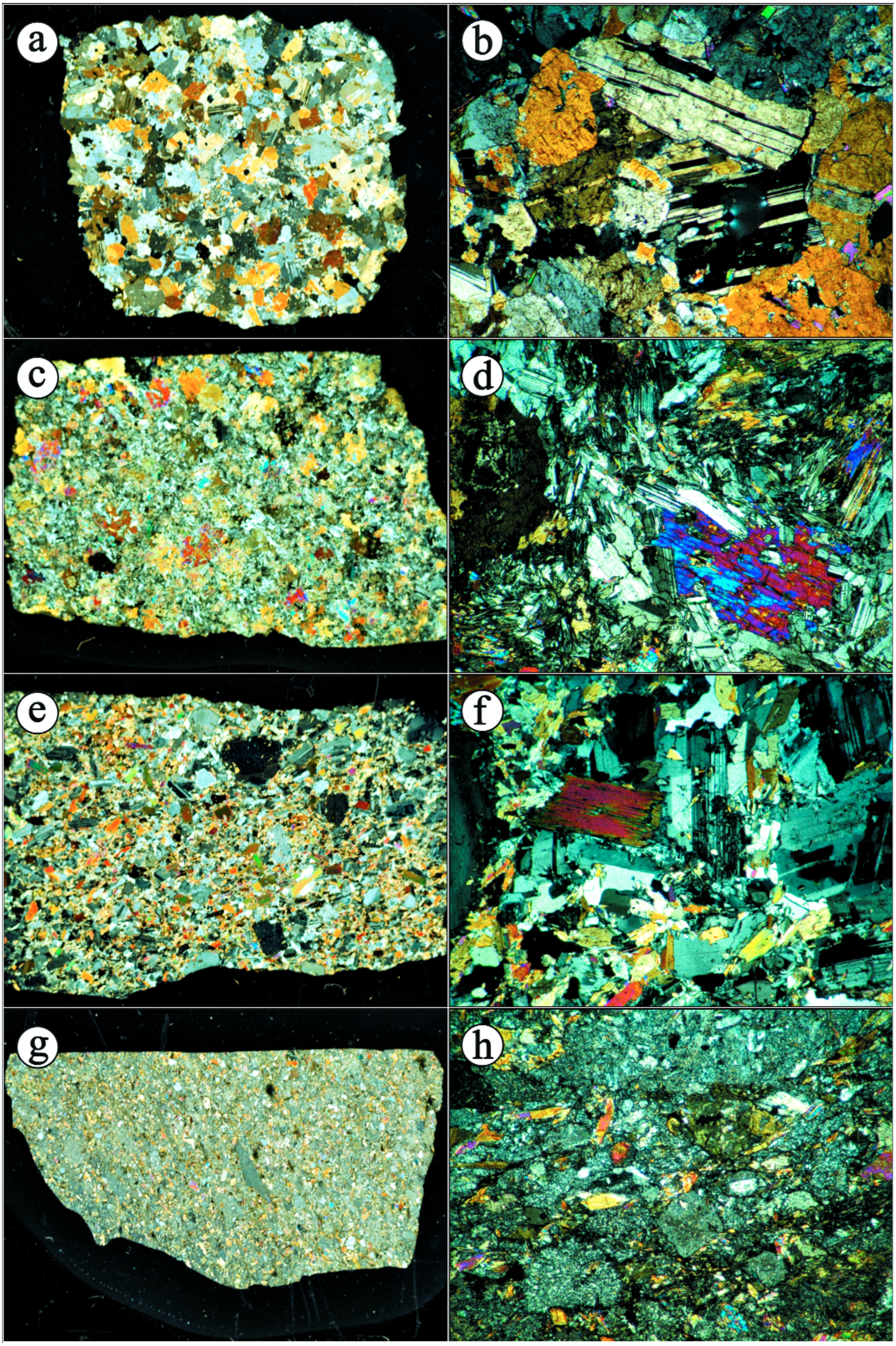
a) Sample J495 – Fine-grained, mylonitized greywacke. The fine-grained matrix is composed of the same minerals that comprise the clast content: mostly quartz and feldspar, besides some mica, mostly biotite but also some sericite, and some chlorite.
Plane polarized light, 2.8 cm wide.
b) Typical microphotograph of J495, showing the deformed quartz and feldspar clasts in this mylonitized sample, within a fine-grained matrix of these minerals and mica.
Cross polarized light, width 3.5 mm.
c) Sample J506 – Typical, undeformed Birimian greywacke. Fine- to medium-grained quartz and feldspar dominate, but there is also a significant proportion of fine-grained biotite flakes.
Cross polarized light, 3 cm wide.
d) Microphotograph of J506, showing the recrystallized nature of many of the quartz clasts as well as a relatively large, twinned plagioclase crystal (upper left). Note the fine-grained nature of the matrix and its biotite-rich composition.
Cross polarized light, 2.5 mm wide.
e) Sample J494 – Mylonitic greywacke, which has experienced a second, post-mylonitization shearing event. Similar in composition to J506.
Plane polarized light, 3 cm wide.
f) Microphotograph (cross-polarized light, 3.5 mm wide) of the micro-deformed greywacke J494.
g,h) A thin section of mylonitized shale (or phyllite as it would have been called in the older Bosumtwi literature) J497, with a pronounced C-S fabric emphasized by micaceous bands.This sample is composed mostly of finest grained biotite and some Fe oxide, but also has some quartz-/quartzitic aggregates and some larger individual biotite crystals.
Plane (g) and cross (h) polarized light, sample 2.8 cm wide.
i,j) Two microphotographs of sample J497, emphasizing the tight banding and lithological variation between bands, as well as showing some nice boudinage of a more quartz-rich band (in j).
Both images are taken with crossed polarizers and 3.5 mm wide.
k) Sample J502: Shale (dark band), interbedded with more silty layers. Most larger clasts are quartz, which indicates significant rotation due to shear overprint.The sample contains a large, rectangular siltstone clast (dark, upper left portion). It is also cut by several thin quartz veinlets trending northeast-southwest in the right part of the thin section).
Plane polarized light, 2.5 cm wide.
l) Microphotograph of sample J502, indicating a variety of clast types (quartz, alkali feldspar [large, grayish], and a large, rectangular siltstone clast [middle left]).
Cross polarized light, 3.5 mm wide.

that road across the crater rim. The crater rim zone has been subjected to impact-induced faulting as well as folding. Steep faults have then become loci for large-scale slumping off the crater rim and into the crater, resulting in a complex structural image.

In Text-Fig. 20, a small number of typical Birimian shale and greywacke samples are shown, both at the thin section scale and as microphotographs.

