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Lithostratigraphic and petrographic analysis of ICDP drill core LB-07A, Bosumtwi impact structure, Ghana

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Abstract–Lithostratigraphic and petrographic studies of drill core samples from the 545.08 m deep International Continental Scientific Drilling Program (ICDP) borehole LB-07A in the Bosumtwi impact structure revealed two sequences of impactites below the post-impact crater sediments and above coherent basement rock. The upper impactites (333.38–415.67 m depth) comprise an alternating sequence of suevite and lithic impact breccias. The lower impactite sequence (415.67–470.55 m depth) consists essentially of monomict impact breccia formed from meta-graywacke with minor shale, as well as two narrow injections of suevite, which differ from the suevites of the upper impactites in color and intensity of shock metamorphism of the clasts. The basement rock (470.55–545.08 m depth) is composed of lower greenschist-facies metapelites (shale, schist and minor phyllite), meta-graywacke, and minor meta-sandstone, as well as interlaminated quartzite and calcite layers. The basement also contains a number of suevite dikelets that are interpreted as injection veins, as well as a single occurrence of granophyric-textured rock, tentatively interpreted as a hydrothermally altered granitic intrusion likely related to the regional pre-impact granitoid complexes.

Impact melt fragments are not as prevalent in LB-07A suevite as in the fallout suevite facies around the northern crater rim; on average, 3.6 vol% of melt fragments is seen in the upper suevites and up to 18 vol% in the lower suevite occurrences. Shock deformation features observed in the suevites and polymict lithic breccias include planar deformation features in quartz (1 to 3 sets), rare diaplectic quartz glass, and very rare diaplectic feldspar glass. Notably, no ballen quartz, which is abundant in the fallout suevites, has been found in the within-crater impact breccias. An overall slight increase in the degree of shock metamorphism occurs with depth in the impactites, but considerably lower shock degrees are seen in the suevites of the basement rocks, which show similar features to each other. The bulk of the suevite in LB-07A appears to have been derived from the <35 GPa shock zone of the transient crater.

INTRODUCTION

The 1.07 Myr old (Koeberl et al. 1997a) Bosumtwi impact crater is centered at 06°32′N, 01°25′W in the Ashanti region of Ghana, West Africa, about 32 km south-southeast of Kumasi (Fig. 1). This complex impact crater is one of 19 currently confirmed impact structures in Africa (Koeberl 1994; Master and Reimold 2000; Koeberl and Reimold 2005). It is well-preserved and has a pronounced rim with a diameter of 10.5 km. The crater is excavated in lower greenschist-facies metamorphic supracrustal rocks of the 2.1–2.2 Gyr old Birimian Supergroup (cf. Wright et al. 1985; Leube et al. 1990; Watkins et al. 1993). It is filled almost entirely by Lake Bosumtwi, which is about 8 km in diameter and up to 80 m deep. Outside the crater rim at a radial distance of between 7 and 8.5 km from the crater center is a slight, near-circular depression and an outer ring of minor topographic elevation with a diameter of about 20 km (Jones et al. 1981; Garvin and Schnetzler 1994; Reimold et al. 1998; Wagner et al. 2002). Bosumtwi is associated with one of the four known tektite strewn fields (the Ivory Coast strewn field) (Fig. 1), which consists of tektites on land in the Ivory Coast territory and microtektites in deep-sea sediments off the coast of West Africa (e.g., Glass et al. 1991; Koeberl et al. 1997a, 2007a).

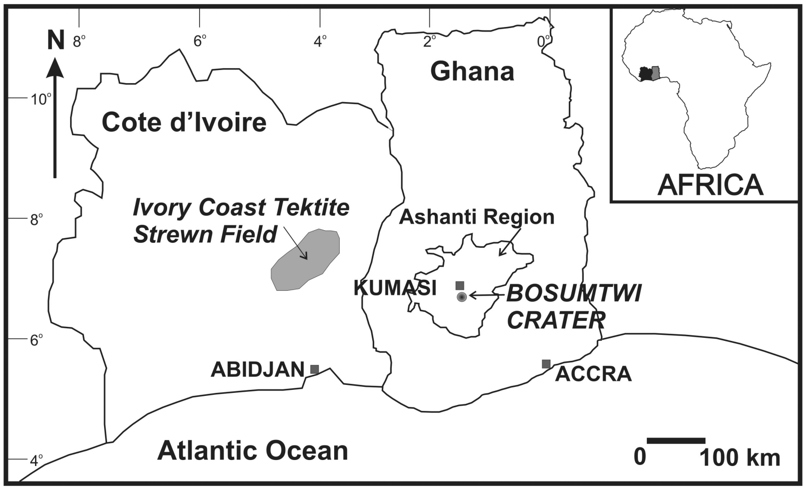


Fig. 1. Map showing the location of the Bosumtwi impact structure, Ghana, and the location of the Ivory Coast tektite strewn field, Côte d'Ivoire.

The Bosumtwi structure was the subject of an interdisciplinary drilling effort by the International Continental Scientific Drilling Program (ICDP) from July to October 2004, which led to the recovery of a series of cores through the sedimentary crater fill as well as two cores LB-07A and LB-08A through the impact breccia fill and underlying crater basement (e.g., Koeberl et al. 2005, 2006a, 2007a). The primary reasons for drilling the Bosumtwi crater were to obtain a complete, 1 million-year paleoenvironmental record and to study the subsurface structure and crater fill of a well-preserved, young, reasonably large and complex impact structure (see Koeberl et al. 2007a). In addition, the recovered cores provide new constraints for the previously obtained geophysical data across the crater and its environs (see Koeberl et al. 2005 and various papers in this issue).

The base of the sediments in core LB-05 is separated from the impactite sequence, as obtained in cores LB-07A and LB-08A, by a thin, impact-glass-bearing, and "accretionary lapilli"–rich fallout layer (Koeberl et al. 2006b; Koeberl et al. 2007b). Hard rock cores have been recovered from two deep drill holes through the impact crater fill: LB-07A and LB-08A (Fig. 2). These sites were chosen in accordance with field and seismic data that define the Bosumtwi impact structure (Karp et al. 2002; Scholz et al. 2002), and the drill sites were constrained by good-quality seismic profiles (Fig. 2). Core LB-07A is from the crater moat surrounding the central uplift and was drilled to a depth of 545.08 m below lake level, whereas LB-08A (e.g., Ferrière et al. 2007) was drilled to a depth of 451.33 m below lake level on the flank of the central uplift (Fig. 2) (Koeberl et al. 2007a).

REGIONAL GEOLOGY

The Bosumtwi crater (Koeberl and Reimold 2005) (Fig. 3) was excavated in lower greenschist-facies supracrustal rocks of the 2.1–2.2 Gyr old Birimian Supergroup (Wright et al. 1985; Leube et al. 1990; Davis et al. 1994; Hirdes et al. 1996; Oberthür et al. 1998; Watkins et al. 1993). Except for the terrain of the Obuom mountain range to the southeast of the crater, and locations along some stream channels in the environs of the crater, exposure is generally very poor. The Birimian Supergroup in Ghana forms a number of parallel, evenly spaced, volcanic belts several hundred kilometers long, that are separated by basins containing dacitic volcaniclastics, argillitic sediments, granitoids, and graywackes (cf. Wright et al. 1985; Leube et al. 1990). The Supergroup has historically been divided into the Lower Birimian (dominated by metasediments) and the Upper Birimian (dominated by greenstone-type metavolcanics), but because both groups gave similar ages (2.17 ± 0.07 Gyr; Leube et al. 1990; Taylor et al. 1992; Davis et al. 1994; Hirdes et al. 1996), this division has more recently been abandoned (e.g., Leube et al. 1990). The Upper Birimian metavolcanics are found to the west and southwest of the crater. The metasediments consist of interbedded phyllites/mica-schists and meta-tuffs, together with meta-graywackes, quartzitic graywackes, shales, and slates (Koeberl and Reimold 2005). These rocks are characterized by a strong regional northeast-trending fabric with steep dips to either the northwest or southeast. Local variations in both strike and dip are seen around Lake Bosumtwi and have been interpreted as the result of the impact event (Reimold et al. 1998; Boamah and Koeberl 2003). Country rock in the immediate environs of the crater is dominated by meta-graywacke and some meta-sandstone, but shale (including graphitic shale) and mica-schist were also observed by Reimold et al. (1998) along their traverse through the northwestern crater rim. The crater rim rocks are locally intensely folded and/or faulted. A number of granitoid intrusions (mainly biotite- and amphibole-bearing granites, but also albitite and diorite) were mapped by Junner (1937) and Moon and Mason (1967); see also Reimold et al. (1998). Reimold et al. (1998) reported the occurrence of

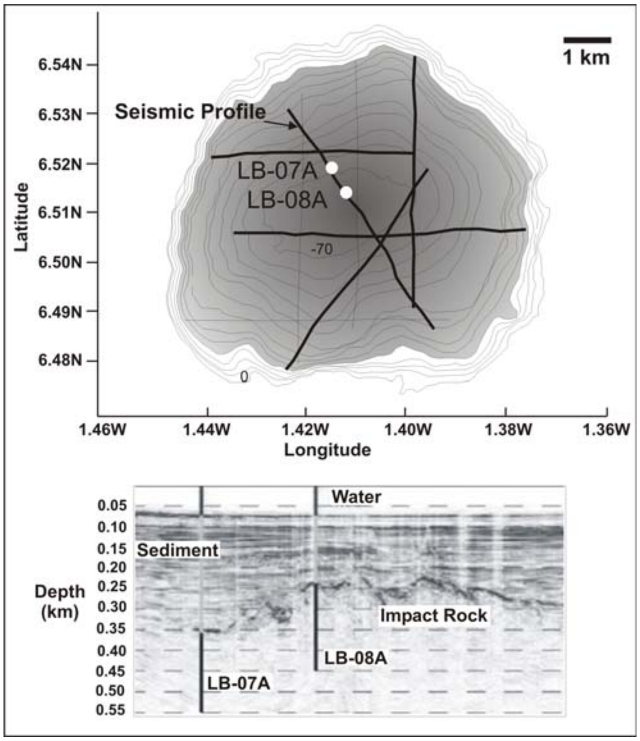


Fig. 2. A bathymetric map and seismic profile across ICDP boreholes LB-07A and LB-08A. Thick black lines show positions of seismic profiles (reflection and refraction data), and the thin black lines are contour lines. Bathymetric contour interval is 5 m (after Scholz et al. 2002; Karp et al. 2002).

