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Petrographic studies of "fallout" suevite from outside the Bosumtwi impact structure, Ghana

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Abstract–Field studies and a shallow drilling program carried out in 1999 provided information about the thickness and distribution of suevite to the north of the Bosumtwi crater rim. Suevite occurrence there is known from an ~1.5 km^2 area; its thickness is ≤15 m. The present suevite distribution is likely the result of differential erosion and does not reflect the initial areal extent of continuous Bosumtwi ejecta deposits.

Here we discuss the petrographic characteristics of drill core samples of melt-rich suevite. Macroscopic constituents of the suevites are melt bodies and crystalline and metasedimentary rock (granite, graywacke, phyllite, shale, schist, and possibly slate) clasts up to about 40 cm in size. Shock metamorphic effects in the clasts include multiple sets of planar deformation features (PDFs), diaplectic quartz and feldspar glasses, lechatelierite, and ballen quartz, besides biotite with kink bands. Basement rock clasts in the suevite represent all stages of shock metamorphism, ranging from samples without shock effects to completely shock-melted material that is indicative of shock pressures up to ~60 GPa.

INTRODUCTION

The Bosumtwi impact structure is one of only four known impact structures associated with tektite strewn fields (Fig. 1a) (Koeberl et al. 1997). It is a well-preserved complex impact structure, centered at 06°30′N and 01°25′W, about 32 km southeast of Kumasi, which is the capital of the Ashanti region of Ghana. The crater structure displays a pronounced rim and is almost completely filled by Lake Bosumtwi, which is 8 km in diameter (Fig. 1b). The structure has a steep rim (250–300 m above the lake level) about 10.5 km in diameter and is surrounded by a slight and irregular circular depression, as well as an outer ring of minor topographic highs with a diameter about 20 km (Jones et al. 1981; Reimold et al. 1998; Wagner et al. 2001). A detailed review, describing all aspects of Bosumtwi, and a new geological map have recently been published by Koeberl and Reimold (2005).

The Bosumtwi impact structure in Ghana is among the most recent (1.07 Myr) large impact crater structures (10.5 km in diameter), and probably one of the best-preserved terrestrial meteorite craters, with ejecta materials in the form of suevite deposits outside the crater rim. Suevite is defined (Stöffler and Grieve 1994) as polymict impact breccia including cogenetic impact melt particles, which are in a glassy or recrystallized state and occur in a clastic matrix containing lithic and mineral clasts of various stages of shock metamorphism. The occurrence of suevite to the north and southwest of the Bosumtwi crater, outside the crater rim, was first described by Junner (1937). The unusualite deposits played a crucial role in the early attempts to explain the origin of the Bosumtwi crater. Earlier geologists first described this rock as volcanic agglomerate or tuff, and the formation of the crater as a product of endogenic forces (Jones et al. 1981).

The Bosumtwi structure is also important because of its association with the Ivory Coast tektites (Fig. 1a). The strewn field extends beyond occurrences on land, as microtektites were found in deep-sea cores off the coast of West Africa (Glass 1968, 1969) and were related to the tektites found on land. The similar age, as well as chemical and isotopic data (e.g., Kolbe et al. 1967; Koeberl et al. 1997, 1998), indicate that the Lake Bosumtwi impact event is most likely the source crater for these tektites.

Recently, a number of geological, geophysical, remote sensing, and deep drilling studies (see Koeberl and Reimold 2005 for a summary) have been conducted at and around the Bosumtwi crater. The present paper focuses on detailed petrographic studies of melt-rich suevite samples from two

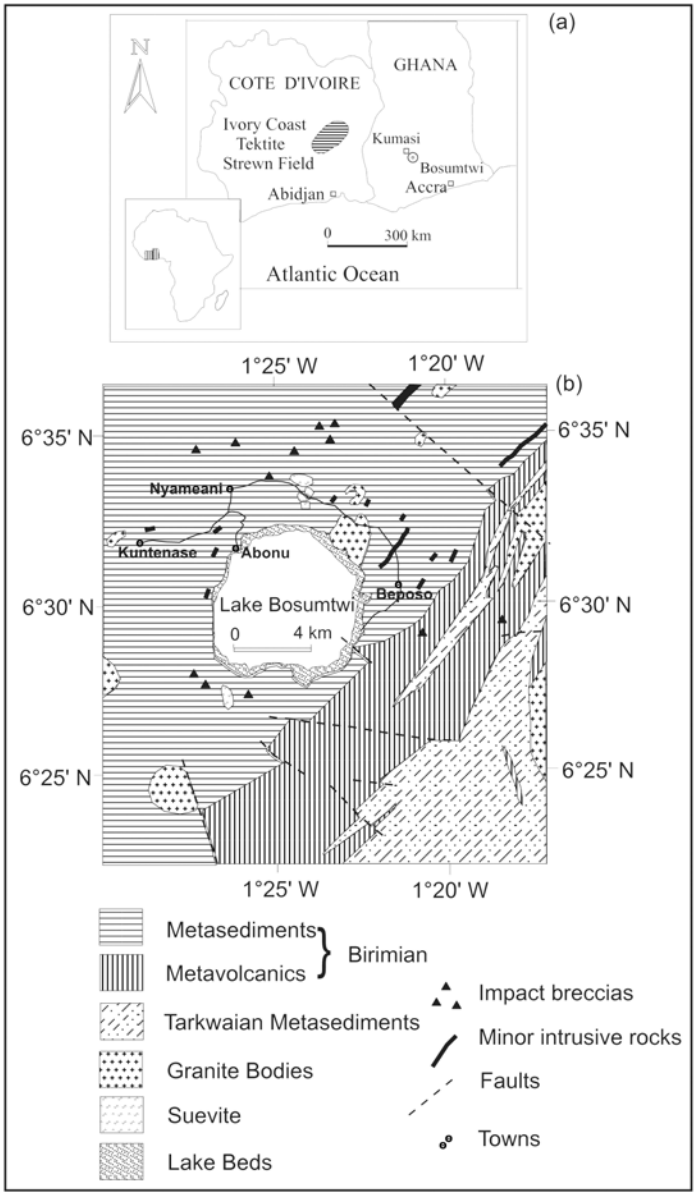

Fig. 1. a) The geographic location of the Bosumtwi impact crater, Ghana, in relation to the Ivory Coast tektite strewn field (after Koeberl et al. 1998). b) A geological map of the area around Lake Bosumtwi, showing the provenance of different target rocks (cf. Koeberl and Reimold 2005).

drill cores from north of the Bosumtwi crater that are outside the crater rim but within the outer ring depression (Fig. 2) (Boamah and Koeberl 2002, 2003). The present study provides data about mineral compositions and abundances, textures, and the presence and nature of shock metamorphic effects in the suevite.

GEOLOGY

Geological studies around Lake Bosumtwi have been carried out since the 1930s (Junner 1937; Woodfield 1966; Moon and Mason 1967; Jones et al. 1981). More recent geological studies were done along the western, northern, and northeastern parts of the crater (Reimold et al. 1998; Koeberl and Reimold 2005). Because dense, tropical rain forest and plantations largely cover the region around Bosumtwi, only studies of rare exposures along streams and road cuts are possible. Figure 1b schematically presents the geology around Lake Bosumtwi.