8.2.2. The Tarkwaian Supergroup

Tarkwaian Supergroup strata occur in each of the five NE–SW-trending volcanic belts in southwest Ghana (KESSE, 1985), overlying the volcano-sedimentary Birimian Supergroup. Clastic sedimentary rocks of the Tarkwaian Supergroup are regarded (e.g., LEUBE et al., 1990; EISENLOHR, 1992; DAVIS et al., 1994; HIRDES & NUNOO, 1994) as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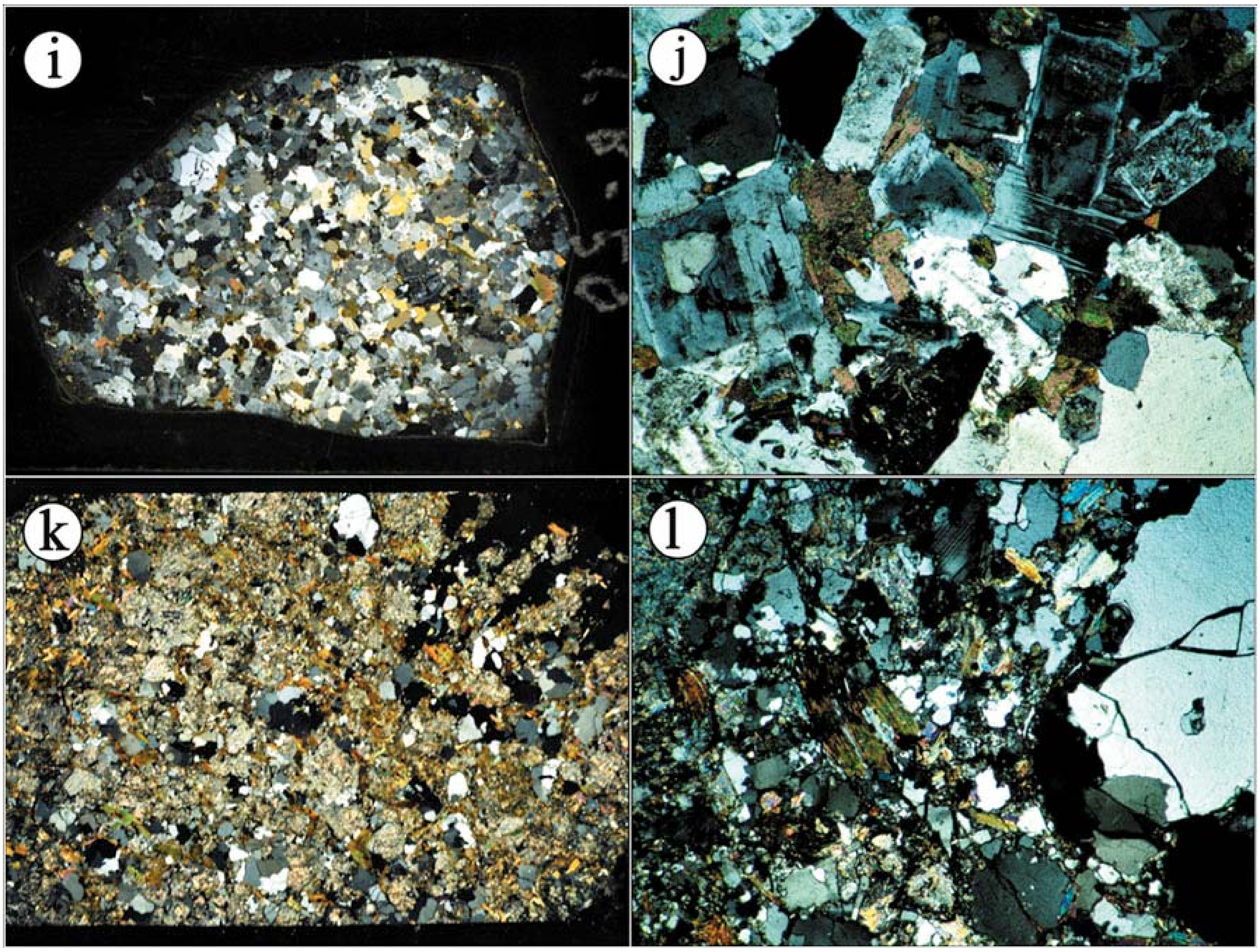


Text-Fig. 21.
Microphotographs of selected granitic samples from the Bosumtwi area.
a) Sample J507 – A medium-grained granite of the Pepiakese type, with very nice mosaic texture. It is composed of plagioclase, alkali feldspar, quartz, some secondary sericite, and minor, strongly altered biotite, besides some opaques.
Thin section, 1.6 cm wide.
b) A typical impression of the mosaic texture of this sample. Feldspar is hardly altered.
c) Sample J508 – Another example of Pepiakese granite, with large, poikilitic and locally uralitized amphibole blasts set into a plagioclase "groundmass", which is quite strongly altered to secondary chlorite and sericite.
Thin section, 2.5 cm wide.
d) Note the porphyritic texture of the granite (shown in c) with large amphibole blasts set into a plagioclase-dominated groundmass of much reduced grain size.
e) Sample J509 – Medium-grained, biotite rich (30 vol%) granite of the Pepiakese suite of granites. The sample has seemingly experienced some deformation (note weak gneissosity in NE–SW direction).
Thin section, 2.7 cm wide.
f) Enlarged texture of J509. Note the numerous biotite laths, many of which have been aligned more or less in NE–SW direction.
g) Sample B091 – Biotite-granite breccia. Feldspar is strongly altered (mainly to carbonate, grey particles). The sample is strongly sheared and fragmented (compare the microphotograph in (h). Thin section, 2.3 cm wide.
i) Sample LB-50 – Medium-grained granite, 2.5 cm wide. This particular granite is characterized by relatively large, strongly zoned K-feldspar blasts.
j) Microphotograph of LB-50, showing the blocky and zoned nature of the K-feldspar.
k) Sample J505 - A sample from a granitic dyke, with strongly sericitized plagioclase (mottled beige) and large, irregularly shaped quartz-aggregates.
l) Compare the microphotograph in (l) that shows one of these partially annealed quartz patches.
All images taken in cross-polarized light. Width of all enlarged images: 3.5 mm.

detritus deposited in the course of erosion of Birimian strata. In the map area, such rocks occur to the east and southeast of the crater. Tarkwaian deposition commenced with the deposition of the Kawere Formation, deposition of which was succeeded by the accumulation of the Banket, Tarkwa Phyllite, and Huni formations (KESSE, 1985). These formations are intruded by numerous sills that are believed to amount to about 20 % of the total thickness of the Tarkwaian Supergroup. The sills consist of quartz-feldspar porphyries and andesitic basalts (metabasites) that are generally altered. Metadoleritic dikes also occur, and SESTINI (1973) reported that the dikes cut the sills. According to DAVIS et al. (1994) Tarkwaian sedimentation probably took place between 2132 Ma (age of the youngest detrital zircon at the base of the Kawere Formation) and 2116 Ma (age of the oldest basin-type granite). Age dating results for detrital zircons from both Birimian and Tarkwaian sediments overlap in the range from 2194 to 2155 Ma, which has been interpreted to indicate that the provenance for the Tarkwaian Supergroup must have been eroding Birimian strata (e.g., TONGU, 2002).

According to WOODFIELD (1966), this suite of sedimentary rocks includes phyllite (also chloritoid-phyllite), sandstone, quartzite, grits, breccias, and conglomerate. The metamorphic grade of these beds seems to be largely greenschist facies, but some garnet-sericite bearing shear zones were mentioned by MOON & MASON (1967). For detailed descriptions of the various Tarkwaian lithologies occurring in the region, refer to the detailed reports by WOODFIELD (1966) and MOON & MASON (1967). Due to the extensive gold mining activity in the wider region of south-central Ghana (centered on the districts around the towns of Tarkwa and Obuasi), much detailed stratigraphic and other geological work has been carried out on the Tarkwaian Supergroup in recent decades (see TONGU, 2002, for a review).

8.3. Intrusive Bodies

Several granitic intrusions of Proterozoic age occur in the region of the crater, and some partially strongly weathered granitic intrusions (dikes) have been described from the crater rim (JUNNER, 1937; WOODFIELD, 1966; MOON & MASON, 1967; JONES, 1985a; REIMOLD et al., 1998). It is believed that these intrusions belong to the Kumasi-Type of granitoid intrusions, for which an age of 2.0–2.1 Ga has been proposed (TAYLOR et al. [1992]; HIRDES et al. [1992]).

A wide variety of compositions has been referred by MOON & MASON (1967) as belonging to this type of intrusion, ranging from adamellitic to granodioritic compositions. Biotite was the dominant ferromagnesian mineral, often accompanied by muscovite, and sometimes by amphibole. Some of these dikes in the crater rim have granophyric textures (REIMOLD et al., 1998), and others are aplitic. BOAMAH & KOEBERL (2003) report that some of these intrusions are strongly shattered and then highly weathered, such as those exposed along the road from Asisiriwa to Boamadumasi. Multiple intrusions have also been noted, with older lithologies foliated and cut by younger aplite and quartz veining. Gneissosity, where measured, generally trends parallel to the regional northeast–southwest fabric, and prominent joints measured in such bodies follow the same trend. Granitic dikes also seem to follow commonly the regional fabric trend of the metasediments that they have intruded.

A somewhat larger granitoid complex, known as the Pepiakese complex, occurs at the northeastern edge of the crater. It comprises various rock types, including hornblende diorite, biotite-muscovite granite, and a nearly pure albitite (JONES, 1985b). REIMOLD et al. (1998) estimated that the overall granitoid component in the crater region was no more than 2 %. Preliminary estimates of granitoid components in the recently obtained breccias from the central part of the crater lend further support to such a small granitoid component estimate for the target region.