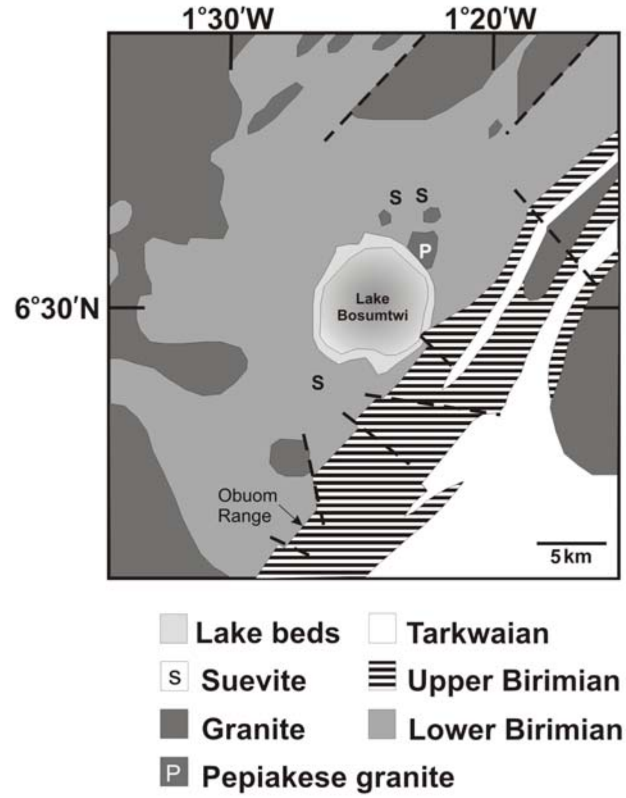


Fig. 3. A simplified geological map showing Lake Bosumtwi and surroundings (after Jones et al. 1981; Koeberl and Reimold 2005). The division into Upper and Lower Birimian, while no longer used because no age difference is evident, is kept here to indicate somewhat different rock types: the Upper Birimian predominantly consists of metavolcanics, whereas the Lower Birimian mostly consists of metasediments.

many biotite-granite dikes intruding the metasediments along the crater rim, and Koeberl et al. (1998) drew attention to the existence of a granophyric-textured lithology of then uncertain origin (compare Results section below). The overall granite component in the vicinity of the crater, and by implication to the target composition, was estimated at less than 2% (Reimold et al. 1998). Some target rock compositions are also reported by Karikari et al. (2007).

To the southeast of the Bosumtwi crater, the younger clastic sedimentary rocks of the ~2.1–2.13 Gyr old Tarkwaian Supergroup (Hirdes and Nunoo 1994) are present. These strata are regarded as detritus of the Birimian rocks and are also metamorphosed to greenschist-facies grade (Leube et al. 1990; Koeberl and Reimold 2005).

The youngest deposits found at the crater include the Bosumtwi lake beds and breccias associated with the Bosumtwi impact (cf. Junner, 1937; Moon and Mason 1967; Jones et al. 1981; Jones 1985; Koeberl et al. 1997b and Reimold et al. 1998). Monomict and polymict lithic impact breccias, as well as suevite (a polymict impact breccia that includes melt particles [glassy or crystallized] in a clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism [see Stöffler and Grieve 1994; Stöffler and Reimold 2006]), have been described by Koeberl and Reimold (2005) and references therein. Suevite deposits have been mapped and studied around the crater by Koeberl et al. (1998), Boamah and Koeberl (2003), and Koeberl and Reimold (2005). The latter authors also provide further details regarding the geology of the Bosumtwi structure and a detailed geological map.

PREVIOUS WORK

Only limited field, geochemical, and petrographic studies of the crater rim rocks (Koeberl et al. 1998; Reimold et al. 1998; Boamah and Koeberl 2003) and ejecta (suevitic breccia) have been carried out to date (Koeberl et al. 1998; Boamah and Koeberl 2003). Boamah and Koeberl (2003, 2006) reported on a shallow drilling program to the north of the crater rim that was done in 1999 and identified a number of different types of impactite, including glass-rich suevite and lithic polymict breccia. They proposed that the graywacke-phyllite lithologies and granite dikes, together with a minor amount of the so-called Pepiakese granite that is found to the northeast of Lake Bosumtwi (Fig. 3), were the dominant contributors to the suevite. The Pepiakese granite differs from the other granite intrusions in being variably altered, and in having a dioritic component that contains a substantial proportion of mafic minerals, including amphibole.

Boamah and Koeberl (2003) determined that the thickness of the fallout suevite was ≤15 m and that it occupies an area of ~1.5 km^2 to the north of the crater. Its distribution is likely an artifact of differential erosion (Boamah and Koeberl 2003). Boamah and Koeberl (2006) reported petrographic information for the suevite from the drill cores. They found that suevite comprises up to 70 vol% matrix and up to 20 vol% impact melt fragments, together with ~10 vol% rock fragments (graywacke, phyllite, shale, slate, schist, and granite), and less than 1 vol% mineral clasts (quartz and feldspar). The matrix, i.e., all material <2 mm in size, was composed of quartz, feldspar, biotite and rock fragments, and rare impact melt particles. Common shock metamorphic features of clasts include planar fractures, planar deformation features (PDFs, up to 5 sets per grain) in quartz, diaplectic quartz and feldspar glasses, kink-banded biotite and ballen quartz (Boamah and Koeberl 2006). The main shock features are consistent with shock pressures between 20 and >60 GPa (Boamah and Koeberl 2006).

THIS STUDY: METHODOLOGY

Detailed logging of the LB-07A core took place during the sampling party at the Geoforschungszentrum (GFZ) in Potsdam, Germany, in January 2005, and then again in March 2006. These results have been used in combination with petrographic analysis to compile the lithostratigraphy of the LB-07A core (Fig. 4) presented here. Seventy-six samples, primarily of the impact breccias, were selected for preparation of 108 polished thin sections that were examined in both transmitted and reflected light. Point-counting of 25 breccia thin sections was carried out (according to the traditional method of Chayes 1949), whereby approximately 500 to 1000 counts are made over 4 to 5 cm^2 areas. Thirty-two thin sections were subjected to “shock point-counting,” whereby all observable quartz and feldspar grains were examined for shock features while rastering whole thin sections on a petrographic microscope. Scanning electron microscopy (SEM) was applied to ascertain the presence of melt in the matrices of the suevites at Humboldt University in Berlin, using a JEOL-JSM 6300 instrument at 15 kV acceleration voltage coupled with a RÖNTEC X-Ray energy-dispersive analytical system. X-ray diffraction (XRD) was performed on a few representative bulk suevite samples at the University of the Witwatersrand, on a Philips PW 1830 machine (CuK alpha radiation, 50 kV, and 50 mA), in order to identify phyllosilicates in the suevites. Results of geochemical analyses of the LB-07A sample suite are reported in a companion paper in this volume (Coney et al. 2007).

RESULTS

Macroscopic Observations

The LB-07A borehole lithostratigraphy produced by this study is shown in Fig. 4. All depths indicated are depths below lake level, which was constant during the drilling period. The drill core was recovered between 333.38 m and 545.08 m depth. Recovery of the core varied between 10% and 100%, with an average of 65%, and the highest recovery was recorded in the upper part of the borehole (to a depth of ~414 m). The coherence of the core deteriorates with depth, with mainly friable and strongly fractured material (some disking) recovered below a depth of 455 m. Consequently, the density of sampling is highest in the upper part of the core (Fig. 4), where the preservation is best.

Figure 4 shows the subdivision of the LB-07A core, and the number of samples taken at various stratigraphic depths, together with information on the detailed lithological variation within the core. The core can be divided into three parts: 1) an upper impactite sequence from 333.38 m to 415.67 m depth (see Fig. 4) comprises polymict lithic impact breccia (see Table 1) alternating with up to 21.89 m of suevite (Fig. 5a; distinction between these two breccia types is based on detailed petrographic analysis, see below); 2) a lower impactite sequence between 415.67 m and 470.55 m depth that comprises monomict impact breccia formed from meta-graywacke with minor shale intercalation (Figs. 5b and 5c; Table 1), with two thin gray suevite intercalations at 430.13 and 445.13 m depth; and 3) below this unit, the borehole intersected metasediments from 470.55 m to 545.08 m depth. The metasediment color varies from dark gray to white. The gray zones comprise highly altered shales with rare remnants of graphitic shale which is potentially a source of the dark color. The white zones contain meta-graywacke fragments. The metasediments are dominantly altered shale (followed in abundance by meta-graywacke) with thin (<1 m thick), light to dark gray suevite intercalations at 483.00–483.60 m and 513.90–514.90 m depth, and a single intercalation of a distinct, granophyric-textured lithology at 487.12–487.42 m depth (Fig. 4). In the absence of any indication that it could be a megablock of target rock floating in impact breccia, we believe the sequence represents crater floor (basement). Contact relationships between the different lithologies are generally indistinct in this interval.

Contacts between the lithic and suevitic breccias in the upper impactite sequence could not be resolved on the macroscopic scale and could be gradational, as the lithic and suevitic breccias are similar but for the fact that the suevite contains minor amounts of microscopic melt particles. Both breccias consist of subcentimeter- to decimeter-sized clasts, and the main phases observable on the macroscopic scale include meta-graywacke, shale, quartz and sandstone. Pre-impact features include folding and lamination in clasts.