The Bosumtwi impact crater was excavated in lower greenschist facies metasediments (graywacke, quartzitic graywacke, metatuffs, phyllites, shales, and schists) of the 2.1–2.2 Gyr Birimian Supergroup (cf. Wright et al. 1985; Leube et al. 1990). Rocks to the southeast of the crater contain

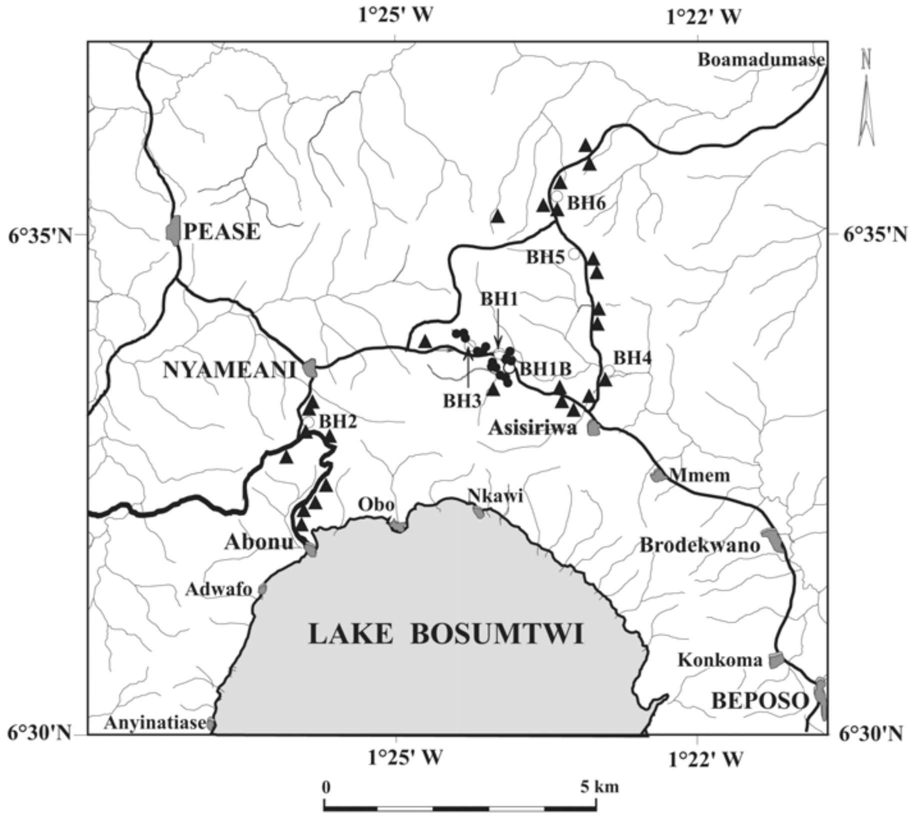

Fig. 2. Distribution of suevite deposits (solid circles) outside the crater rim to the north of the crater. Also shown are the locations of brecciated rocks examined, indicated by solid triangles, and the locations of the drill holes (open circles). Suevite was found in cores BH1 and BH3.

altered basic intrusives (Birimian metavolcanics) in addition to metasediments. Clastic Tarkwaian sediments occur further to the east and southeast and are thought to have been formed by erosion of Birimian rocks.

The Birimian metasediments are generally folded, dipping at high angles with a general NE-SW strike. Around the crater rim, irregular strikes and dips are believed to have been caused by the impact event that created the crater. Several Proterozoic granitic intrusions are found in the structure, and some strongly weathered granitic dikes occur in the crater rim (Junner 1937; Woodfield 1966; Moon and Mason 1967; Reimold et al. 1998). The granitic complexes and dikes probably mainly belong to the Kumasi-type granitoid intrusions, for which an age of 2.0–2.1 Gyr has been obtained (Taylor et al. 1992; Hirdes et al. 1992). In addition, a few dikes of dolerite, amphibolite, and intermediate rocks (minor intrusives) have been noted around the crater (Fig. 1b).

In the immediate environs of the crater, lithology is dominated by graywacke and sandstone/quartzitic rocks, but shale and minor mica schist are also present, especially in the northeastern and southern sectors (Woodfield 1966; Moon and Mason 1967; Reimold et al. 1998). Quartz veins and stringers of up to 20 cm in width cut through all the rock formations in the area or occur in the form of pods.

Recent rocks include the Bosumtwi lake beds, as well as soils and breccias associated with the formation of the crater (Junner 1937; Kolbe et al. 1967; Woodfield 1966; Moon and Mason 1967; Jones et al. 1981; Reimold et al. 1998; Koeberl and Reimold 2005). Massive suevite deposits have been observed just outside of the northern and the southwestern crater rim sections (Figs. 1b and 2). As a result of deep weathering profiles produced by lateritization, outcrops of fresh rock are few, except in steep hill country, and usually found only in road cuts and stream beds.

THE 1999 SHALLOW DRILLING PROGRAM

A shallow drilling program was undertaken in 1999 by the University of Vienna (Austria) in cooperation with the Geological Survey Department of Ghana (GSD), and guided by airborne radiometry (cf. Plado et al. 2000; Pesonen et al. 2003). Holes were drilled to a maximum depth of 30 m, using a skid-type rotary drill rig with core bits 5 cm in diameter, and continuous core was retrieved in 1 m sections from each hole using a 1.5 m conventional core barrel. Seven holes were drilled to the north of the crater, at a distance of 2.5 to 8 km from the lake shore (locations in the area 1°22′–1°27′W and 6°33′–6°36′N). The locations of the drill holes were chosen to recover specific impact-related lithologies.