Both the Bansu (also known as Banso) and Trobokro granites are considered by staff of the Geological Survey Department of Ghana as so-called “Belt-Type” intrusives. The Bansu granite is exposed only in a small area in the southeast corner of the map area. MOON & MASON (1967) refer to a coarse, foliated biotite adamellite and finer-grained, leucocratic microcline granite. The Trobokro granite is also intrusive into the Birimian Supergroup. It occurs in the map region as a thin strip south of the village of Odumasi. MOON & MASON (1967) classify this lithology as a biotite granodiorite.

Examples of granite samples obtained from the Bosumtwi crater area are shown in Text-Fig. 21.

In the Bosumtwi area, some occurrences of mafic intrusives have also been described, including dolerite, amphibolite, pyroxenite, olivine gabbro, hornblende-biotite diorite, and so-called epidiorite. It is not clear when these mafic to intermediate intrusives were formed. Earlier workers (WOODFIELD, 1966; 1967) proposed that these intrusives could partially be of Birimian, and partially of post-Birimian age. Birimian intrusives included epidiorite, amphibolite, carbonated dikes of intermediate composition, and hornblende-biotite diorite hybrid (MOON & MASON, 1967). The post-Tarkwaian basic dike lithologies listed by these workers include relatively fresh rocks with little or no alteration. This includes a coarse-grained dolerite, olivine dolerite to olivine pyroxenite, hornblendite, and gabbro, carbonated micro-diorite, and a quartz and tourmaline rock.

The Birimian and Tarkwaian of southern Ghana have been the subject of gold mining and related exploration for many decades. A major gold mining district occurs around the southwestern town of Tarkwa, but major mines are operated also near Obuasi, a mere 35 km to the SW from the Bosumtwi crater structure. Reviews of the gold economic significance of this region are, for example, contained in OBERTHÜR et al. (1994) and TONGU (2002). Gold exploration is currently conducted in the immediate environs of Lake Bosumtwi, and has already raised strong concerns in the regional press regarding the environmental effects that mining in the close neighbourhood to the crater structure could have on the drainage including the lake, and thus on the lifelihood and quality of life for thousands of local inhabitants.

8.4. Impact Breccia

Numerous breccia exposures have been mapped around the crater in the past (e.g., JUNNER, 1937; MOON & MASON, 1967; WOODFIELD, 1966). It is, however, not certain whether all of these breccias represent impact breccia. As pointed out by REIMOLD et al. (1998), it is likely that at least some of the breccias are the results of lateritization and secondary mass-wasting processes in this tropical and topographically varied environment, where the weathering horizon can attain a thickness in excess of 50 m.

The breccias at Bosumtwi can be grouped into three types, based on their composition and texture. These are: an apparently brecciated single rock type (monomict breccia; in many cases seemingly autochthonous); breccia formed from more than one rock type (polymict lithic breccia; in many cases seemingly allochthonous); and breccia with glass or melt fragments, occurrences of which are only known from just north and south of the crater rim. This latter breccia type also contains shock metamorphosed inclusions and, thus, is clearly related to the impact event. Impact breccia of this kind corresponds to one of the main impactite types, suevite.

A road cut along a recently constructed road between the villages of Asisiriwa and Boamadumasi, to the north-northeast of the crater, outside the crater rim, exposes an instructive exposure of partly consolidated polymict breccia. It consists of unsorted angular fragments of graywacke (~60 % by volume), phyllite (~30 %), schist (~7 %) and granite (~3 %) in a matrix of smaller fragments and dust derived from the same rocks. Most of the clasts are highly weathered and up to about 30 cm in size. Clast shapes range from angular to subrounded. This exposure is interpreted as a mixture of impact breccia and other, locally accumulated, products of secondary mass-wasting processes along the steeply dipping outer rim slope. Coarse pieces of quartz are rare, but fine-grained quartz occurs in the matrix. From the exposure along the road cut (width about 2 m) and the core from drill hole BH1 (see section 8.6.) the thickness of this impact breccia is estimated at more than 20 m. Similar breccias are exposed in other nearby road cuts. Clast sizes are larger, up to 60 cm, towards the Nyameani-Asisiriwa main road, compared to around 30 cm in the breccias farther to the north from the crater towards Boamadumasi. A similar or maybe identical breccia was also observed along a steep slope about 50 m to the south of the Nyameani – Beposo road, about 150 m to the SSE of shallow borehole BH1, where this clearly polymict clastic breccia seems to be located stratigraphically below suevite exposed in the upper part of this slope (Text-Fig. 22). Not a single macroscopically recognisable clast of impact melt was observed in this breccia – leading to the suspicion that it could represent a Bunte Breccia-type deposit (as is observed at the Ries crater in Germany, where suevite overlies Bunte Breccia).

Text-Fig. 22.
A possible Bunte Breccia-like deposit (polymict breccia) underneath a suevite deposit north of the crater rim, about 50 m S of the Nyameani – Beposo road.
a) This image shows the about 12-meter-high ledge of the breccia (with a corn plantation on top), which is (towards the right of the picture) overlain by a patchy suevite deposit of several meters thickness.
b) Close-up image of this breccia, with hammer for scale.

Text-Fig. 23.
Field occurrence of suevite at Bosumtwi north of crater rim, near the Nyameani – Beposo road, about 200 m to the south of the location of 1999 shallow borehole BH1.
a) Broad outcrop of suevite, about 10–20 m high (depending on pre-impact topography); the crater rim is towards the left at a distance of about 1–1.5 km, and suevite has obviously been removed by erosion between here and the crater rim (one of the authors, CK, with D. BOAMAH, Geological Survey Department of Ghana, for scale).
b) One of many large blocks of suevite in that area (which are often above a several meter thick layer of suevite, which is badly exposed because of the heavy vegetation), with one of the authors (CK).
c) Another large suevite block with D. BOAMAH (left) and F. KARIKARI (right), near the top of the south-looking ledge of suevite, about 80 m S of BH1.
d) Large suevite boulder weathering out of suevite layer; immediately to the left and also below the hands of D. BOAMAH are two 15 cm wide and 30–40 cm long brownish impact glass fragments.
All photos by C. KOEBERL (1999 and 2004).

The other main type of breccia is monomict – only fragments of one rock type can be seen, often grading into unbrecciated rock. The rocks are shattered more or less in situ without much relative displacement between, and rotation of, clasts. The breccias consist of angular fragments of different sizes, irregularly distributed and cemented in a matrix of the same material. This type is, for example, found on the road from Nyameani to Asisiriwa, and along the crater rim. This breccia type was described by MOON & MASON (1967) as the result of lifting and dropping of the surface without much lateral displacement, resulting in a breccia of coarse blocks in a matrix of the same rock type.

Rarer is the Bosumtwi suevite, a glass and/or melt-bearing breccia similar to the suevite of the Ries crater in Germany (JONES et al., 1981). The occurrence of suevite to the north and southwest/south of the Bosumtwi crater, outside the crater rim, was first mentioned by JUNNER (1937), who referred to the deposit as volcanic tuff and agglomerates. Suevite is defined (STÖFFLER & GRIEVE, 1994) as polymict impact breccia including cogenetic impact melt particles which are in a glassy or crystallized state, included in a clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism. The Bosumtwi suevite from outside of the crater rim is generally grayish in color, and typically contains a lot of glassy or devitrified melt (in many samples between 20 and 40 vol%, and of wide size range – mm to 40 cm), and lithic and mineral clasts of highly variable size, from sub-millimeter to about 40 cm.

The suevite represents that type of impact breccia that contains fragments of all target rocks, in all stages of shock metamorphism, from unshocked to various stages of shock metamorphism, to partial and complete vitrification. The Bosumtwi suevite (Text-Fig. 23a–d) occurs as large blocks of up to several meters width and as patchy massive deposits (Text-Fig. 23a) more or less covered by thick vegetation in a marginal zone (to about 1.5 km from the crater rim) outside the rim of the crater in the north, that is about 2.5 km from the lakeshore (in the area between 1°23.5'–1°24.5'W and 6°33.5'–6°34.2'N). One such outcrop comprises massive suevite, exposed at an approximate thickness of two meters. It contains melt inclusions and rock fragments (graywacke, phyllite, shale, granite) up to about 40 cm in size, with graywacke being the main clast type. Most of the rock fragments are subangular in shape and less than 20 cm long and arranged in a disordered fashion. Individual grains of quartz and feldspar are also present. The matrix is essentially composed of fine-grained particles of mainly quartz, feldspar and highly vesicular glass, besides small (sub-millimeter) aggregates of the various minerals forming the main target rocks.