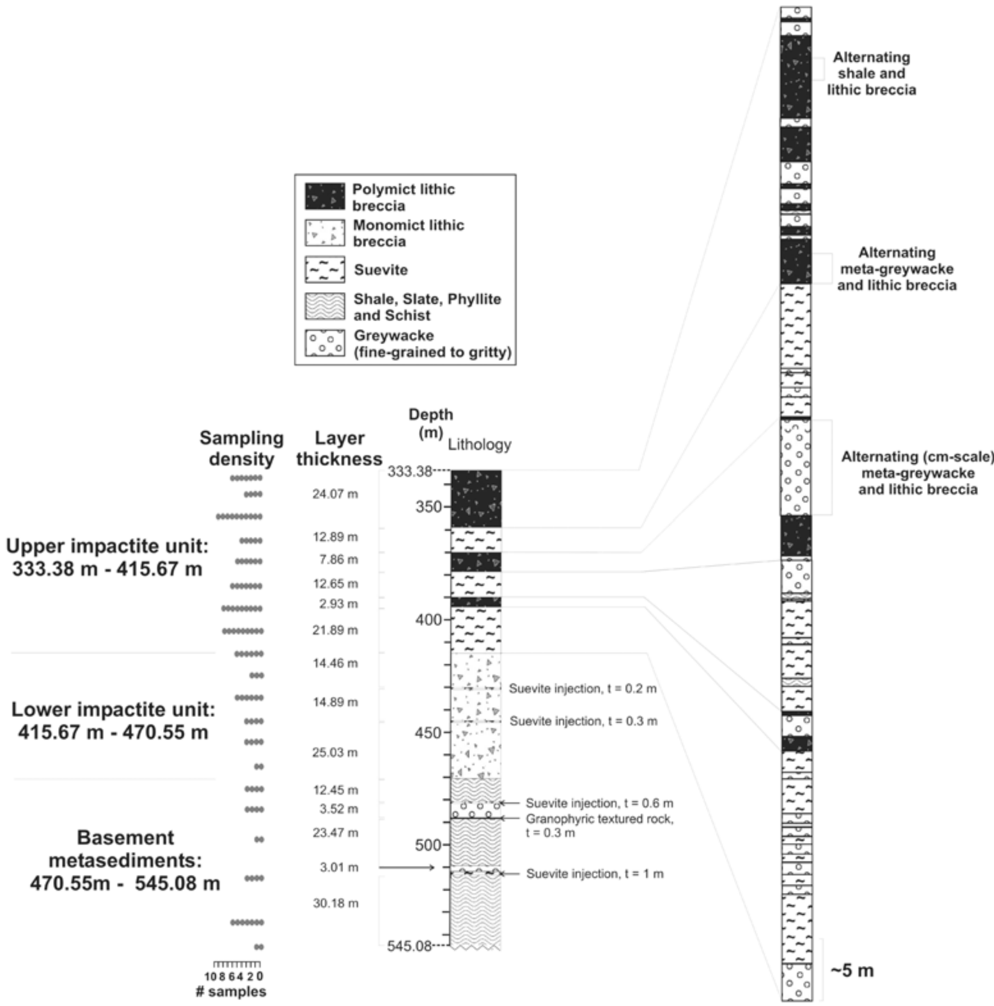


Fig. 4. A detailed lithostratigraphic column of the LB-07A borehole, Lake Bosumtwi. Upper impactites: alternating lithic and suevitic breccias. Lower impactites: upper unit (415.67–430.13 m) consists of meta-graywacke; middle unit (430.33–445.22 m) consists of phyllite for 4 m, followed by meta-graywacke; lower unit (445.52–470.55 m) consists of meta-graywacke ending in 3.6 m of mylonitic, shale-rich, thinly banded lithologies. Basement rocks are highly disaggregated, partially powdered. Also shown is the sample density over this interval.

Only a single, 1 cm large, macroscopic melt particle was macroscopically observed at 430.13 m depth. It has been suggested that the upper impactite sequence should entirely be considered suevite and that lack of melt fragments in samples from specific depths could be the result of accidental sampling bias. However, it is also possible that the turbulent processes during and after impact (slumping producing debris flows) could have caused the intercalation of lithic and suevitic breccias.

The contact between the upper and lower impactite sequences at 415.67 m depth is sharp (Fig. 5). The contacts between the thin suevite intercalations and monomict breccia also appear distinct, indicating that, most likely, these suevites, represent injections into the monomict breccia, although it must be noted that the deterioration of the core is already substantial in the lower impactites, so that detailed analysis of contact zones is severely hampered. The meta-graywacke and the altered shales in the basement metasediments are intercalated on millimeter to meter scales. Contacts are commonly sharp but typically undulating, presumably owing to the low-amplitude folding that is noted throughout the metasediment sequence both in the core and in outcrop outside of the crater.

Throughout the impactite sequence calcite pods and millimeter- to centimeter-wide calcite and quartz veins, as well as rare sulfide occurrences are observed. The alteration is most pronounced in the upper impactites (above 415.67 m depth). Secondary veins seem to have variable dips with respect to the core axis, ranging from moderately steep to shallow. These veins are distinct from pre-impact quartz veins that are restricted to large clasts and, on the microscopic scale, display evidence of shock deformation. A number of such pre-impact quartz veins occur parallel to bedding in meta-graywacke or altered shale. The lower impactites show

Table 1. Main lithologies recognized throughout the LB-07A borehole, and their defining characteristics.

Rock type	Description
Suevite	Polymict impact breccia that includes melt particles (in a glassy or crystallized state) in a clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism.
Polymict lithic impact breccia	An impact breccia that contains shocked and unshocked clasts of multiple progenitors, but that lacks cogenetic melt particles.
Monomict lithic breccia	A cataclasite produced from a single precursor lithology as the result of impact; generally displaying weak or no shock metamorphism.
Shale	A fine-grained, fissile sedimentary rock composed of clay- and silt-sized particles of unspecified mineral composition. Commonly appears dark gray-black and may be iron-stained, and is commonly laminated.
Meta-graywacke	Metamorphosed, texturally and mineralogically immature sandstone that contains more than 15% of phyllosilicate. It may consist of quartz and feldspar, small pebbles, and a matrix of phyllosilicate, chlorite and carbonate. The clasts of feldspar and quartz are usually rounded.
Phyllite	Regional metamorphic rock, light silvery-gray in color, and metamorphically intermediate to slate and schist. Sericite gives sheen to rock. Similar to both a shale and metapelite, but contains a schistose fabric, defined by fine-grained phyllosilicates.
Schist	Metamorphic rock that is not defined by mineral composition but rather by the well-developed parallel orientation of more than 50% of the minerals present, especially those of elongate habit.
Slate	A fine-grained metamorphic rock derived mostly from shale. It is characterized by slaty cleavage, i.e., the ability to be split into large, thin, flat sheets.

Definitions after Stöffler and Grieve (1994); Stöffler and Reimold (2006); Allaby and Allaby (1999); Lapidus and Winstanley (1990).

less evidence of secondary alteration (both macroscopically and microscopically) but the relatively poor state of the core has hampered a full investigation of this aspect. Calcite pods of up to 10 cm size and sulfide-filled fracture networks up to 1 cm wide are observed in the underlying metasediments.

The lower part of the core displays a feature called disking—where centimeter-wide pieces have broken essentially perpendicular to the core axis (apparent dip of 10–20°), with fracturing generally parallel to metasediment bedding orientations. This disking effect is clearly related to the well-laminated and lithologically diverse (at a scale of centimeters to decimeters) nature of this section, with many, if not all, fractures originating on lithological contacts and bedding-planes. The effect is thought to be caused by the drilling-induced shear stress (see also Deutsch et al. 2007).

Microscopic Observations

The microscopic findings, to some degree, mirror the macroscopic changes observed. Throughout the impactite sequences, mostly metasedimentary lithic clasts have been found, besides a trace of granitic clasts, with no evidence for a metavolcanic input.

Upper Impactite Unit (333.38–415.67 m)

The upper impactite unit is well preserved and three lithic breccia sections alternate with three suevitic breccia sections (Fig. 4). All these breccias are macroscopically very similar, but we distinguish here lithic breccias from suevites by the absence or presence of melt fragments. No sharp contacts are seen between the lithic breccias and the suevites and, thus, we treat them as a single sequence. In the suevites 1.6–6.8 vol% (see the modal data in Table 2; Fig. 6) of melt particles were counted. All these breccias are either matrix- or clast-supported, with no discernible trend with depth. Both lithic and suevitic breccias are dominated by meta-graywacke clasts (commonly mylonitic and dominated by quartz; Fig. 7a); phyllite, mica-schist, quartzite and well-laminated shale (Fig. 7b) are the other significant lithic clast phases (Table 2). Partial destruction of features such as lamination (giving the clasts a “boiled” appearance) has taken place in some of the lithic clasts, and is thought to have been caused by shock metamorphism. The shale clasts are locally iron-stained. Kinked cleavage of the shales (also some slates) and the phyllites has been observed and is well known from similar rocks collected outside the crater (e.g., Koeberl and Reimold 2005). Other minor (generally <0.1 vol%) lithic clast components include leucogranite, graphitic schist, limestone, and discrete—but rare—clasts of impact breccia (breccia-in-breccia) (see Table 2). These breccia clasts represent lithic breccia. In terms of mineral clasts, quartz, plagioclase, K-feldspar, various phyllosilicates (biotite, chlorite, and muscovite), and calcite clasts are significant. Traces of amphibole (tremolite-actinolite) and sphene were noted during point-counting. Biotite and chlorite are the main phyllosilicate phases. Chlorite is generally present as a secondary alteration product of biotite.