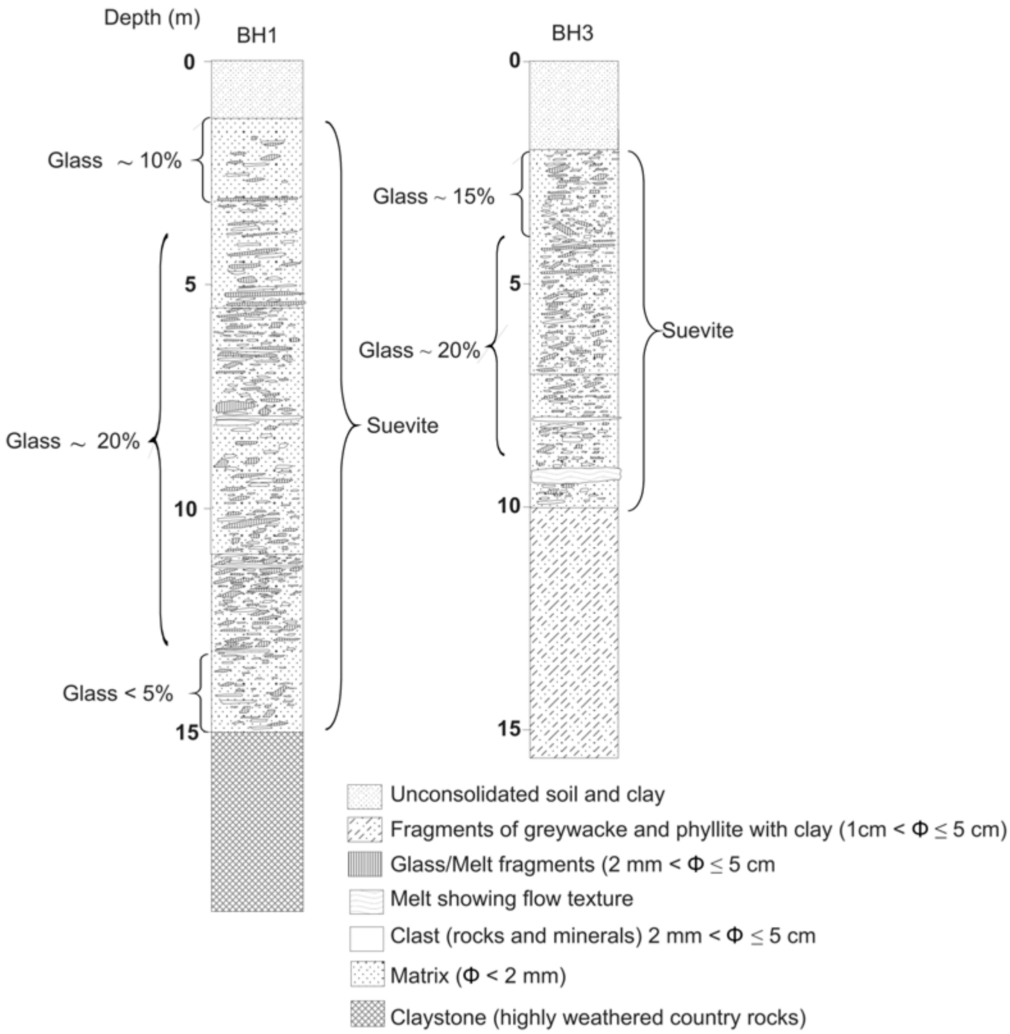

Fig. 3. Stratigraphic column of the two drill holes through suevite: drill cores BH1 (drilled to 19 m) and BH3 (drilled to 16 m). In BH1 suevite occurs between 1.5 m and 15 m (thickness of about 13 m), whereas in BH3 it occurs between 2 m and 10 m (thickness of about 8 m).

Drill holes were sited where the water tanker for the supply of water for the drilling could go and, to the extent possible, where radiometrically determined K concentrations were high. 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 the drill sites BH4, BH5, and BH6. These sites were in lithic breccia terrain. Drill holes BH1 and BH3, on the other hand, were sited not very far from known suevite outcrops (Fig. 2), with the aim of recovering suevite and determining the thickness of the fallout suevite deposit.

SAMPLES AND EXPERIMENTAL METHODS

This study is based mainly on microscopic examination of 42 thin sections of melt-rich suevite, which provide data about mineral compositions and abundances, textures, and the presence and nature of shock metamorphic effects. These samples were obtained from two drill holes (BH1 and BH3), located just north of the crater rim of the Bosumtwi crater, about 2.5 km from the lake shore. The rock formation encountered in these sections was mainly suevite and was between 2–10 m in BH3 and 1.5–15 m in BH1 (Fig. 3). These intervals were selected for petrographic studies. Nineteen samples were obtained from BH1 and twenty-three from BH3. Sample numbers given in the text, tables, and figures consist of the drill hole number and the depth in centimeters. The following investigations were carried out: 1) Modal analyses of the drill core sections by estimating the fragment types and the matrix; 2) microscopic studies of thin sections for various types of shock effects, especially in quartz and feldspar, to estimate the possible degree of shock pressure attained; and 3) measurements of the crystallographic orientations of planar deformation features (PDFs) in individual quartz grains of 20 thin sections were made using a four-axis universal stage (U-stage; cf. Emmons 1943).

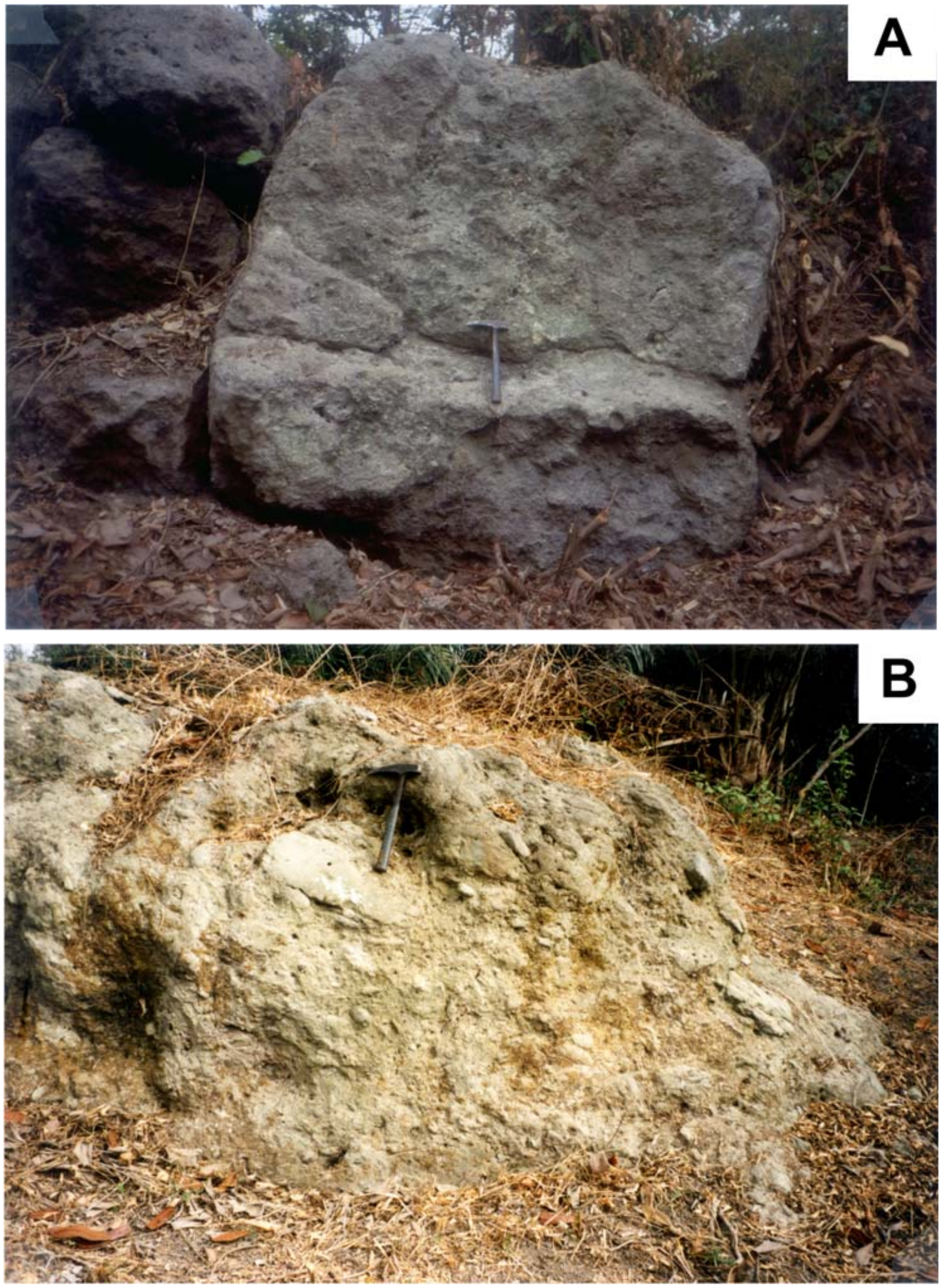

Fig. 4. Photographs of suevite deposits from the Bosumtwi impact structure. a) Large displaced blocks of suevite. b) Patchy suevite deposit resembling tuff. The tuffaceous nature of the deposit might have caused early geologists to refer to it as a volcanic tuff or agglomerate.