Text-Fig. 24 shows a variety of macroscopic views of suevite samples from Bosumtwi. Text-Fig. 24a shows a cut surface of a suevite sample, in which the polymict nature of the breccia, and the presence of large glass inclusions, is evident. High-resolution X-ray computed tomography (HRXCT), which is a non-destructive method used to study the interiors of opaque solid objects, was used by KOEBERL et al. (2002) to image the interior of a massive sample of Bosumtwi suevite. This study allowed to determine the three-dimensional distribution of clasts within the matrix of the suevite and to test, generally, this technique with respect to its suitability for the recognition of different clast types of different densities. The target rock fragments in the Bosumtwi sample consist of greywacke and sandstone/quartzitic rocks, shale and phyllite, and granite. Another large clast component is composed of impact melt and glass fragments (Text-Fig. 24). Besides allowing to determine the three-dimensional distribution of clast populations in the impact breccias by image processing techniques, the HRXCT method provided data to quantify their abundances in volume percent which turned out to be about 76 vol. % matrix and 24 % clasts (including about 9 vol% melt/glass).

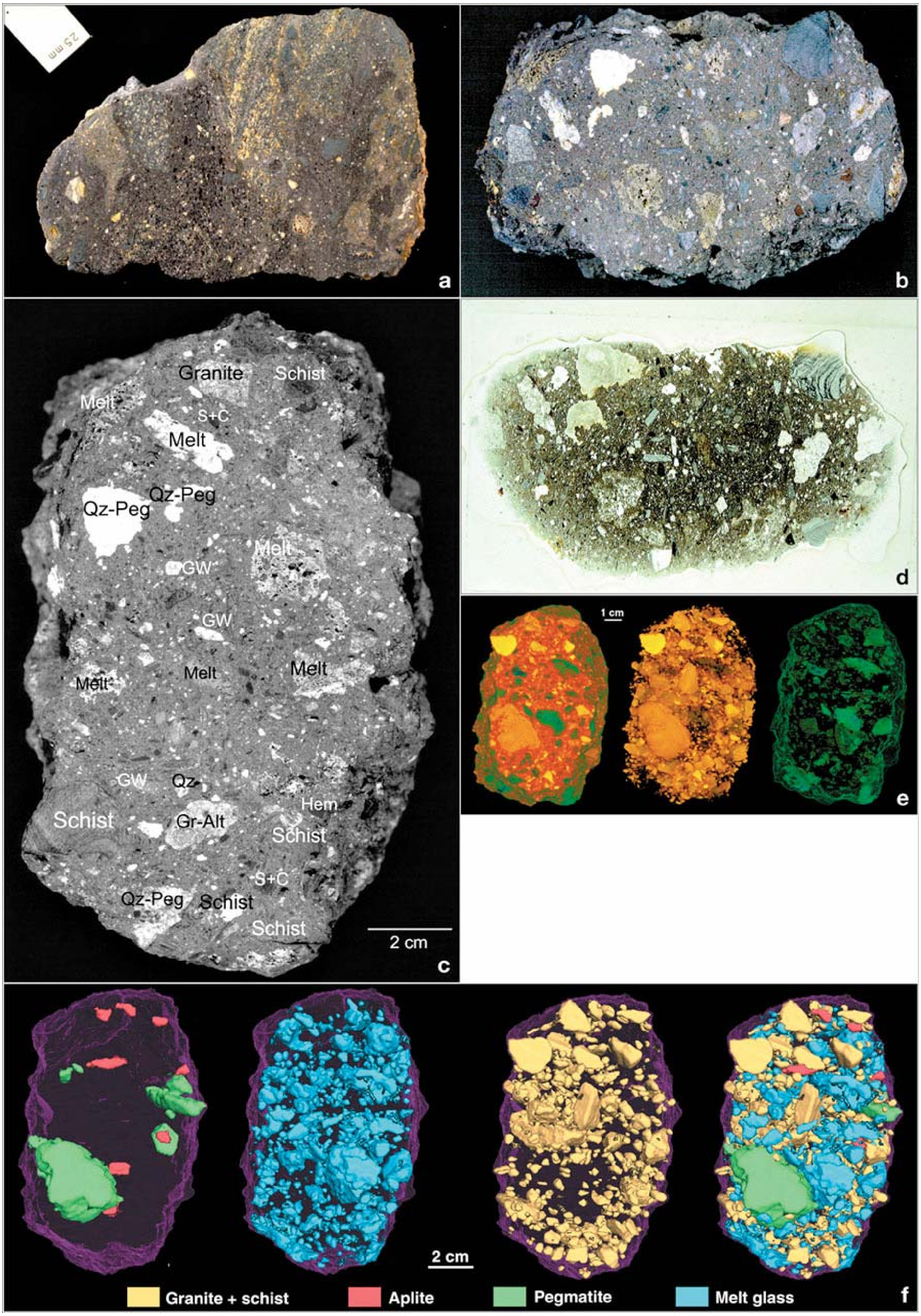
8.5. Shock Petrography and Geochemistry of Impactites

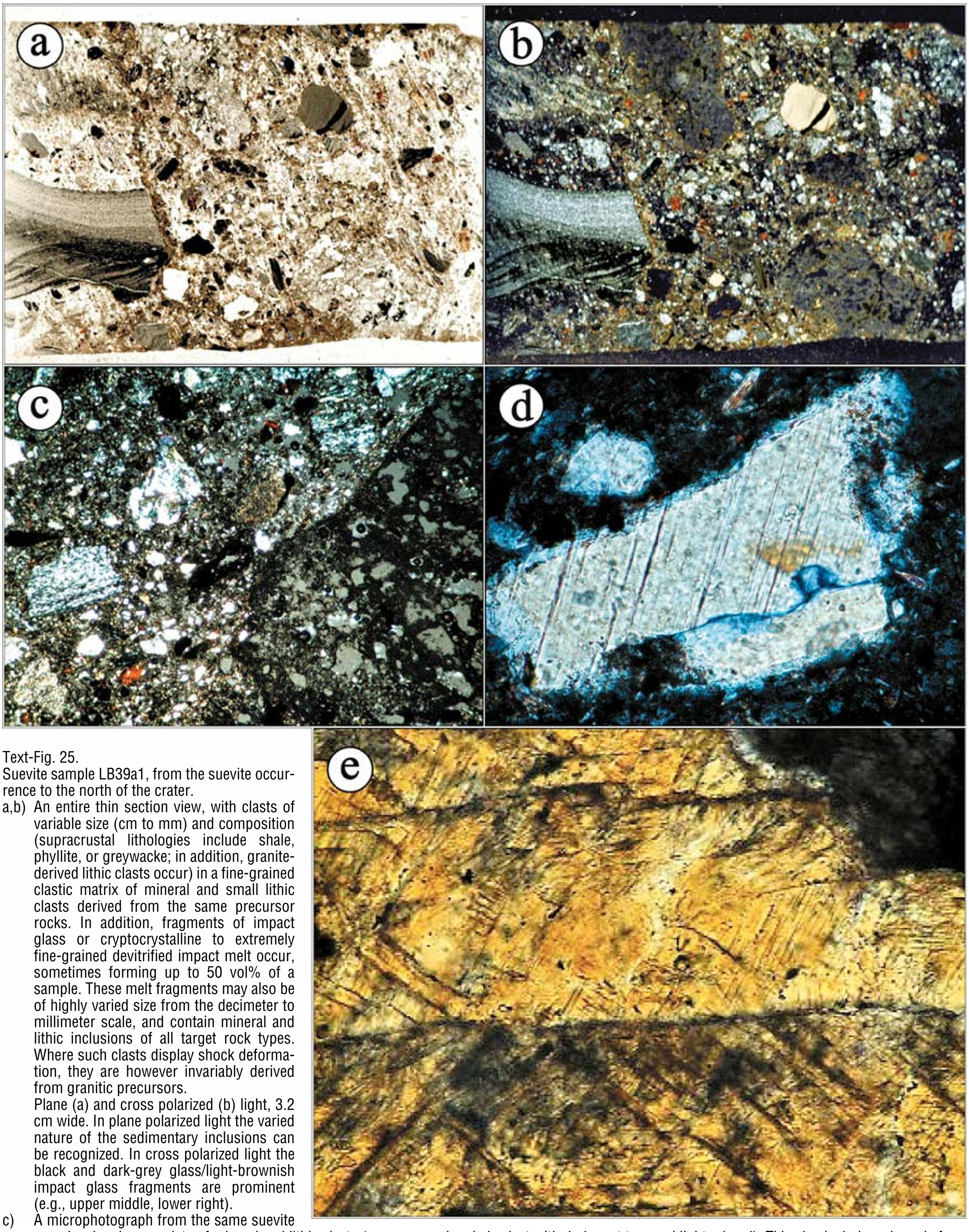
Some first petrographic and geochemical studies of rocks from the Bosumtwi impact crater were recently performed by KOEBERL et al. (1998). Characteristic shock features are shown in Text-Figs. 25 and 26. A variety of target rocks from the Bosumtwi impact structure were selected to represent the major rock types that have been described from the region, namely four groups: shale, phyllite/graywacke (it must be noted that until recently the various schistose lithologies of the Birimian in the crater area have been collectively termed phyllite, in keeping with the tradition of earlier Bosumtwi workers), and two different types of granites (from dispersed dikes and from the so-called Pepiakese intrusion at the NE side of the crater). These rocks were analyzed for their major and trace element composition and their petrographic characteristics. In addition, representative samples were also analyzed for their O, Sr, and Nd isotopic compositions. The target rocks do not show any unambiguous evidence of shock metamorphism.