Hydrothermal effects are observed in the form of fine (up to 1 mm wide) quartz veining and sericitization of plagioclase, and secondary chlorite after biotite. Discrete bands, up to several mm in width, of primary calcite (distinguished from secondary calcite pods by larger grain size and well-developed mosaic texture), which up to now was not considered a significant component of the target volume, have been recognized as a distinct lithology in large coherent basement rock sections (metasediment units) of the lower sequence. This material is also present as clasts of euhedral calcite crystals in the impact breccias (<5 vol%). In addition, calcite occurs as aggregates of ~100–700 µm size grains in secondary veinlets (Fig. 8).

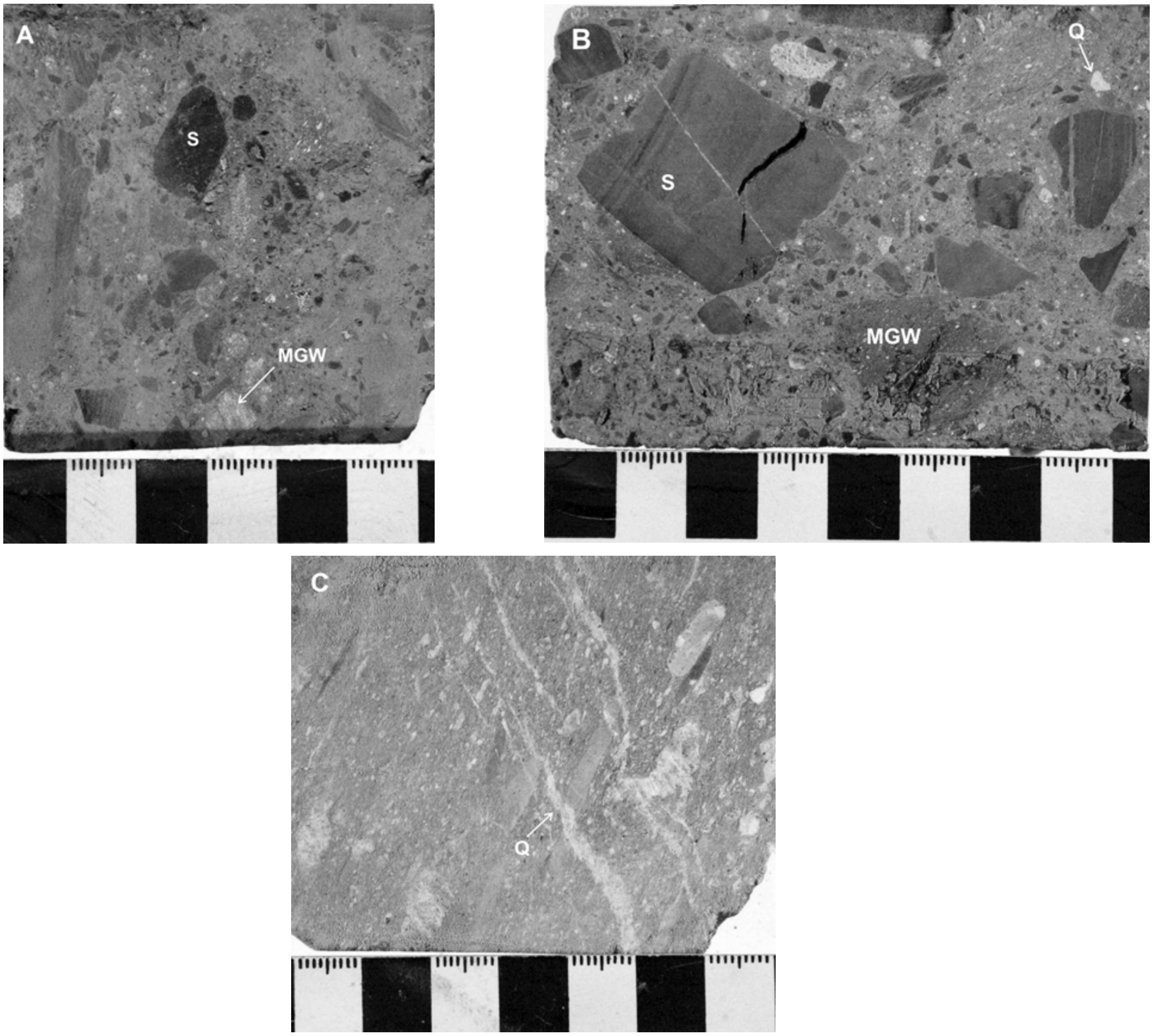


Fig. 5. Photographs of hand specimens from the LB-07A borehole. a) Upper impactite unit: matrix-supported suevite with sub-cm to cm lithic fragments: organic-rich shale (S), meta-graywacke (MGW); melt particles are microscopic; scale bar in cm, sample depth = 383.14 m. b) Upper impactite unit: matrix-supported suevite with sub-cm to dm lithic fragments: laminated shale (S) with cross-cutting pre-impact quartz veinlets, quartz-rich meta-graywacke (MGW), quartz (Q); melt particles are microscopic. Flow textures apparent in the lower half of the sample; scale bar in cm, sample depth = 402.73 m. c) Lower impactite unit: mylonitic meta-graywacke clast in monomict breccia with cross-cutting quartz veinlets (Q); scale bar in cm, sample depth = 468.28 m.

The lithic and mineral clast size varies from 0.1 mm to 2 cm throughout the impact breccia interval. Clast shapes vary from sub-rounded to angular, with an overall tendency towards angularity. Only the shapes of microscopic melt fragments vary from well-rounded to angular. No systematic size or shape variation has been recognized with increasing depth or within the upper impactite sequence.

Microscopically, the matrix (here considered as everything with a grain size of less than 50 μm) of these breccias is rather heterogeneous in terms of size and shape of the fragments: there is strong variation in the color of the matrix as a whole from light to dark gray-brown (colors after the Munsell system), presumably relating to iron content (see Coney et al. 2007). Flow structures have been observed in a few samples in the breccia matrix, in both the lithic breccias and suevites of the upper impactite section. Flow is indicated by minerals and matrix flowing around grains larger than 1 mm in diameter. It is, however, possible that this feature was produced by compaction of the deposit. SEM analysis shows that the matrix grains are highly angular, and matrix composition is seemingly dominated by quartz, with minor feldspar and mafic minerals (including some biotite). Locally, small particles with vesiculated structure are present in the matrix of suevite samples and are interpreted as tiny (50–100 μm) melt fragments (Fig. 9). Their abundance is estimated at <5% of the overall matrix component.

Table 2a. Modal analyses (in vol%) by optical microscopy on thin sections of selected representative samples of impact breccia.

Sample no.	KR7-35	KR7-6	KR7-7	KR7-36	KR7-8	KR7-50	KR7-37	KR7-51	KR7-43	KR7-52
Depth (m)	359.33	360.65	363.20	364.45	370.34	378.20	379.09	383.14	384.84	392.00
Breccia type	Suevite	Suevite	Suevite	Suevite	Lithic	Suevite	Suevite	Suevite	Suevite	Lithic
Matrix	43.1	43.3	44.4	61.8	52.3	43.0	68.8	56.4	72.2	56.2
Meta-graywacke	13.9	19.6	12.1	10.5	12.3	42.2	9.6	7.1	13.7	25.2
Shale	12.5	7.1	7.7	7.6	9.1	2.9	4.6	x	2.4	1.8
Phyllite	4.9	6.7	x	1.8	1.4	2.4	1.3	28.4	3.9	10.2
Schist	4.5	12.1	x	x	x	x	2.5	x	x	x
Breccia	4.9	x	x	x	x	x	x	x	x	x
Leucogranite	x	x	x	6.5	0.5	3.2	x	1.0	x	x
Phyllosilicates[a]	x	x	1.0	0.4	13.6	x	0.4	x	x	x
Quartz	9.0	8.5	12.6	9.1	10.9	1.3	7.9	4.6	5.1	6.6
Total feldspar[a]	0.4	0.4	0.5	x	0.5	0.5	2.5	0.5	x	x
Carbonate	2.8	0.4	16.4	0.4	0.9	0.5	0.4	x	x	x
Sphene	0.7	x	x	x	x	x	x	x	x	x
Diaplectic glass[a]	x	x	x	x	x	x	x	x	x	x
Melt	3.5	1.8	5.3	1.8	x	3.7	2.1	2.5	2.7	x
Total	100.2	99.9	100	99.9	101.5	99.7	100.1	100.5	100	100

Table 2a. *Continued*. Modal analyses (in vol%) by optical microscopy on thin sections of selected representative samples of impact breccia.

Sample no.	KR7-14	KR7-40	KR7-53	KR7-15	KR7-16	KR7-17	KR7-20	KR7-41	KR7-42	KR7-23a
Depth (m)	398.44	400.06	400.58	402.73	404.26	405.57	408.32	408.72	412.17	430.13
Breccia type	Suevite	Suevite	Suevite	Suevite	Suevite	Suevite	Suevite	Suevite	Suevite	Suevite
Matrix	66.9	73.6	76.3	43.6	60.2	58.3	66.8	66.2	73.5	39.6
Meta-graywacke	20.1	6.1	2.8	11.5	24.1	23.4	25.1	13.6	10.5	9.3
Shale	2.5	7.1	14.7	31.4	5.4	3.3	2.5	7.5	2.2	11.0
Phyllite	2.9	2.8	0.9	0.6	x	1.0	x	1.1	2.9	3.5
Schist	x	x	x	x	x	x	x	x	x	x
Breccia	x	x	x	x	x	x	x	0.4	x	x
Leucogranite	x	x	x	x	x	x	x	x	x	x
Phyllosilicates[a]	x	x	x	x	x	4.8	x	3.8	x	x
Quartz	3.3	x	1.4	1.9	0.4	x	0.5	4.1	1.5	x
Total feldspar[a]	0.8	0.5	x	1.3	x	x	1.5	0.8	0.4	x
Carbonate	0.4	2.8	0.9	6.4	x	x	x	x	x	x
Sphene	x	x	x	x	x	x	x	x	x	x
Diaplectic glass[a]	x	1.4	0.9	x	3.7	2.4	x	x	4.0	x
Melt	2.9	5.7	1.9	3.2	6.2	6.8	3.5	2.6	4.4	36.1
Total	99.8	100	99.8	99.9	100	100	99.9	100.1	100.1	99.9

[a]Total feldspar = plagioclase + K-feldspar, where plagioclase > K-feldspar; phyllosilicates = chlorite + biotite + muscovite (primary and secondary); diaplectic glass = diaplectic quartz glass and diaplectic feldspar glass. Approximately 500 to 1000 grains counted over a 4–5 cm^2 area.
x = traces (<0.1 vol%). Matrix consists of grains which are less than 50 µm in size.