RESULTS AND DISCUSSION

Distribution of Suevite

Recent field studies have shown that the Bosumtwi suevite occurs as large displaced blocks up to several meters in size, as well as patchy deposits (Fig. 4) more or less covered by thick vegetation (Boamah and Koeberl 2002, 2003). These "fallout" suevite ejecta occur in a marginal zone of about 1.5 km^2 outside the crater rim to the north. (Fig. 2).

At this time, it is not clear whether the suevite was deposited as a blanket of ejecta or as isolated blocks. According to Engelhardt (1997), fallout suevite (suevite outside the crater rim) is deposited on top of earlier ejecta formations. Koeberl and Reimold (2005) noted the possible presence of Bunte breccia–like deposits underneath suevite to the north of the crater. Since the fallout suevite thickness ranges from a few to only tens of meters at the Ries crater (Hörz 1982), and to ≤15 m at Bosumtwi (Boamah and Koeberl 2003), it is possible that much of the original suevite

Table 1. Fragment counts on 1 m × 1 m areas of suevite outcrops (data in vol%). About 1000 fragments were counted at each outcrop.

Outcrop no.	1	2	3	4	5	6	7	8
Location	6°33.85′N 1°23.95′W	6°33.72′N 1°23.73′W	6°33.72′N 1°23.75′W	6°33.9′N 1°23.8′W	6°33.9′N 1°23.8′W	6°33.9′N 1°23.8′W	6°33.83′N 1°23.92′W	6°33.8′N 1°23.87′W
Matrix	65	70	65	69	70	70	70	70
Glass/melt	18	20	20	15	20	17	20	18
Graywacke	7	8	8	4	3	5	5	6
Phyllite	5	2	4	1	1	3	4	3
Granite	1		1			3		1
Shale	1				2			
Slate	1				2	2		
Sandstone			1					
Quartz/ feldspar	2		1	1	2		1	2

deposits were eroded in this tropical environment. Thus, the occurrences are regarded as remnants of the original suevite ejecta blanket. Garvin et al. (1992) reported the possibility of finding other suevite deposits to the north of the crater outside the crater rim based on their remote sensing studies, but none have been identified so far.

Clast Population in Bosumtwi Suevite Outcrops

One objective of the study was to identify the main clast components in the suevites in both outcrops and drill cores. A table has been prepared regarding the occurrence of various lithologies and minerals. Counts of fragments greater than 1 cm from 1 m × 1 m outcrop sections at eight suevite outcrops are summarized in Table 1. In these outcrop studies, “matrix” refers to any material smaller than 1 cm (as also applied by Engelhardt 1997). About 1000 clasts were counted at each outcrop; counting smaller clasts would have been impractical because of the time involved. It is obvious that not all of the material <1 cm is groundmass, but also contains rock fragments.

Components in the suevite include “matrix” (up to 70 vol%) (i.e., including all fragments <1 cm), glass/melt fragment (up to 20 vol%), graywacke (up to 8 vol%), metapelite (up to 5 vol%), and granite (up to 3 vol%). Other minor fragments observed include slate, shale, schist, quartz, and feldspar. Such fragment population may reflect the characteristics of the basement volume from which the suevite deposits were derived. Maximum clast size was found to be about 40 cm. Most of the melt fragments are apparent glass bombs, with sizes ranging up to 20 cm. The melts consist of highly vesicular or massive material. The matrix of the suevite essentially consists of angular mineral clasts, predominantly quartz and feldspar, and scattered melt particles set in a rather porous but coherent matrix of a fine-grained (microscopic) nature.

Drill Core Lithostratigraphy

Unconsolidated soil and clay are found on top of the suevite in both holes. Highly weathered country rocks (claystone) underlie the suevite in BH1, whereas BH3 is underlain by fragments of graywacke and phyllite with clay (which could be an alteration product of melt right at the bottom of the suevite deposit, or a remnant of the soil at the pre-impact surface) (Fig. 3). Also, the rock clasts immediately underneath the suevite section in both cores were rounded, implying movement—possibly the suevite blanket was moving laterally due to the topography during initial deposition, grinding/rounding either clasts within the suevite from the surface sediment deposit on top of which the suevite was deposited. The suevite samples from the two holes are almost identical in appearance to each other. They are generally grayish in color, altered, with vesicular melt and glass inclusions, and lighter colored granite-derived lithic and mineral fragments, as well as other rock fragments (Fig. 5a). The melt bodies are irregular in shape, with some of them showing flow structures (Fig. 5b). In the drill cores, the groundmass occupies up to 70 vol% of the suevite, with melt occupying about 15–20 vol%. Rock fragment (graywacke, phyllite, shale, schist, and granite) size exceeds the diameter of the core (5 cm); such fragments amount to about 10 vol%, and mineral clasts (mostly quartz and feldspar) to less than 3 vol%. Graywacke and phyllite dominate the rock-clast population. Anything less than about 2 mm was considered matrix, which consists of very small glass particles, mineral fragments (mostly quartz and feldspar), and clay. The rock fragments and larger melt bodies are irregularly distributed within the matrix. Because the vertical sections through the suevite revealed no primary variation in composition or grain size, the process of deposition is assumed to have been uniform, allowing no time for the larger fragments to settle out before reaching the ground.

Petrographic Observations

The Bosumtwi suevite is composed of impact glass/melt, crystalline and sedimentary rock inclusions in a fine-grained matrix (mainly quartz, feldspar, and glass/melt), and clay (Table 2). Fragment sizes, at the thin section scale, range from ≥0.05 mm to ~1 cm. Lithic and mineral fragments are

Fig. 5. The macroscopic appearance of suevite in Bosumtwi drill cores outside the crater rim. Note (a) the vesicular nature of the impact glass in the suevite from drill hole BH1 (depth is 10.2 m for the top part and 11.3 m for the bottom part), and (b) melt glass with flow structure in a suevite from drill hole BH3 (depth 15 m). The core diameter is 5 cm.

heterogeneously distributed throughout the matrix. This results in fragment-rich and fragment-poor areas. Dominant fragment types are glass/melt and graywacke. Other clasts are phyllite, shale, schist, and granite. Most of the rock fragments are derived from mylonitic schist, are highly altered, and contain abundant chlorite and carbonate as secondary minerals. Some lithic fragments are internally brecciated (cataclasite). Fragment shapes are sub-rounded to angular. In a single rock fragment, a range of shock features exists that represent different degrees of shock metamorphism (unshocked quartz, quartz with PDFs, and diaplectic quartz glass). This is probably due to the complex response to shock loading by rocks of varied mineral modes and textures. The clast population is dominated by quartz and feldspar, besides minor biotite.