Distinct impact-characteristic shock effects (for example, planar deformation features, PDFs – see section 3.1.) were identified only in clasts in suevite (i.e., within melt fragments, and as part of the clastic component of suevite). KOEBERL et al. (1998) described small melt fragments that were originally part of suevite samples (parts of samples B026, B034, and B075, which represent glassy, vesicular melt rock, are shown in Figs. 26a–c). Of those samples, B075 is unique in that it constitutes a frothy melt (Text-Fig. 26c), similar to many glass inclusions seen in suevites. The other two melt samples contain many inclusions, with a number of shocked quartz clasts with one set or multiple sets of PDFs (Text-Figs. 25f, 26d-f). Many of the clasts in these melt rocks are granitoid-derived.

Shock metamorphic effects in rocks from the Bosumtwi crater were first mentioned by LITTLER et al. (1961) and CHAO (1968), who described the presence of coesite and shocked minerals in suevite (ejecta) from outside the crater

Text-Fig. 24 (opposite page).
Suevite from the Bosumtwi crater. All samples shown here were taken from near the Nyameani – Beposo road to the north of the crater rim, not far from 1999 shallow borehole BH1.
a) Suevite slab, showing a variety of rock clasts and a large frothy impact glass inclusion, which makes up the central third of this sample.
b) Suevite sample with a variety of clasts; this sample is the one that was studied by high resolution X-ray computed tomography (HRCXT) by KOEBERL et al. (2002).
Sample width dimension ca. 14 cm.
c) Facing cut of the sample shown in the previous image, with annotations indicating the various rock clasts.
d) Large thin section of sample in previous image (cf. KOEBERL et al., 2002); section taken a few cm from the surface shown in c; compare with Text-Fig. 24c for clast identification.
e) Series of reconstructed 3D images composed of about 200 X-ray slices through the suevite sample – on the left, the full opacity view, in the center, the matrix has been made transparent, showing the clasts, and on the right only the low-density (glass/melt) clasts are visible (after KOEBERL et al., 2002).
f) Identification of clast types in the Bosumtwi suevite done from thin section (Text-Fig. 24d) and HRXCT density data (after KOEBERL et al., 2002).


a
b
Granite
Schist
Melt
S+C
Melt
Qz-Peg
Qz-Peg
Melt
GW
GW
Melt
Melt
Melt
GW
Qz
Hem
Schist
Gr-Alt
Schist
S+C
Qz-Peg
Schist
Schist
2 cm
c
d
1 cm
e
2 cm
Granite + schist
Aplite
Pegmatite
Melt glass
f



Text-Fig. 25.
Suevite sample LB39a1, from the suevite occurrence to the north of the crater.

a,b) An entire thin section view, with clasts of variable size (cm to mm) and composition (supracrustal lithologies include shale, phyllite, or greywacke; in addition, granite-derived lithic clasts occur) in a fine-grained clastic matrix of mineral and small lithic clasts derived from the same precursor rocks. In addition, fragments of impact glass or cryptocrystalline to extremely fine-grained devitrified impact melt occur, sometimes forming up to 50 vol% of a sample. These melt fragments may also be of highly varied size from the decimeter to millimeter scale, and contain mineral and lithic inclusions of all target rock types. Where such clasts display shock deformation, they are however invariably derived from granitic precursors.
Plane (a) and cross polarized (b) light, 3.2 cm wide. In plane polarized light the varied nature of the sedimentary inclusions can be recognized. In cross polarized light the black and dark-grey glass/light-brownish impact glass fragments are prominent (e.g., upper middle, lower right).

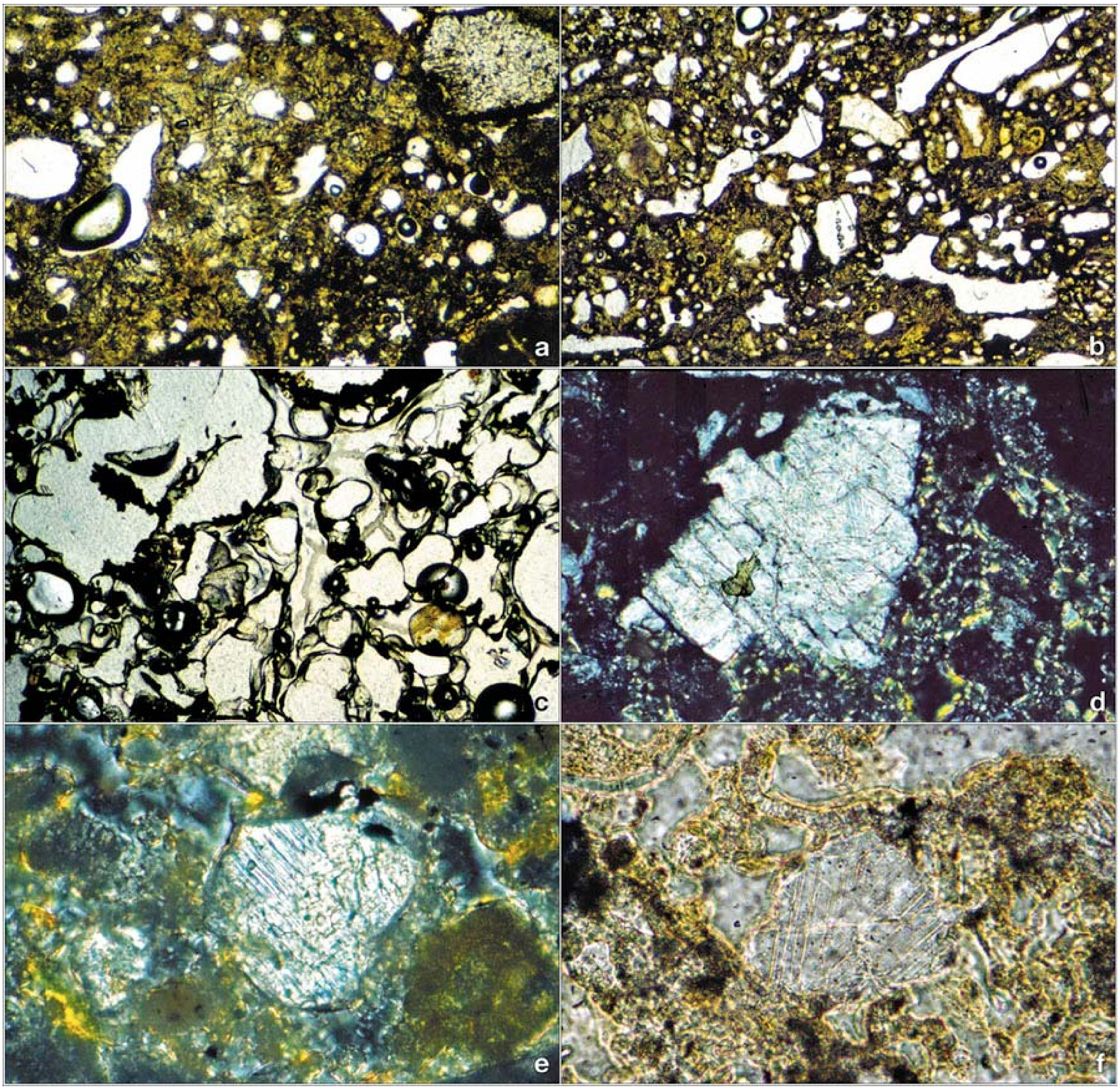
c) A microphotograph from the same suevite sample, showing a variety of mineral and lithic clasts (e.g., an angular shale clast with darker, at top, and lighter band). This also includes a breccia fragment, at upper left (note the straight edges of this fragment), as well as a large, mostly dark impact glass fragment at right, which contains a large number of clasts, many of which have been plasticized (note their amoeboid shapes).
Cross polarized light, 3.5 mm wide.