Rutile is a trace component in a number of shale clasts and considered of pre-impact origin (see Fig. 7b). Sulfide minerals (pyrite >> chalcopyrite; no pyrrhotite was observed at the optical scale, but compare Kontny et al. 2007) have been observed within shale clasts, usually parallel to the lamination, which indicates that these occurrences likely formed during sediment formation. These minerals are also found in the breccias as small, dense, irregular aggregates of tiny crystallites and some aggregates of larger (1 mm) euhedral crystals (see Fig. 10), and these are considered of post-impact hydrothermal origin.

Lower Impactite Unit (415.67–470.55 m)

The lower impactite breccias differ from the upper impactite breccias in that they are monomict; they are formed from either meta-graywacke or altered shale clasts (Fig. 4). The breccias in this interval are well preserved for part of the interval, but below 455 m depth they are disaggregated. Alternation between meta-graywacke and shale breccia types is on a decimeter- to meter-scale. Suevitic breccia intercalations are found at 430.13 m (~20 cm thick) and 445.13 m (~30 cm thick).

The meta-graywacke monomict breccias are characterized by angular to subrounded clasts, which are very fine-grained (~0.1–0.2 mm) at the top of the sequence. With increasing depth, the clast size increases to ~0.4 mm and locally to 1 mm but clast size is variable throughout. The matrix consists of very fine, angular clasts of meta-graywacke. The meta-graywacke consists of quartz, K-feldspar, and phyllosilicates. The matrix-to-clast ratio is variable and increases with increasing depth from approximately 40 to 60 vol%. The clasts are weakly to strongly mylonitized in the interval 454.35–470.55 m. Locally, secondary, rounded pods of calcite up to ~0.5 mm in diameter and calcite veinlets (0.2 to 0.5 mm thick) are evident. The suevite intercalations in the lower impactites differ from the suevites of the upper impactites in that the matrix color is moderate greenish yellow. Kinked shale, phyllite, and mylonitic meta-graywacke form the dominant lithic clast types in the suevites, and quartz and plagioclase mineral clasts are common in both suevite intercalations. The lithic/mineral clasts are angular to sub-rounded, and vary in size from <0.1 mm to 0.5 mm, which is smaller than the clasts seen in the upper impactite suevites.

Basement Metasediments (470.55–545.08 m)

Due to the highly disaggregated nature of this unit—many samples provided were completely pulverized—only grain mounts could be prepared. Thus, only randomly preserved fragments (mostly quartz-rich) were studied, with severe doubt whether or not these are fully representative of the lithological composition of these strata. However, it is reasonably certain that altered shale dominates the interval.

Table 2b. Modal analyses (in vol%) by optical microscopy on thin sections of selected, representative samples of impact breccia.

Sample no.	LB-39a	LB-39c
Breccia type	Fallout suevite	Fallout suevite
Matrix	38.1	46.2
Graywacke	3.9	1.6
Shale	4.8	2.3
Phyllite	3.8	3.7
Schist	1.2	4.5
Granite	17.8	5.5
Phyllosilicates[a]	0.2	0.9
Quartz	8.1	9.7
Opaques/Fe-rich	4.5	5.2
Grano. lith.	0	4.3
Diaplectic glass[a]	0.1	8.4
Melt	17.0	7.7
Total	99.5	100

[a]Total feldspar = plagioclase + K-feldspar, where plagioclase > K-feldspar; phyllosilicates = chlorite + biotite + muscovite (primary and secondary); diaplectic glass = diaplectic quartz glass and diaplectic feldspar glass; grano. lith = granophyric-textured lithology. About 750 grains counted over a 4–5 cm^2 area.

The two suevite intercalations in the basement (at 483.00 and 513.90 m depths) show different characteristics from the suevites of the upper and lower impactites, and from each other, particularly in terms of the color of the matrix and clast type. The clast size is substantially smaller than the clast size seen in the upper and lower impactite suevites. Similarities between these two suevites include variable clast size ranging from 0.1 to 1 mm and shape (elongated/flattened). The clasts are angular to subrounded, but rarely round.

The suevite intercalation at 483.00 m is ~60 cm thick, dark gray, and characterized by a dense, homogeneous, gray-black matrix. Meta-graywacke and laminated shale form the dominant lithic clasts, with quartz dominating the mineral clast population. In general, all mineral and lithic clasts are approximately 0.1 to 0.5 mm in size, with the lithic clasts being slightly larger than the mineral clasts. The suevite at 513.90 m is ~1 m thick and is characterized by a light gray matrix together with an abundance of lithic fragments that are predominantly meta-graywacke, followed by shale, but it also includes one clast of felsic granophyre ~2 mm in size (Fig. 11a). The granophyre clast is dominated by kinked muscovite, together with smaller proportions of quartz-feldspar granophyric intergrowth, plagioclase and secondary calcite in a locally spherulitic to ophitic intergrowth. The mineral clasts in the suevite include quartz, kinked muscovite, rare plagioclase, and a single ~1 mm-size elongate clast of actinolite-tremolite amphibole.

From 487.12 m to 487.42 m, a remnant of granophyric-textured igneous rock consisting of quartz-feldspar intergrowth, calcite, and muscovite is found (Fig. 11b). The rock is slightly different from the clast found in the suevite at

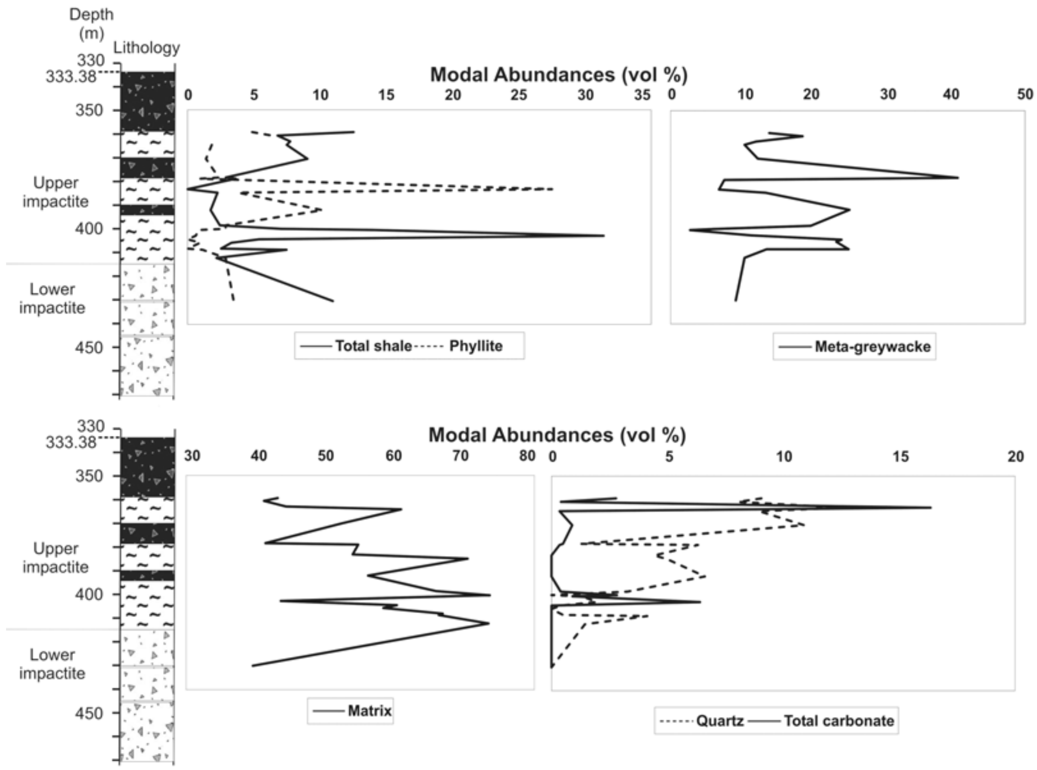


Fig. 6. Main lithic and mineral clast and matrix variations throughout the upper section of impactites in drill core LB-07A.

483.00 m in that it is more quartz-feldspar rich. The quartz-feldspar granophyric intergrowth is dominant, followed by calcite that is interpreted to be of secondary origin and that occurs as rounded masses (~1 mm in diameter). Muscovite is present as platy crystals (0.1 mm long), and is generally associated with the carbonate component. After examination of the hand specimen, it was concluded that this lithology may represent a hydrothermally altered intrusion of the granophyric granitoid lithology first described by Reimold et al. (1998) from the northwestern rim of the crater.