Two types of glass have been identified in the suevite: vitreous glass and devitrified glass. The vitreous glasses are macroscopically recognizable by their light color, glassy luster, and transparency, whereas devitrified glasses are more or less darkly colored, dull, and essentially opaque. Vitreous glasses are, however, heterogeneous on a microscopic scale, involving incomplete mixing of melts of different composition. Numerous vesicles indicate that melt was interspersed with a gas phase and that solid particles are present in the glass as well (see, e.g., Engelhardt 1997).

Petrographic observations indicate that suevite matrix and clasts exhibit various degrees of fluidization, vesiculation, and devitrification. Most of the large clasts (>2 mm) are shock-metamorphosed or shock-melted graywacke, phyllites, and granites. Smaller clasts (0.05–

Table 2. Modal composition of 32 thin sections of the suevite from of the two drill cores (BH1 and BH3) (counting of about 1800 points) (vol%).

	Quartz	Feldspar	Matrix	Glass/melt	Rock	Others
BH1/0300	4.6	2.1	56.2	29.6	6.9	2.0
BH1/0390	2.6	0.4	36.1	57.6	3.49	
BH1/0565	3.7	0.7	46.0	46.0	3.7	
BH1/0580	9.7	7.0	72.2	9.3	1.5	0.2
BH1/0627	8.9	1.9	78.9	8.9	1.1	0.2
BH1/0695	5.2	0.4	28.1	51.7	14.6	
BH1/0753	2.2	0.6	74.2	11.8	11.2	
BH1/0790	1.0	0.1	4.6	17.9	76.3	
BH1/1050	5.8	0.5	44.8	41.7	7.1	
BH1/1115	11.1	5.7	70.4	11.2	1.0	0.3
BH1/1155	2.3	0.2	37.1	58.8	1.6	
BH1/1190	10.4	9.8	70.9	4.2	1.7	3.0
BH1/1265	10.7		51.1	36.6	1.36	
BH1/1330	6.0	2.2	55.8	11.3	24.3	0.5
BH1/1400	8.3	2.8	80.3	7.2	1.1	0.3
BH1/1425	8.4	2.7	66.7	6.4	15.0	0.8
BH1/1475	8.5	0.7	62.7	6.1	21.5	0.5
BH3/0200	4.9	0.8	39.8	44.7	9.6	0.3
BH3/0265	2.9	2.1	39.4	50.2	5.3	0.2
BH3/0335	2.2	0.5	27.1	62.3	8.0	
BH3/0390	5.2	1.4	49.4	22.8	20.9	0.2
BH3/0490	4.4	1.3	51.0	37.6	5.4	0.2
BH3/0530	3.4	1.3	54.6	36.9	3.6	0.3
BH3/0585	4.2	1.2	53.3	25.9	15.7	0.3
BH3/0640	15.2	0.46	39.3	39.2	5.9	
BH3/0670	3.2	0.3	41.9	49.5	4.83	0.2
BH3/0716	5.2	1.1	42.1	26.5	25.0	0.1
BH3/0735				100		
BH3/0765	6.5	1.2	51.6	20.3	20.2	0.2
BH3/0810	1.3	0.7	17.2	10.2	70.6	
BH3/0885	4.4	2.2	56.0	15.4	21.8	0.1
BH3/0885	4.8	1.6	45.0	43.0	5.5	0.2

1 mm) are mostly monocrystalline or polycrystalline quartz and feldspar. Other minerals in this size fraction include biotite, muscovite, zircon, sphene, and apatite, and are present in small amounts. Several glass particles were observed, but were fewer than melt clasts.

For the microscopic observations presented here, the term matrix refers to all material within the suevite (breccia) consisting of fine-grained crystalline matter, glass (usually devitrified), and fragments smaller than 0.05 mm. It is composed mainly of quartz, feldspar, biotite, and rock fragments plus sporadic glass that occupy generally between 30 and 70% of the thin section area between larger clasts (Table 2).

Two glass varieties, with flow structures and schlieren, form a major part of the matrix. The first type is dark yellowish to light or dark brown with a high content of iron oxide (in reflected light, numerous tiny crystallites of magnetite can be recognized). The other glass variety is clear and translucent but partially devitrified. Devitrification products occur in the form of numerous needles and laths of mainly feldspar and some pyroxene.

Rock clasts (mainly graywacke and metapelite) are observed in the melt glasses in some of the thin sections, with sizes not exceeding 10 mm. Some of the rock clasts are so severely shocked (e.g., vesicular) that petrographic identification is impossible. Some glasses are compact and contain only few and small vesicles, while others are of a foamy, pumice-like texture. Most vesicles are elongated and, together with glass and mineral-rich schlieren, form a fluidal texture that delineates internal laminar flow and is especially close to the surfaces of what appear to be aerodynamically shaped glass bodies. The walls of vesicles in vitreous and devitrified glasses are coated by secondary minerals. Main secondary minerals are microcrystalline quartz and montmorillonite. Quartz and montmorillonite also fill cracks in the glasses and appear as alteration products on outer surfaces of glass particles. Both minerals were produced after deposition of the suevites under hydrothermal conditions by a fluid phase that also transformed the finest size fraction of the breccia, presumably glassy, into montmorillonite. Most crack fillings consist of quartz. In many bombs, all vesicles are coated only by quartz. The abundance of quartz in vesicles and cracks