d) A quartz fragment in this suevite sample, displaying a well defined set of planar fractures – indicative of relatively low grade (<8 GPa) shock deformation.
Crossed polarizers, 1.2 mm wide.

e) This quartz clast from the same sample displays a well defined, subhorizontal set of subplanar shock fractures, another set of planar fractures that are more closely set and trend in NW–SE direction, as well as three sets of planar deformation features (PDFs: E–W, NE–SW, and N–S trending) that are best observed in the light area of the right-middle portion of this image.

rim. The work of KOEBERL et al. (1998) confirmed the presence of PDFs in quartz within clasts in suevites, but did not yield a large enough number of shocked quartz grains in our present sample suite to perform a statistically relevant universal stage study of the crystallographic orientations of the PDFs. It is interesting that none of the country rocks – some of which were exposed and sampled directly at the crater rim – show any evidence of shock metamorphism. Shocked minerals are restricted to clasts within suevitic breccias, which occur outside of the crater rim (but inside the outer ridge zone) and which represent ejecta from the lower part of the crater.

The compositional range of these target rocks is significantly wider than that of the Ivory Coast tektites, but overlaps the tektite compositions. A best-fit line for the Bosumtwi crater rocks in a Rb-Sr isotope evolution diagram yielded an "age" of 1.98 Ga, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.701, which is close to results previously obtained



Text-Fig. 26.
Microscopic images of impact glass and melt rocks from within Bosumtwi suevite (for sample details see KOEBERL et al., 1998).
a) Aphanitic melt breccia with devitrification textures; the glass is locally altered. Clasts include metasediments and granitoids. Sample B026; plane polarized light; image width 3.4 mm.
b) Clast-poor aphanitic melt breccia; note small quartz clast with ballen texture slightly to the top and right of the center. Sample B034, plane polarized light, image width 3.4 mm.
c) Vesicular impact glass sample B075, almost devoid of clasts and showing flow structures. Plane polarized light, image width 3.4 mm.
d) Quartz clast with multiple sets of PDFs from sample B034. Cross polarized light, image width 355 µm.
e) Quartz fragment with one dominant and one faint second set of PDFs in partially brecciated and altered granitoid clast. Sample B034; cross polarized light, image width 355 µm.
f) Quartz clast with multiple sets of PDFs in altered micaceous matrix, possibly from a graywacke precursor. Cross polarized light, image width 85 µm.

for granitoid intrusions in the Birimian of Ghana. The Nd isotopic data of KOEBERL et al. (1998) yielded depleted mantle model ages ranging from 2.16 to 2.64 Ga, and εNd values of –17.2 to –25.9 ‰.

8.6. Shallow Drilling into Ejected Impact Breccias to the North of the Crater Rim

In early 1999, a shallow drilling program was undertaken by the University of Vienna with the cooperation of the Geological Survey Department of Ghana (GSD). Seven short holes were drilled to the north of the crater, at a distance of 2.5 to 8 km from the lakeshore (locations in the area 1°22'–1°27' W and 6°33'–6°36' N). Each hole was drilled to a maximum depth of about 30 m and core samples of suevite and other rock types were recovered (BOAMAH & KOEBERL, 2002, 2003).

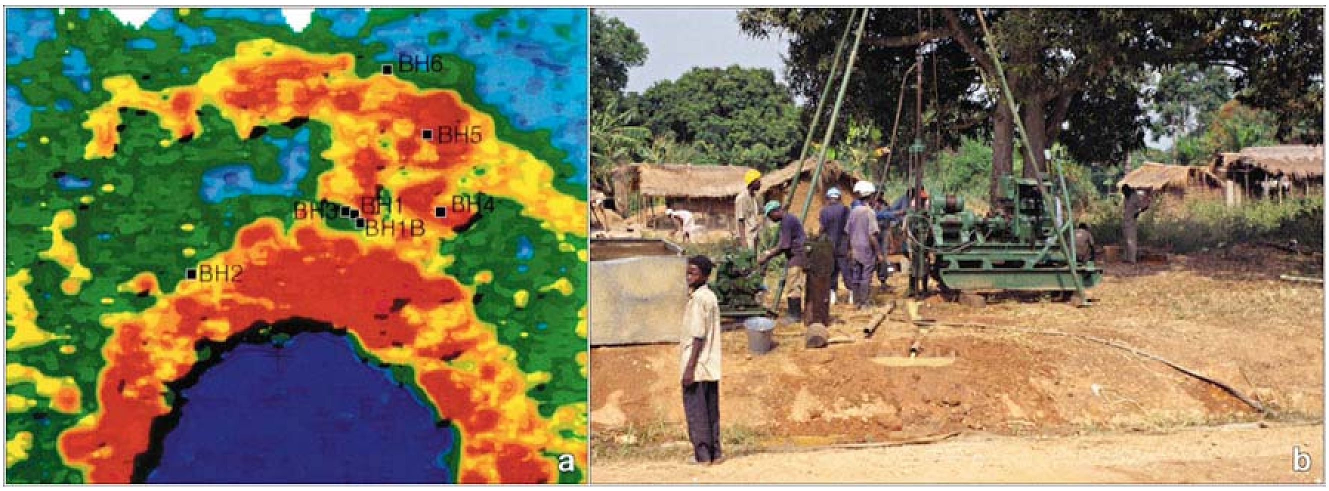
The drilling locations (Text-Fig. 27a) were chosen based on geophysical information obtained from an airborne radiometric (equivalent concentrations of potassium and total radiation) map produced by the high-resolution aerogeophysical survey across the Bosumtwi structure (see section 5.1.). The airborne radiometric map shows high concentrations of potassium (see Text-Fig. 13b) around the crater and farther north where the drill holes were sited (Text-Fig. 27). The siting of the drill holes was also correlated with breccia outcrops as shown on the geological map of MOON & MASON (1967), in order to recover a variety of impact lithologies, especially suevite.

The drilling sites were individually chosen by BOAMAH & KOEBERL (2002, 2003) as the best available locations to recover specific lithologies relative to the goals of the drilling project. To the extent possible, drill holes were sited where the K concentrations were high and also where the water tanker for the supply of water for the drilling could find access. Fortunately, a new road was under construction crossing the area where the geophysical airborne radiometric highs occur in the north, and this road provided access to some of the drill sites. These sites were in lithic breccia terrain. Two of the drill holes were sited not far from suevite outcrops, with the aim of recovering suevite and determining the thickness of the fallout suevite deposit. Details of this study are described by BOAMAH (2001) and BOAMAH & KOEBERL (2002, 2003).

Geological mapping was also undertaken at that time to determine the extent of the outcrops of various rock types and, especially, of different types of breccia. Because of the thick vegetation cover, bedrock and impact formations outside of the crater are only accessible along road cuts and in stream beds. Traverses were mapped along four road cuts, covering a total of about 30 km. The results show that a variety of lithologies are present and were intersected by drilling, consisting of impact glass-rich suevite and several other types of breccia: lithic breccia of a single rock type, often grading into unbrecciated rock, and lithic polymict breccia that apparently does not contain any glassy material. The question whether this material is allochthonous could not be resolved conclusively, as contacts to adjacent lithologies could not be mapped. The suevite cores show that melt rock inclusions are present throughout the entire length of the cores, in the form of vesicular glasses, with no significant change of abundance with depth. Major and trace element analyses of the bulk suevite yielded compositions similar to the target rocks in the area (graywacke-phyllite, shale, and granite). Graywacke-phyllite and granite dikes seem to be important contributors to the compositions of the suevite and the road cut samples (also in the fragmental matrix), with a minor contribution of Pepiakese Granite. The results also provide information about the minimum thickness of the fallout suevite in the northern part of the Bosumtwi structure, which was determined to be ≤15 meters. Besides the known surface occurrences of suevite, this drilling project confirmed the existence of this breccia type over an area of about 1.5 km^2 to the north of the crater.