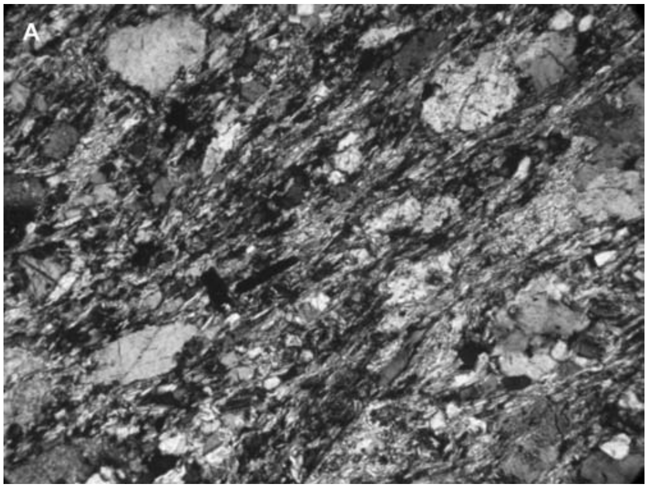
Suevite Variation throughout the LB-07A Borehole

The various suevites from the upper and lower impactites, as well as from the basement section, appear different chiefly on the basis of color; this seems to be the result of variable alteration. The melt fragments from upper and lower suevites do resemble each other in terms of shape, size and general appearance, and all contain quartz fragments. Iron content is variable throughout the sequence (see Coney et al. 2007), but other forms of alteration may also be responsible for the color change. In order to examine potential sources of alteration, X-ray diffraction was performed on selected samples from the different units from the following depths: 382.94 m (suevite, upper impactites); 430.13 m (suevite, lower impactites); 483.00 m (suevite, basement); 513.90 m (suevite, basement). Besides comparable quantities (semi-quantitative) of chlorite, muscovite and quartz in all samples, the major differences noted were that significant plagioclase and calcite occur in the upper impactites, lower impactite suevites and the upper basement suevite, but not in the lowermost basement suevite, and that the lowermost basement suevite contains a minor amount of smectite.

Shock Variation in the LB-07A Borehole

The nature and degree of shock deformation were determined both qualitatively (on all sections) and quantitatively (point-counting of a number of representative samples; between 90 and 250 quartz grains were counted per section; results are given in Table 3) for the various intervals. It must be emphasized that in some sections less quartz was counted either owing to the presence of larger clasts of other lithic material or large amounts of micrometer-scale quartz grains, for which elucidation of shock features was not possible at the optical scale.

Quartz grains in the lithic breccias and suevites (occurring as individual quartz grains, polycrystalline aggregates, or within meta-graywacke) display planar fractures and PDFs. Usually only one or two sets of PDFs are observed (Fig. 12); only a few grains have been noted containing 3 sets of PDFs in the clasts of the upper impactites. In contrast, PDFs with 3 sets are somewhat more common in



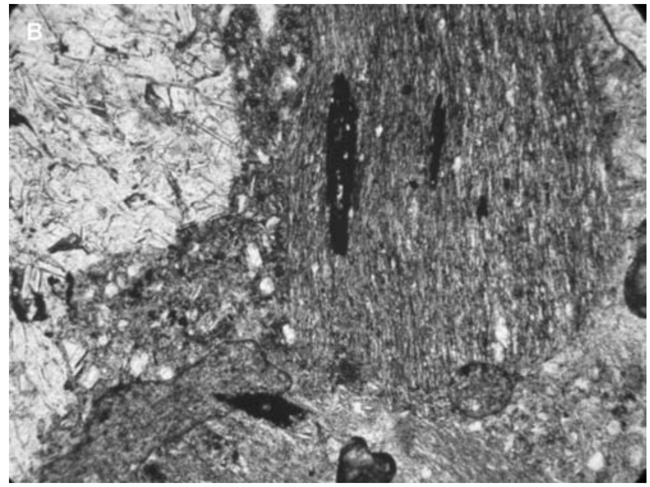
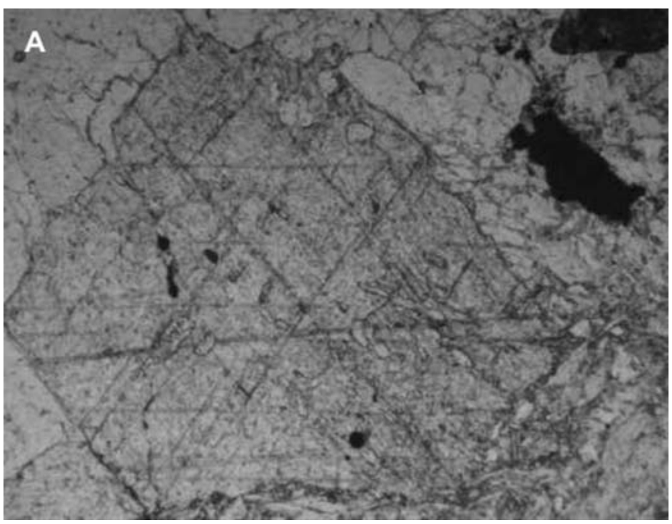


Fig. 7. Photomicrographs of the main lithic phases in suevites observed throughout the borehole. a) Mylonitic meta-graywacke; main minerals are quartz, K-feldspar and phyllosilicates; image width = 3 mm, cross polarized light (CPL), sample depth = 334.91 m. b) Upper impactite suevite breccia showing laminated shale with rutile in plane of lamination. Meta-graywacke to the left hand side of the slide; image width = 3 mm, plane polarized light (PPL), sample depth = 363.20 m.



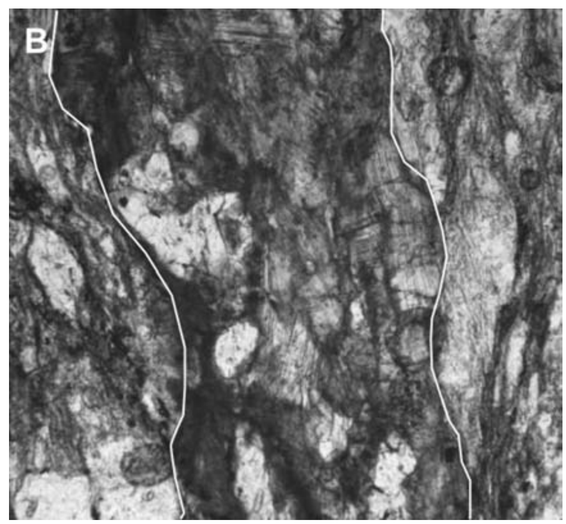


Fig. 8. Photomicrographs of calcite in suevites—primary and secondary phases. a) Authigenic calcite crystal; image width = 2 mm, PPL, sample depth = 370.34 m. b) Pre-impact veinlet of highly strained, secondary calcite; image width is 1.3 mm, PPL, sample depth = 468.28 m.

suevite from core LB-08A (Ferrière et al. 2007). Reduced birefringence and isotropism are common in both quartz and feldspar. No PDFs in feldspar have been noted, and this is consistent with observations from the LB-08A core (Ferrière et al. 2007). Undulatory extinction of quartz is evident throughout the core, as is planar fracturing, but no correlation of the respective abundances of various shock level indicators with depth was detected.

Both the lithic breccias and the suevites contain similar proportions of shocked quartz. The proportion of shocked quartz grains containing 1 or 2 or more PDFs, calculated as a percentage of the total number of quartz grains analyzed per sample, varies between 3 and 12%, with the maximum occurring in the upper impactites. Rare decorated PDFs have also been observed (Fig. 12). However, not all breccia samples contain shocked quartz. In the monomict breccias and in the basement suevites very low levels of shock were observed, with only a few percent shocked grains (only quartz with planar fracturing, indicating low shock) noted. In the suevites injected into the basement sequence, no PDFs in quartz or feldspar were observed. Table 3 shows the volume percent of melt and the relative percentages of quartz grains with 1 or 2 sets of PDFs, as a function of depth, in the upper impactite sequence. Clearly, there is an increase in the number of quartz grains with PDFs with depth in the upper impactites, though this is not a linear trend. Below this, the suevites show lower levels of shock, and it is tentatively hypothesized (as the disaggregated nature of the basement samples does not allow for the full evaluation of shock levels) that the level of shock decreases with depth below the upper impactites.

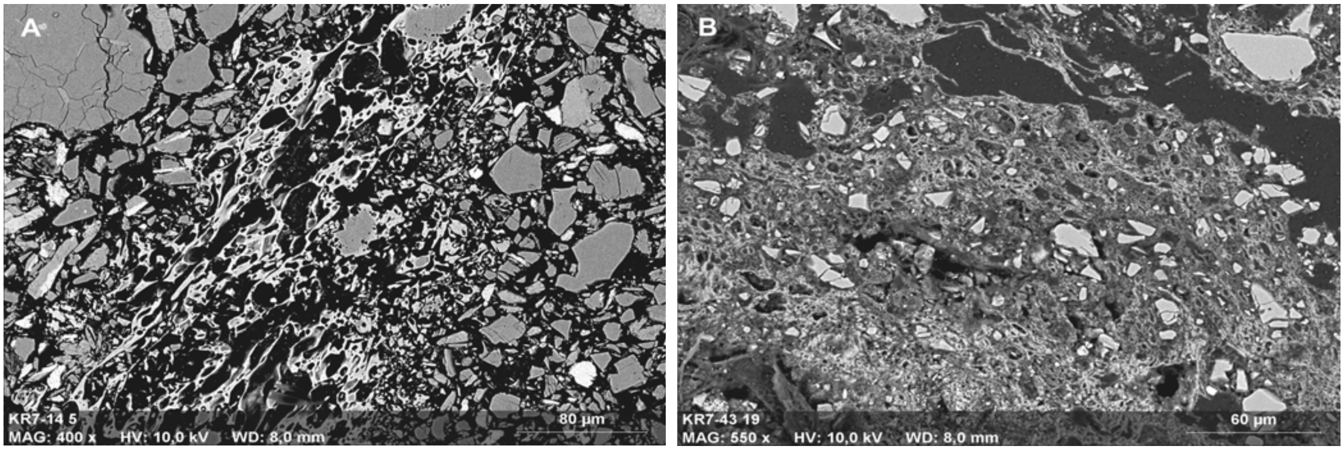


Fig. 9. Backscattered electron images of melt clasts within upper impactite suevitic breccia: the gray fragments correspond to quartz (moderately gray indicates silica-rich lithologies), with lighter white-gray and dark-gray indicating the mixed melts. a) Width of scale bar = 80 µm, sample depth = 398.44 m. b) Width of scale bar = 60 µm, sample depth = 384.84 m.