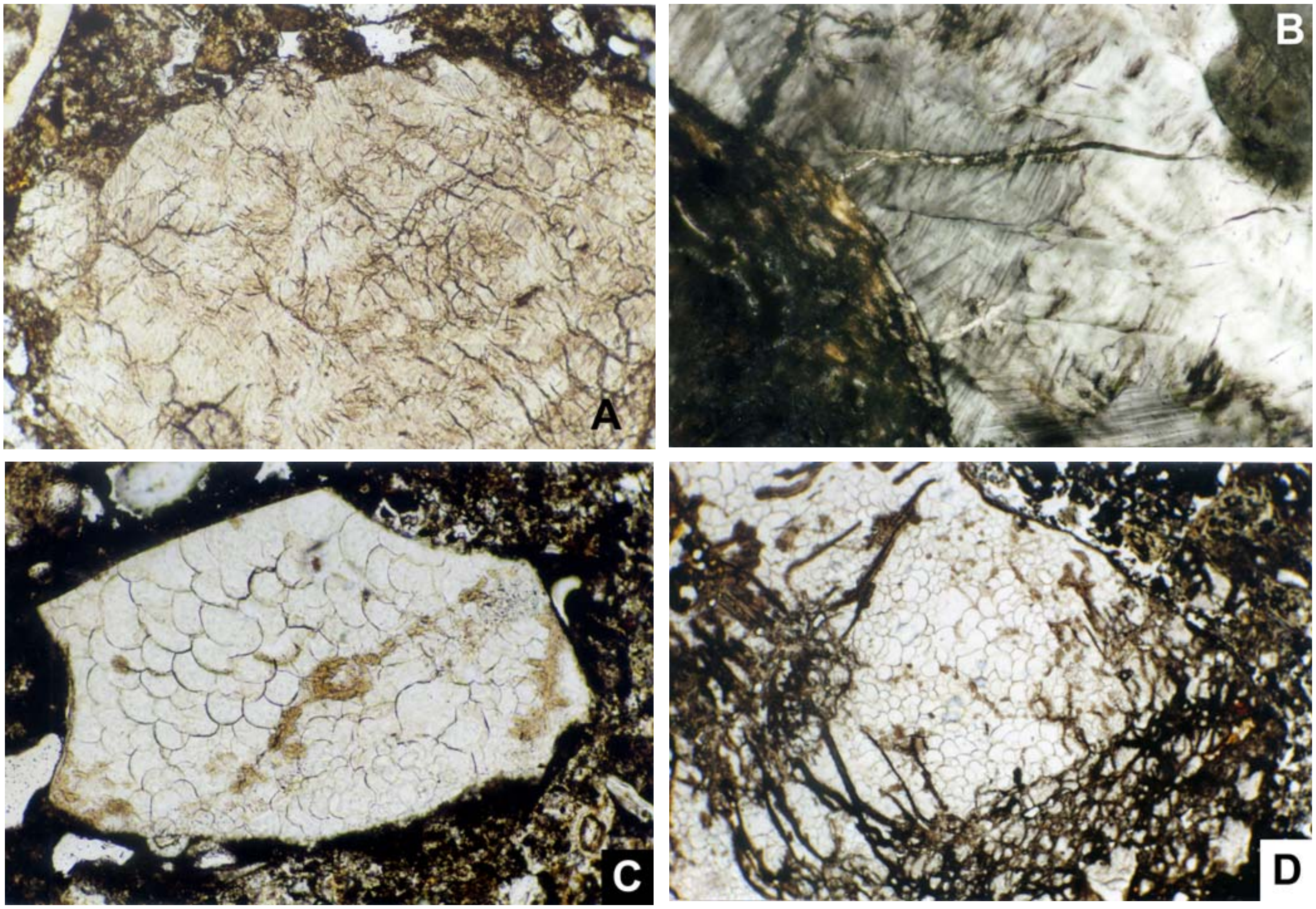

Fig. 6. a) A photomicrograph of multiple sets of PDFs in a large shocked quartz grain within a granite clast in the suevite. Sample BH1/1425. Plane-polarized light; width of image = 0.77 mm. b) A photomicrograph of a shocked quartz grain with multiple sets of PDFs in melt inclusion in the suevite. Sample no. BH3/0885. Cross-polarized light; width = 0.29 mm. c) A photomicrograph of shocked quartz with ballen texture. Sample BH1/0695. Plane-polarized light; width = 0.77 mm. d) A photomicrograph of shocked quartz with ballen texture and some alteration. Sample BH1/0695. Plane-polarized light; width = 1.82 mm.

shows that the hot fluids that were in contact with the glass first deposited silica due to the decrease of silica solubility with decreasing temperature (see, e.g., Engelhardt 1972).

Shock Metamorphism

The presence of rocks and minerals exhibiting evidence for shock metamorphism unambiguously indicates the high pressures uniquely associated with impact cratering (see, e.g., French and Short 1968; Hörz 1968; Stöffler and Langenhorst 1994; Grieve et al 1996; Huffman and Reimold 1996; French 1998). Shock pressures and temperatures during impact may reach many 100 GPa and several 1000 °C, which is far above the conditions reached during endogenic metamorphism of crustal rocks, with maximum temperatures of 1200 °C and pressures rarely exceeding 2 GPa.

Evidence of shock metamorphism is common in the rock and mineral clasts in the Bosumtwi suevite. Almost all the shock-induced deformation types known from well-studied impact structures, such as the Ries in Germany, were found in the suevites from the drill cores at Bosumtwi. These are planar fractures (PFs), planar deformation features (PDFs) (Figs. 6a and 6b), mosaicism, diaplectic quartz and feldspar glasses, biotite with kink banding, and fused or melted rocks. Shock melting occurs when granitic rocks are subjected to peak pressures of >50–60 GPa (Stöffler and Langenhorst 1994; Grieve et al 1996; French 1998). Coesite has been identified in vesicular glass and melt within the suevite outside the crater rim to the north, first by Littler et al. (1961). Baddeleyite (the high temperature decomposition product of zircon) within vesicular glasses (probably derived from suevites) outside the crater rim to the north was first reported by El Goresy (1968). These observations indicated that the shock pressure that led to the formation of the Bosumtwi fallout suevite exceeded 50 GPa.

Quartz inclusions containing multiple sets of planar deformation features (PDFs) (Figs. 6a and 6b) occur in almost all the suevite thin sections, together with diaplectic quartz glass. In addition, quartz with a distinctive ballen structure (Figs. 6c and 6d) was found in some of the thin