8.7. Meteoritic Component in Tektites and Impact Breccias

Negative thermal ionization mass spectrometry was used by KOEBERL & SHIREY (1993) for the measurement of concentrations and isotopic ratios of osmium and rhenium in four Ivory Coast tektites, two Bosumtwi impact glasses, and five different target rocks from the Bosumtwi crater. The tektites have major and trace element compositions, as well as large negative εNd (–20) and positive εSr (+260 to +300), which are characteristic of old continental crust. As mentioned above, the Bosumtwi impact crater has been inferred as the source crater for the tektites. The tektites and the target rocks have Os concentrations ranging from 0.09 to 0.30 ppb, and 0.021–0.33 ppb. However, the $^{187}Os/^{188}Os$ ratios in the tektites are close to meteoritic values at about 0.155 to 0.213 ($^{187}Os/^{186}Os$, 1.29–1.77), whereas the Bosumtwi crater rocks have values of 1.52–5.01. Their $^{187}Os/^{188}Os$ values are typical for old continental crust (12.3–41.4). The low $^{187}Os/^{188}Os$ ratios in the



Text-Fig. 27.
a) Locations of the shallow boreholes (drilled in 1999) described by BOAMAH (2001) and BOAMAH & KOEBERL (2002, 2003), superimposed on the K-radiometry map obtained in 1997 (PESONEN et al., 2003).
b) Shallow drilling in January 1999 at site BH1 next to the Nyameani – Beposo road, using the Ghana Geological Survey drill rig.

tektites are unambiguous evidence for the existence of a meteoritic component (on the order of 0.1 to 0.6 wt %). More recently, KOEBERL et al. (2004) used Cr isotopic data to indicate a possible ordinary chondrite contribution to an Ivory Coast tektite.

In these investigations, the geochemistry of target rocks and breccias from the Bosumtwi crater was studied for comparison with Ivory Coast tektites. However, another important line of research, which is necessary for the identification of a meteoritic component in impact breccias and melt rocks, namely the determination of siderophile elements (especially the PGEs) in the target rocks at the crater, has so far been somewhat neglected. KOEBERL et al. (1999) and DAI et al. (2000, 2005) tried to calculate the contribution of the meteoritic component from the content of PGEs in the target rock samples, but found that the concentrations of the PGEs in the target rocks are very high and do not show a flat abundance pattern when normalized to chondritic (meteorite) abundances (in this context, it is noteworthy that the region around Bosumtwi is gold exploration area, and elevated siderophile element abundances are found in samples of regional country rock as well; cf. OSAE et al. [1995]; JONES [1985a]). This makes it difficult, if not impossible, to obtain reliable information on an extraterrestrial component from elemental abundances alone. Massive impact melt rocks, which are not exposed on the surface but could have been intersected in the drill cores from the crater interior, may help to solve this problem.

8.8. Structural Geology of the Crater Rim

KOEBERL et al. (1997b) and REIMOLD et al. (1997, 1998) reported on detailed geological studies at and around the Bosumtwi crater, with sampling of all rock types for petrographical and chemical analysis. Excellent road cuts along the then new road into the crater (towards the village of Abono) allowed detailed mapping along a significant portion of a NW–SE crater rim traverse.

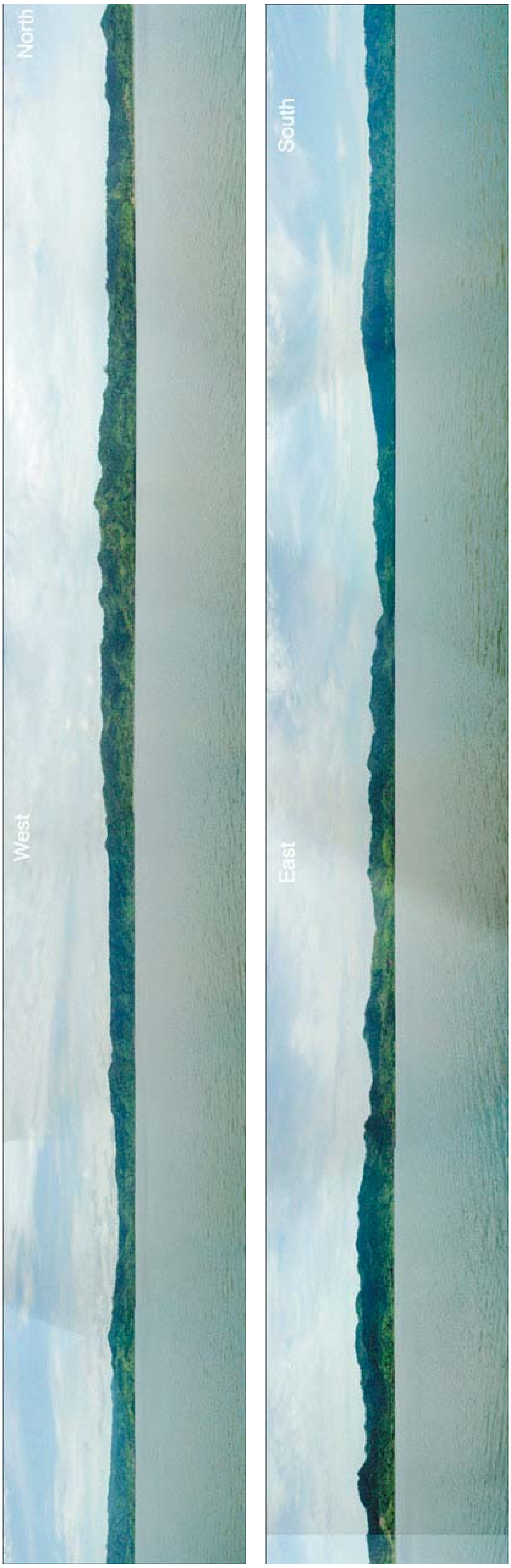
A so-called Zone 1, just outside of the crater rim, displays thick deposits of lithic impact breccia, intercalated with products of local mass wasting (the tropical climate is very conducive to weathering and rapid erosion processes). The outer flank of the crater rim – called Zone 2 – is characterised by inward-dipping thrust planes, conjugate radial fractures, isoclinal folding of the metasediments, and overturning of the stratigraphic sequence. Zone 3 represents the central crater rim zone and is basically a megabreccia zone, in which block size seems to decrease upward and outward across the rim crest. The inward-following Zone 4 involves the entire inner slope of the crater rim and is dominated by intense thrust faulting with faults of several orientations, which has resulted in a complex assemblage of duplex- and lens-shaped bodies (Text-Fig. 19). It is interesting to note that this sequence of deformation styles observed at Bosumtwi is very similar to that described from the crater rim section at the small, simple bowl-shaped Tswaing Crater, South Africa (BRANDT & REIMOLD, 1995).

Fragmental ejecta breccias occur in places outside of the crater rim. However, it is very likely that at least some of the fragmental breccias described in the past as impact ejecta represent locally produced, often lateritic, weathering products. In the tropical environment of south-central Ghana, such weathering formations can attain thicknesses in excess of 20 meters. Breccia dikes are rare in the crater rim (only meter-sized pods and a few up to 0.5 m wide dikes were observed), and only fragmental breccia, usually polymictic, was recorded. Another interesting aspect is the cause of the annular depression about 3–5 km outside of the crater rim. REIMOLD et al. (1998) and BOAMAH & KOEBERL (2002) suggested from their study of surface exposures and topography that it is possible that this shallow depression could be the result of preferential, structurally-controlled erosion in a region around the crater rim that was strongly deformed during the impact event. WAGNER et al. (2002) favored locally enhanced erosion of relatively loose breccia formations just outside of the outer rim slope – in an area that would be subject to extensive erosion by the run-off from the slope.