The proportion of melt fragments relative to the sample volume throughout the upper suevites generally varies between 1.5 and 7 vol%. The largest proportion found overall in the suevites is in a sample from the suevite intercalation at 430.13 m (18 vol%; see the Suevite Melt Particle Characteristics throughout the LB-07A Borehole section). Owing to the poor recovery within this lower section, and the strongly pulverized nature of the material, full shock evaluation was seriously hampered. Nevertheless, it appears that the bulk of the lower impactites is shocked to a lower degree than the clast population in the upper impactite sequence.

Rare toasted quartz (see Whitehead et al. 2002) has been noted in suevite and lithic breccia samples (from a depth of about 378 m), and in the lowermost suevite injection where all PDF occurrences are confined to toasted quartz grains. No ballen quartz has been observed in any of the samples of the LB-07A borehole.

Diaplectic quartz glass is present in impact breccia sections below a depth of ~384 m, but is noted also in a few sections of impact breccia from the uppermost part of the core (at 2% or less of total quartz examined). Below 400.06 m the volume of diaplectic quartz glass increases markedly, with a maximum of 3.7 vol%. The average amount of diaplectic quartz glass for the point-counted samples is 2.5 vol%. Several small diaplectic quartz glass clasts have been observed in the basement suevites. Feldspar diaplectic glass is generally rare, and has been noted only in three sections at 404.26, 408.72, and 411.17 m depth, out of a total of 60 thin sections checked.

Suevite Melt Particle Characteristics throughout the LB-07A Borehole

The main differences between the suevites of the LB-07A borehole are highlighted in Table 4. Melt particle abundances in the suevites of the upper impactite unit are limited to 1.5 to 7 vol% (Table 2). No variation in shape or size distribution of the melt particles was detected between the three suevitic breccia units in the upper impactite sequence. The melt particles here are generally rounded (Fig. 13), although some shard-like particles have also been found. The size of the melt particles is mostly on the order of 1 mm (longest dimension), with a few melt particles having maximum diameters of 500 µm. Melt particles are either mafic (brown-black; with flow structures, with or without vesicles) or felsic (colorless to white, aphanitic in appearance, commonly with vesiculated flow structures). The mafic particles comprise 95% of the melt particles. Clasts within the melt particles consist of round quartz grains, some with planar fractures, and are around 50 µm in diameter or smaller.

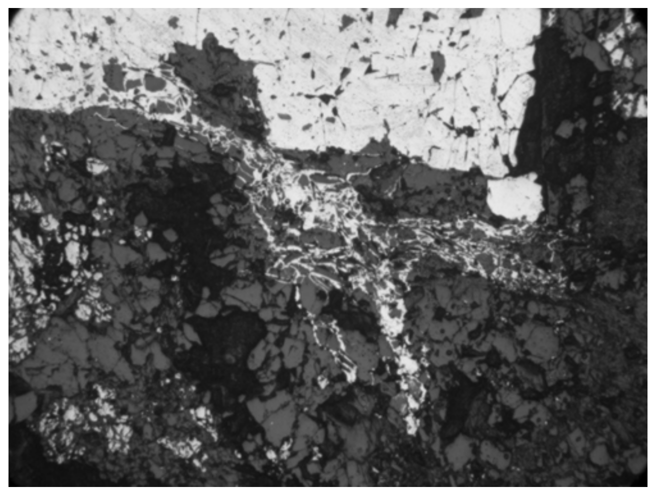


Fig. 10. A photomicrograph of a primary agglomerate of euhedral (cubic) pyrite crystals overgrown on the lower left side by a network of fine-grained, secondary, partially acicular pyrite crystals, in a sample of basement shale. Light phases = pyrite, light gray phase = carbonate material, black phase = silicate material; image width = 1.3 mm, reflected light, sample depth = 530.63 m.

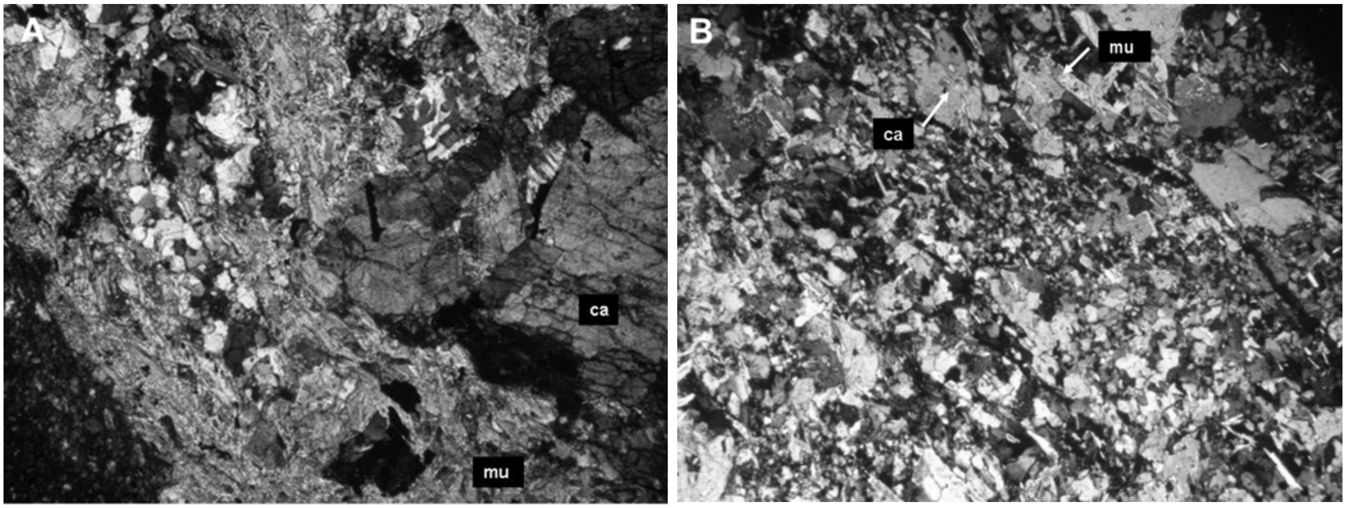


Fig. 11. Photomicrographs of granophyric intergrowth of quartz and feldspar; carbonate (ca) and muscovite (mu) indicated. a) Granophyric-textured clast in suevite in basement rocks; image width = 3 mm, CPL, sample depth = 513.90 m. b) Granophyric-textured basement rock; image width = 3 mm, CPL, depth = 487.12 m.

The upper suevite intercalation (at 430.13 to 430.33 m) in the lower impactite unit apparently contains the largest amount of melt noted so far. Two thin sections of this sample were examined: one yielding 36 vol% melt and the other yielding 18 vol% melt. The largest melt fragment yet observed in the LB-07A borehole was from the former sample and is a subrounded clast with a maximum length of 1 cm and a width of 4 mm. We believe this estimate of melt abundance is not representative, but it must be emphasized that the other thin section from this interval also contains a substantial proportion of rounded melt particles. The melt particles in the second thin section are 0.2–1.5 mm in diameter and the majority are <1 mm in diameter, and they comprise 18 vol% of the thin section. Within both thin sections many subrounded to subangular melt particles with diameters between 100 µm and 5 mm were found. The melt particles contain quartz fragments (angular to rounded), which in part contain shock fractures (in some clasts to such a great extent that the particles appeared shattered). Some quartz clasts also display undulose extinction. The clasts within the melt fragments seem to be slightly larger than those observed in melt fragments of the upper impactite suevite (100 µm versus 50 µm). The melt fragments themselves show evidence of flow (schlieren) and are commonly vesiculated. The suevite intercalation at 445 m depth has similar matrix and melt fragment characteristics, although it has a relatively smaller proportion of melt particles (5.6 vol%).

In both suevite intercalations of the basement some discrete melt particles display a vesicular texture (Figs. 13e and 13f). Core disaggregation does not allow good melt particle statistics to be compiled. Melt particles as seen in grain mount are similar in size to the lithic and mineral clasts in the suevites (0.1–0.5 mm).

DISCUSSION

Main Findings in the LB-07A Borehole

The LB-07A borehole provides a cross-section through the fill and floor of the moat surrounding the central uplift (less than 1 km from the central uplift) of this complex impact structure [lithic and suevitic breccias overlying monomict breccias that in turn overlie (here powdered and likely at least intensely fractured) the basement rocks]. The lithostratigraphy has been divided macroscopically into three units: the upper impactites, lower impactites, and the crater basement sequence. The overall abundance of different rock lithologies is as follows: 16.5% polymict lithic breccia, 23.4% suevite, 25.7% monomict lithic breccia, and in the basement section 31.2% shale and 3.2% meta-graywacke. The basement rocks comprise ~35% of the sequence, throughout which difficulties have been experienced owing to the poor state of preservation of the core and relatively lower core recovery in the lowermost parts of the core.

The upper impactites consist of alternating lithic impact breccia and suevite, with the presence of melt particles identified as the main difference between the two breccia types. The fact that no other evidence differentiates between these units allows the possibility that all the breccias may in fact be suevitic and that, due to the sample and thin section selection, rare melt particles were not always sampled. However, a number of thin sections have been examined for the lithic breccia samples, and based on our data set, we currently favor the possibility that interfingering of lithic breccias and suevites has taken place.

The lower impactites represent monomict impact breccia after either meta-graywacke or shale (where meta-graywacke >> shale). Two intercalations of suevite are

Table 3. Shock degree in quartz grains, and melt fragment size distribution, in the upper impactites (drill core LB-07A, from 334.91 m to 408.72 m).