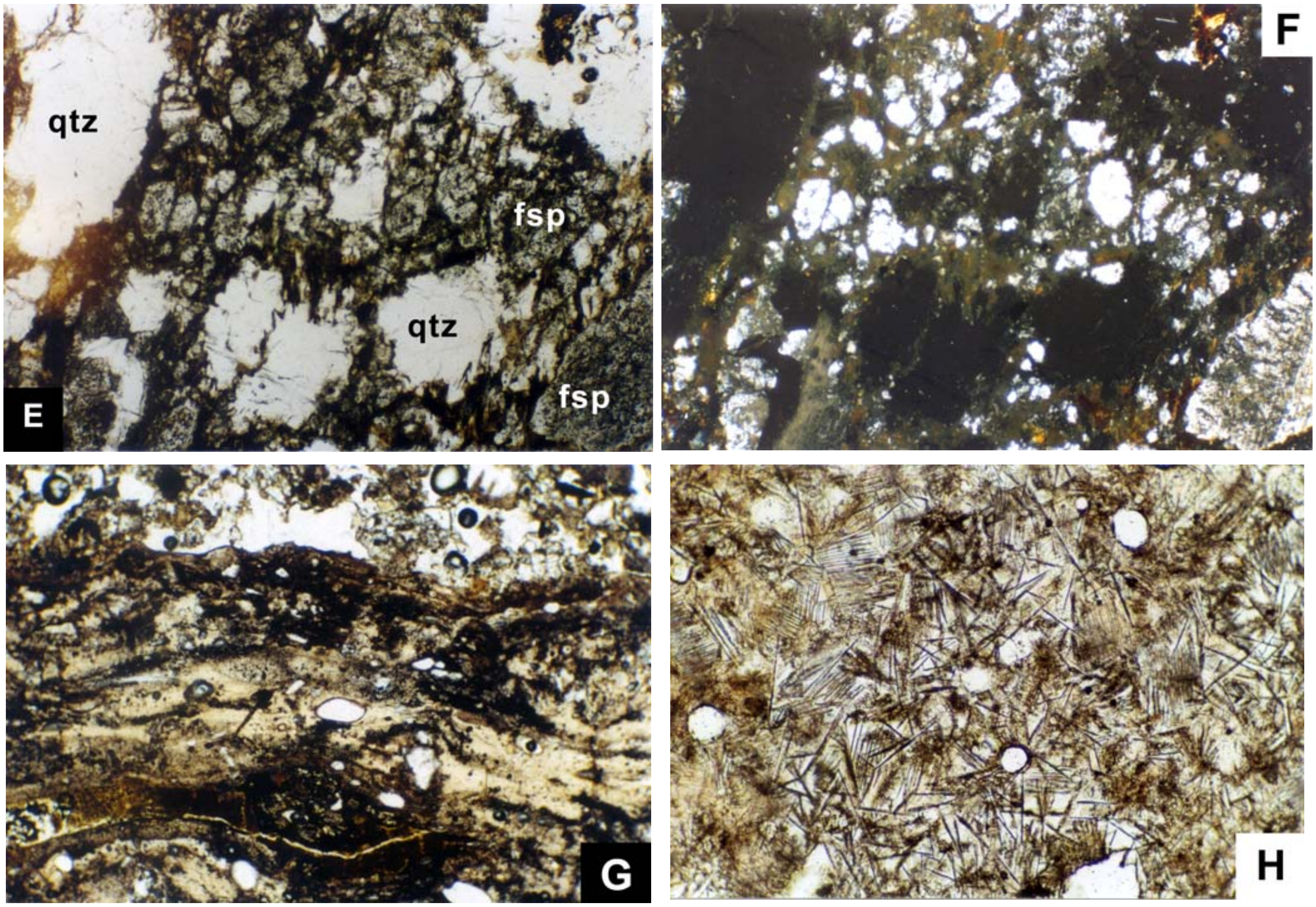

Fig. 6. *Continued*. e) A photomicrograph of a shocked graywacke clast in the suevite showing quartz (qtz) and feldspar (fsp) grains. Sample BH1/1325. Plane-polarized light; width = 0.29 mm. f) Also sample BH1/1325, but with cross-polarized light. The quartz grains in this photo are converted to diaplectic glass, whereas the feldspar remained crystalline. g) A photomicrograph of impact glass with flow structure; dark streaks may represent decomposed and melted opaque minerals. Sample BH3/0885. Plane-polarized light, width of image = 1.7 mm. h) Fine-grained recrystallized matrix with pyroxene quench crystals. Sample BH1/1190. Plane-polarized light, width of image = 0.72 mm.

sections. Similarly textured ballen quartz has been found in impact glasses and crystalline impact melts of many impact craters (e.g., French et al. 1970; Engelhardt 1972; Carstens 1975; Dressler et al. 1997). This ballen quartz has been interpreted to represent pseudomorphs after cristobalite, which, in turn, is thought to have replaced lechatelierite, originally formed by shock-induced melting of quartz (Carstens 1975), or to represent recrystallized diaplectic quartz glass that underwent transition to cristobalite and then α-quartz (Bischoff and Stöffler 1981; 1984). It should be mentioned that ballen quartz was observed in thin sections from only the top 8 m of suevite samples from BH1; no ballen quartz was observed in samples from BH3. It is not clear why within a distance of about 100 m (relatively flat terrain) there are some (minor) differences in the abundance and type of shock features.

Quartz with PDFs is generally considered reliable evidence of meteorite impact (French and Short 1968; Stöffler 1972, 1974; Alexopoulos et al. 1988), as are high pressure silica polymorphs (Stöffler 1971). Being the best criterion for distinguishing between various stages of shock metamorphism, the shock deformation of quartz (quartz without PDFs, quartz with PDFs, quartz with partial isotropization, quartz with complete isotropization (diaplectic quartz glass), quartz with ballen structure, and shock melted) has been used to estimate the shock pressure in the Bosumtwi suevite samples In shocked shale and graywacke, quartz is completely transformed to diaplectic glass, whereas adjacent individual feldspar grains are not (Figs. 6e and 6f). This transformation may be due to a pressure threshold difference between diaplectic quartz and feldspar glasses formations (cf. Engelhardt et al. 1967, 1995). According to Stöffler (1972, 1974), shock recovery experiments indicate that quartz seems to be slightly more resistant to transformation to diaplectic glass than feldspar. This is in contrast to what was observed in the clasts of metasedimentary rocks in the Bosumtwi suevite samples, where it seems feldspar is rather more resistant than quartz in forming diaplectic glass. Why high temperatures

Table 3a. PDF planes in the quartz grains from suevite from drill core BH1.

Sets of planes	No. of grains	Percent (rel%)
1	3	4.4
2	41	60.3
3	20	29.4
4	3	4.4
5	1	1.5
162	68	100

162 planes were measured from 68 grains; plane/grain ratio (P/G = 2.38). One third of the total quartz grains were unshocked. Only shocked grains are listed here.

Table 3b. PDF planes in the quartz grains from suevite from drill core BH3.

Sets of planes	No. of grains	Percent (rel%)
1	5	8.5
2	41	69.5
3	13	22
126	59	100

126 planes were measured from 59 grains (P/G = 2.14).

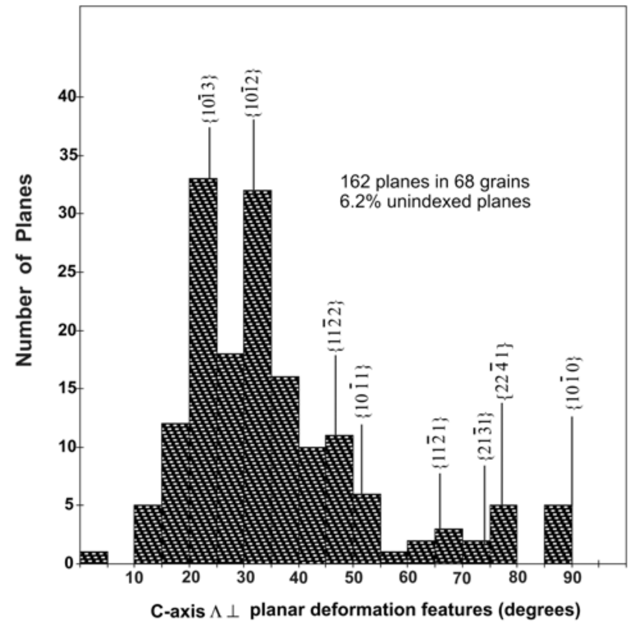

Fig. 7. A histogram of angles, binned at 5°, between c-axis and poles to PDFs in quartz from suevite from drill hole BH1 at the Bosumtwi impact structure. The plot shows a strong concentration of planes at 23° and 32° that is characteristic for the ω {10$\bar{1}$3} and π {10$\bar{1}$2} orientations, respectively. 162 PDFs in 68 grains were measured; average plane/grain (P/G) ratio = 2.38 (6.2% of unindexed planes).

render feldspar more resistant than quartz to amorphous phase transition in the solid state in these metasedimentary rocks is not understood. More detailed studies are necessary to explain these observations. Higher shock pressures are indicated by larger-scale melting and, in some cases, quenching (Figs. 6g and 6h).