As mentioned in section 8.2., most rocks (graywackes) observed in road cuts are highly fractured and shattered, and at several locations outside the crater rim graphitic schist, which stands almost vertical and shows intense folding, has been observed (Text-Fig. 28a), and this lithology is also an important clast component in impact breccia from both outside of the crater rim and from the recently drilled crater fill (Text-Fig. 28b).

Despite the limited outcrop, past and present workers have compiled a large data base of structural measurements, including bedding, cleavage (schistosity), and joint orientations. Most information is derived from WOODFIELD (1966), MOON & MASON (1967), and own investigations since 1996. Earlier workers (WOODFIELD, 1966; MOON & MASON, 1967) inferred the presence of several large faults based on an early airborne magnetic survey (see magnetic susceptibility report by J.W. PRIOR, appendix in MOON &

Text-Fig. 28.
a) Steeply dipping graphiitc schist on the Nyameani – Beposo road, near the village of Brodekwano (with P. CLAEYS, University of Brussels, for scale).
b) Deformed or brecciated graphitic schist in the deep crater fill, as seen in deep borehole BH7, drilled in 2004, in the form of monomict autochthonous breccias (the image shows a portion of the core drilled at a depth between 542 and 545 m below lake level).



Text-Fig. 29.
Panoramic view of the crater rim taken from near the center of the Lake Bosumtwi (in September 2004 from the GLAD800 drilling barge at location hard core LB08; each of the two panels is a merge of seven individual images). This panorama shows the structure and morphology of the complete crater rim. The western portion of the rim (from South to West to North) is shown in the upper panel, the lower panel shows the eastern half of the rim; there is no overlap between the two panels.

MASON, 1967). Strike and dip measurements over the entire map region testify to large-scale folding. However, it is significant that since the recognition of this large impact structure in this area no detailed structural work has been carried out comparing the immediate crater environs with the wider region. Satellite imagery demonstrated that an at least 8–10 km wide zone around the crater structure must have been structurally affected by the impact (WAGNER et al., 2002). This zone should be compared with the structural grain in the wider environs.

Also no comprehensive structural studies have yet been done on the morphological crater rim, with the exception of the work of REIMOLD et al. (1998). Text-Fig. 29 shows a complete 360° panoramic view of the crater rim (in two sections, the eastern and western half of the rim), as seen from the center of the lake, showing a variety of large-scale structure and deformation. For example, in the eastern part of the crater, on the latitude of Beposo, a large, at least 0.5 km long, block of the crater rim seems to have moved tangentially inwards, probably along an inward-dipping listric fault (compare Text-Fig. 3). Bosumtwi would be a good location for such a detailed structural study of a complete crater rim.

9. Summary and Conclusions

We have summarized the information (status summer 2005) available on the geology, origin, and importance of the Bosumtwi impact structure and the lake that fills most of it. First results of petrographic analysis of the two impact breccia intersections in borehole LB-7 from the 2004 ICDP drilling project have confirmed the presence of extensive suevite deposits. It is expected that the detailed multidisciplinary study of these breccias by the multi-national consortium will make a major contribution to the knowledge about Bosumtwi, and about impact cratering in general. It is also hoped that the new map that accompanies the present summary will fertilize further geological analysis of the crater structure and surrounding area. Bosumtwi already must count among the world's best studied impact structures.

However, the current attempts at improving the knowledge about this impact event and its consequences, as well as the detailed paleoclimatic investigations that Lake Bosumtwi has spawned, will place this geological structure firmly onto the world-map of unique geological features.

Bosumtwi is a unique geological feature. It has provided the livelihood for thousands of Ashanti people for a very long time, but with the fish resources in the lake dwindling, it may become necessary to diversify. Ecotourism – and especially impact tourism – may be one avenue to support the local economy in future, as shown in a new study (PRAKASH et al., 2005), and local efforts at Bosumtwi to establish a crater museum at or near the crater rim deserve to be strongly supported.

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Caption to the Map Supplement: Geological Map of the Bosumtwi Impact Crater

The enclosed map of the Bosumtwi impact structure is based on the geological maps by WOODFIELD (1966) and MOON & MASON (1967), with new information added. In the original maps the crater area was split between two maps. The present map combines the relevant parts of these two maps, with topographic information taken from sheets No. 0602D1 for the southern part and No. 0602B3 for the northern part (Survey Department of Ghana, 1972). The topographic information was scanned and used as a base of the geology, which was digitized. Where possible, road information within the vicinity of the crater was updated based on GPS measurements by the compilers and collaborators. The scale of the map was changed to 1 : 50,000 (the original geological and topographical maps of Ghana were produced at the scale of 1:62,500). For consistency reasons, the coordinate and projection systems used in the previous maps had to be kept for the present map as well. The thin red lines indicate latitude and longitude in degrees North and East; the gray lines (and numbers) refer to the Accra Ghana Grid. The most important parts of the legend from the original topographical maps were incorporated into the legend of the present map. The color scheme of the map was adapted as closely as possible to the new scheme used today by the Ghana Geological Survey Department. Additional geological information used for the present map was contributed by P. WATKINS and E. SHARP (University of South Carolina, Columbia, USA), A. DEUTSCH (University of Münster, Germany), D. BOAMAH (University of Vienna, Austria, now at Ghana Geological Survey Department, Accra, Ghana), and the compilers of the map (C. KOEBERL and W.U. REIMOLD) (see also chapter 2 and elsewhere in the main text of the "Explanations").

Here we provide some additional notes and information regarding the map. In the legend, various breccias are listed. It needs to be noted that it is very difficult to distinguish, in the field, between impact-related breccias and other breccias produced by geological surface processes (mass-wasting, such as erosion off the pronounced crater rim). Therefore, we distinguish several types of breccias: Two types of obviously impact-related breccias, namely "suevites" (polymict, glass-bearing breccias) and "polymict clastic impact breccias"; the occurrences of the latter were verified by us. In addition, we list two other types of breccias that may or may not be impact-related. The first are "polymict and monomict clastic breccias (unspecified)", including most locations listed by WOODFIELD (1966) and MOON & MASON (1967), for which it was not always clear if they referred to impact-related breccia or not, and "polymict clastic breccias (genetically unclassified)", which were added by us based on new information, and for which it was not possible to unambiguously confirm an impact origin from field observation (even though it appears likely, in our opinion, that these breccias could represent impact deposits).

The connotation "upper" and "lower" Birimian has been officially abandoned due to recent geochronological results that indicate coeval deposition of both. However, we have kept the traditional color separation for upper and lower Birimian in order to remain consistent with the older maps. The different units are listed as metavolcanics and metasediments, which agrees with the predominant rock types in the upper and lower Birimian formations. Bedding, cleavage, and joint signatures have been kept in accordance with the earlier maps, and new observations were added and coded in the same way.

In order to emphasize that Bosumtwi is a meteorite impact crater, we have added some features that were not available on the earlier maps. First, a reddish-purple dashed line, marked "topographic crater rim", outlines the rim crest (topographically highest elevations) of the prominent crater rim. Second, we indicated the approximate outer limit of deformation (in terms of breccia distribution), and the outer limit (not the highest elevation) of the shallow, subdued outer ring feature (which encircles a broad, slight topographic depression outside of the crater rim, which is also evident in a circular drainage pattern – see section 3.2 of the "Explanations", and Text-Figs. 5–7). Because this feature is very subtle and only apparent along about two thirds of the crater circumference (in the south to southeast the Obuom mountain range truncates this ring), it is not possible to draw its precise outline; thus, we opted to simply enhance a zone between the crater rim and up to about 20 km distance from the crater center by reducing the map colors to 80 % opacity. However, to avoid confusion in the colors of dikes, intrusions, and other minor features, this transparency increase was done only for the two main units, the metavolcanics and metasediments of the Birimian Supergroup, and is indicated in the legend by a vertical division of the color field for these two units. The locations of boreholes are indicated as well. North of the crater rim are the shallow (≤30 m depth) boreholes drilled in 1999 to study extension and thickness of the fallback breccias, and within Lake Bosumtwi the locations of boreholes drilled in 2004 by the ICDP Bosumtwi crater drilling project have been indicated. Red numbers 1–6 indicate positions of cores that penetrated into the lake sediments, and the two green symbols (numbers 7 and 8) indicate the positions of the two deep coreholes that penetrated into the fallback breccia and brecciated bedrock, to a maximum depth of 540 m. Details of these coreholes are given in the main text (see section 7 of the "Explanations").

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