Shock-Induced Deformation of the Important Rock-Forming Minerals

Orientations of Planar Deformation Features (PDFs)

The crystallographic orientations of PDFs were analyzed on 20 thin sections of suevite samples, according to the method of Engelhardt and Bertsch (1969) (see also Stöffler and Langenhorst 1994; Grieve et al. 1996). If the polar and azimuth angles fall within 5° of poles of rational crystallographic planes, the PDF poles were indexed with Miller indices (hkil) for quartz (hexagonal). The numbers of PDF sets of different crystallographic orientation per grain were found to be generally two or more (up to 5, Table 3). Figures 7 and 8 show histograms with the orientations of the poles of the PDFs relative to the c-axis of the quartz grains (after Engelhardt and Bertsch 1969) and a fence diagram of the frequency of indexed PDFs versus angle between c-axis and PDFs, including only indexed planes, following Grieve et al. (1996). Almost all the measured sets could be assigned to angles corresponding to prominent planes in typical shock fabrics: {10$\bar{1}$3}, {10$\bar{1}$2}, {11$\bar{1}$1}, {22$\bar{4}$1}. The absence of (0001) in the Bosumtwi suevite shocked quartz studied is similar to shocked quartz (type D) from ten Canadian craters (Robertson et al. 1968), which indicates high shock pressure (>16 GPa) (French 1998, Fig. 4.26).

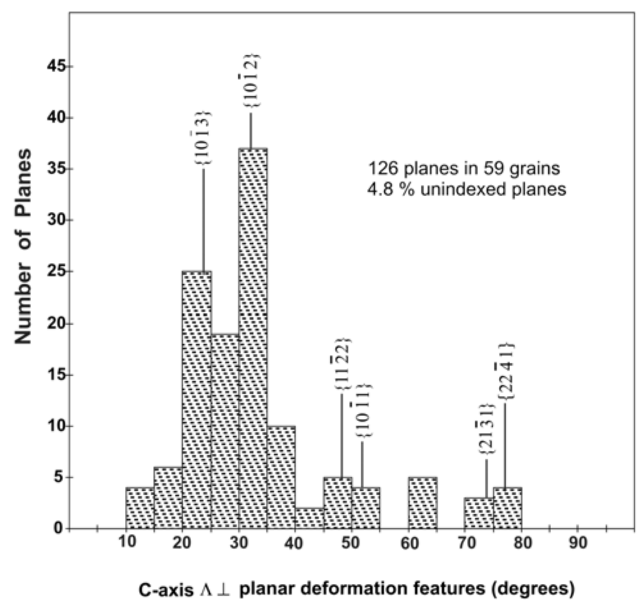

Fig. 8. A histogram of angles, binned at 5°, between c-axis and poles to PDFs in quartz from suevite from drill hole BH3 at the Bosumtwi impact structure. The plot shows a strong concentration of planes at 23° and 32° that is characteristic for the ω {10$\bar{1}$3} and π {10$\bar{1}$2} orientations respectively; 126 PDFs in 59 grains were measured; average plane/grain (P/G) ratio = 2.14 (4.76% unindexed planes).

Most poles to the PDF planes are oriented at about 23° and 32° to the quartz c-axis (Figs. 7 and 8), corresponding to the ω {10$\bar{1}$3} and π {10$\bar{1}$2} orientations that are diagnostic for impact-produced shock metamorphism (see, e.g., Stöffler and Langenhorst 1994; Grieve et al. 1996), and indicating a shock pressure of at least 20 GPa.

SUMMARY AND CONCLUSIONS

We summarize petrographic information from suevite samples from the first (and only) drill cores taken so far outside the crater rim. The major conclusions are:

1. Ejecta deposits in the form of suevite cover an area of about 1.5 km^2 to the north of the crater that is outside the crater rim but within the outer ring depression. The maximum thickness of this fallout suevite was determined to be about 15 m.
2. Macroscopic studies of the recovered suevite cores show that melt inclusions are present throughout the whole length of the suevite cores in the form of mainly vesicular melts. Individual fragments are irregular in shape, and with some showing flow bands. In general, the groundmass or matrix occupies up to 70 vol%, glass/melt fragments about 15–20 vol%, rock fragments (graywacke, phyllite, shale, slate, schist and granite) about 10 vol%, and mineral clasts (mainly quartz and feldspar) less than 5 vol%.
3. Until now distinctive shock metamorphic effects at Bosumtwi have been found only in the preserved suevite deposits outside of the crater rim, which represent ejecta from the lower part of the crater (similar shock features have now been reported from suevite in drill cores beneath the crater lake; cf. Koeberl et al. 2006). Petrographic examination of the suevite drill cores from outside the structure indicates that fragments in these breccias record several stages of shock metamorphism. These shock effects include planar deformation features (PDFs) in quartz and feldspar, biotite grains with kinked bands, diaplectic quartz and feldspar glasses, lechatelierite, ballen-structured quartz, and shock melted rocks. None of the other (lithic) breccias of probable impact origin (fractured and shattered metasediments and granites) display definite shock effects (cf. Koeberl et al. 1998).
4. The thin sections studied contain quartz with PDFs, with up to five sets of different crystallographic orientations per host grain, and yielded the shock characteristic $\{10\bar{1}3\}$, $\{10\bar{1}2\}$, $\{11\bar{2}2\}$, $\{11\bar{2}1\}$, $\{22\bar{4}1\}$, $\{21\bar{3}1\}$, $\{10\bar{1}0\}$, $\{10\bar{1}1\}$ orientations, with the dominance of ω $\{10\bar{1}3\}$ and π $\{10\bar{1}2\}$ crystallographic orientations, indicating a shock pressure of at least 20 GPa. This agrees with the absence of (0001) orientations, which indicate a shock pressure of >16 GPa.
5. Shock metamorphosed rock fragments and impact glasses at Bosumtwi are characterized by a wide range of textures and mineralogical and geochemical compositions, reflecting the variety of target rocks and shock levels experienced by them. From apparently undeformed fragments to observations of ballen-structured quartz from cristobalite after lechatelierite or α-quartz, and to impact glasses indicate that the rocks experienced a range of shock pressures from less than 5 GPa to at least 50 GPa.
6. The Bosumtwi impact structure has several unusual characteristics that make it a particularly attractive target for future cratering mechanic studies focused on the formation of small complex impact structures. It is one of the only four craters associated with a tektite strewn field and with ejecta material in the form of suevite only in the north and southwest outside the crater rim. The extensive lateral and vertical exposures in the road cuts make accessible impact-produced fracturing of basement rock and formation of lithic breccias for detailed studies. It may be possible to use preserved petrographic shock effects to estimate original shock pressures and their attenuation across and beneath the crater floor (as is currently being done using samples from the 2004 ICDP drilling project; cf. Koeberl et al. 2005, 2006). The occurrence of fallout suevite at only restricted areas to the north and southwest of the crater deserves more studies to determine whether this is related to cratering mechanics or is a related to selective erosion of the mechanically weaker breccias.

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