Sample no./depth (m)	No. of grains	% lacking PDFs or PFs	% with PFs	% with PDFs		No. melt fragments			Type of breccia
				1 set	2 or > sets	<1 mm	~1 mm	>1 mm	
KR7-1/334.91	144	48.6	41.0	10.4	0	0	0	0	Lithic
KR7-35/359.33	172	90.7	2.3	5.8	1.2	3	2	2	Suevite
KR7-6/360.65	186	90.3	7.5	2.2	0	2	0	1	Suevite
KR7-7/363.20	98	92.9	2.0	4.1	1.0	9	1	0	Suevite
KR7-36/364.45	143	95.8	2.8	1.4	0	5	0	0	Suevite
KR7-8/370.34	118	92.4	2.5	4.2	0.8	0	0	0	Lithic
KR7-9/377.46	143	97.2	2.8	0	0	0	0	0	Lithic
KR7-37/379.09	137	96.4	2.2	1.5	0	4	3	0	Suevite
KR7-51/383.14	143	90.2	4.2	4.2	1.4	1	2	1	Suevite
KR7-13/393.78	133	88.0	0.75	9.8	1.5	0	0	0	Lithic
KR7-14/398.44	94	89.4	3.2	6.4	1.1	6	2	0	Suevite
KR7-40/400.06	233	94.4	2.1	2.1	1.3	4	1	1	Suevite
KR7-53/400.58	213	94.4	2.8	4.7	0	2	0	1	Suevite
KR7-15/402.73	177	91.5	3.4	4.5	0.6	5	0	0	Suevite
KR7-16/404.26	206	85.9	4.4	8.4	1.5	12	2	1	Suevite
KR7-17/405.57	181	77.9	9.9	11.0	1.1	13	10	0	Suevite
KR7-44/407.77	227	93.4	4.4	1.8	0.4	2	4	2	Suevite
KR7-20/408.32	245	90.2	2.9	6.9	0	6	1	0	Suevite
KR7-41/408.72	206	85.9	2.4	8.3	3.4	3	2	2	Suevite

Average sample size examined is 1.5 cm^2; % refers to relative percent of the total.

found, one of which contains significantly more melt fragments than the other suevite samples studied from core LB-07A. Overall, however, the possibility that selective thin sectioning could have yielded biased results by "accessing" a few larger melt fragments could mean that the melt fragment abundance is similar to the suevite of the upper impactite succession.

Lithological Composition of the LB-07A Borehole

Overall, our samples strongly support that the impact breccias were primarily derived from metasedimentary precursors, as indicated by the composition of the basement and the clast population in the impact breccias. The lithic breccias and suevites of the upper impactites, together comprising ~40% of the LB-07A borehole, yielded the following average clast compositions: 45 vol% meta-graywacke, 20 vol% shale, 12 vol% quartz (presumably also mostly derived from argillitic or graywacke metasedimentary sources), and 10 vol% phyllite are chief contributors to the clast population. Approximately 4 vol% carbonate is noted (this reflects both primary and secondary carbonate, where primary > secondary carbonate). The remaining 9 vol% of the total clast composition consists of minor amounts of phyllosilicates, feldspar, schist, and rare granite and impact breccia. The monomict breccias in the lower impactites are made up of 86 vol% meta-graywacke, 7.4 vol% phyllite and 6.6 vol% shale. Factoring the clast compositions into the overall abundance of the LB-07A, the following "average" composition of the LB-07A borehole emerges: 43.6 vol% meta-graywacke, 40.9 vol% shale, 5.9 vol% phyllite, 4.8 vol% quartz, and 1.6 vol% carbonate. Other contributors make up the remaining 3.2 vol% and include phyllosilicates, feldspar, granite, schist, and impact breccia.

These results are comparable to the findings of Ferrière et al. (2007) who noted that meta-graywacke makes up the largest component (65 vol%) of the LB-08A core. The country rock in the immediate environs of the crater is also dominated by meta-graywacke (see Koeberl and Reimold 2005) and this is also similar to the fallout suevite clast populations determined by Boamah and Koeberl (2006).

However, the pulverized basement unit is dominated by shale (over meta-graywacke), and this apparent difference may be explained by a number of factors. The target rocks for the Bosumtwi crater are heterogeneous, not only on the kilometer scale but even on the meter scale or less (as seen in this borehole; see the Regional Geology section). Also, meta-graywacke fragments may be—and most likely are—more resistant than shale to shock metamorphism and, especially, melting. Chemical analysis of melt fragment compositions, which is in progress, should provide further clarity on this issue.

The granitoid component in the breccias and in the lithostratigraphic column is insignificant. The basement sequence shows only one very thin occurrence of granophyric granitoid. From field studies outside and along the crater rim, Reimold et al. (1998) estimated the total granitoid component in the vicinity of the crater as no more than 2%, which agrees with the findings of this work.

Shock Variation

In the LB-07A borehole, the presence of planar deformation features indicates shock pressures between

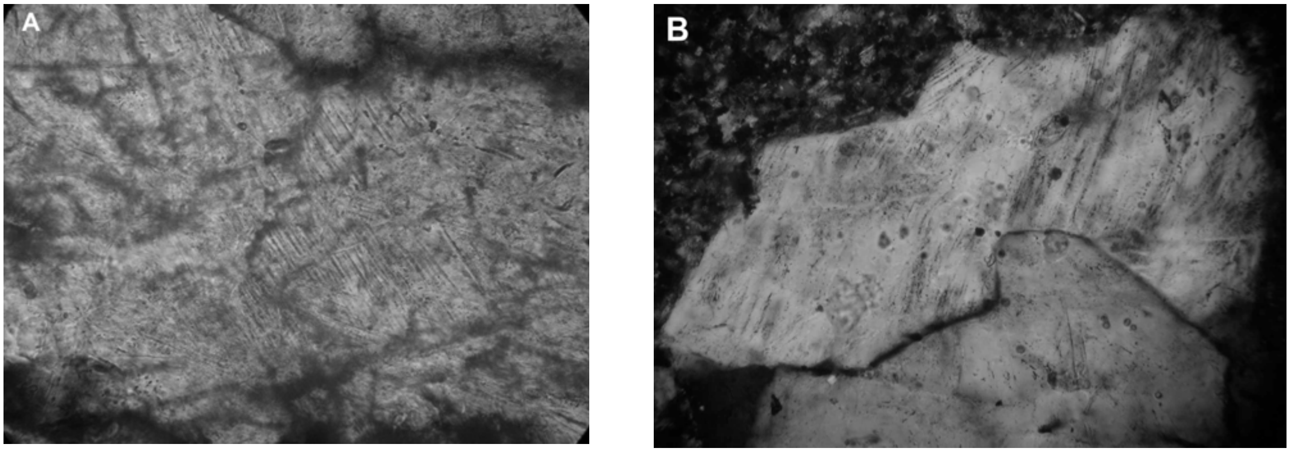


Fig. 12. Photomicrographs of planar deformation features in quartz grains. a) Lithic breccia, upper impactites (2 sets, NW-SE and WNW-ESE); image width = 0.25 mm, CPL, sample depth = 359.33 m. b) Suevite with decorated planar deformation features in quartz (2 sets, NNE-SSW and NE-SW); image width = 0.20 mm, CPL, sample depth = 408.72 m.

Table 4. Differences between suevite varieties throughout borehole LB-07A.

	Color of matrix[a]	Color of melt particles[a]	Size of lithic and mineral clasts	Mean size melt particles	Mean % total quartz grains with PDFs
Upper impactites	Gray-brown	Gray-brown or whitish	0.1 mm–2 cm	~1 mm	3–12%
Lower impactites	Moderate greenish yellow	Moderate greenish yellow	0.1–1 mm	~0.1 mm (up to 1 cm)	<3%
Basement suevite: 483 m depth	Dark gray	Gray-brown	0.1–0.5 mm	0.1–1 mm	–
Basement suevite: 513.90 m depth	Light gray	Gray-brown	0.1–0.5 mm	0.1–0.5 mm	–

[a]Colors after Munsell system.

8 GPa (1 set of PDFs per host quartz grain) and 30 GPa (multiple sets of PDFs, incipient isotropization) (e.g., Stöffler and Langenhorst 1994; Huffman and Reimold 1996) for non-porous crystalline rocks, while the presence of diaplectic quartz glasses in the suevites lower in the borehole indicates higher shock pressures of >30–45 GPa (e.g., Stöffler and Langenhorst 1994; Huffman and Reimold 1996). The presence of minor melt particles indicates limited admixture of material shocked to even higher pressures (>45 GPa; e.g., Stöffler and Langenhorst 1994; Huffman and Reimold 1996).

A slight overall increase in the degree of shock metamorphism appears to occur from the top to the bottom of the upper impactites as the proportions of diaplectic quartz glass and melt particles increase slightly (Table 2). However, in the suevite intercalations within the basement rocks, lower shock degrees are evident in terms of the relative amounts of quartz grains with sets of PDFs and overall number of shocked grains. This agrees with the observations made in the LB-08A borehole (see the Comparison with Results from the LB-08A Borehole section). That suevites from the lower parts of the core seemingly contain less severely shocked grains than the upper part could be a function of admixture of basement material during the injection of such veinlets.

Impact-Induced Hydrothermal Alteration?

On a regional scale, extensive evidence of pre-impact hydrothermal alteration has been found, which is also implicated in the genesis and modification of the regional gold mineralization in the Ashanti region (at ~2100 Myr, see Yao and Robb 2000), in which the Bosumtwi crater is situated. Yao and Robb (2000) cited as evidence for regional hydrothermal alteration quartz veins/stockworks and pervasive alteration zones throughout the country rocks, sericitization, and the widespread occurrence of secondary sulfide (pyrite and arsenopyrite) and carbonates.

Within individual lithic clasts, evidence of the pre-impact hydrothermal alteration is apparent in that cross-cutting quartz and carbonate veins are restricted to clasts. Cross-cutting quartz veins have been noted in the target rocks outside the crater by Koeberl et al. (1998). Within the LB-07A core impact breccias, sericitization of plagioclase and the development of secondary chlorite is common. Outside the crater, Koeberl et al. (1998) noted that only the Pepiakese granite contains secondary chlorite, whereas sericitization is a common feature in the granite dikes, the Pepiakese granite, and one sample of phyllite-graywacke. Sericitization of plagioclase and secondary chlorite (after biotite) have been noted by other authors in rocks outside the crater (e.g., Moon

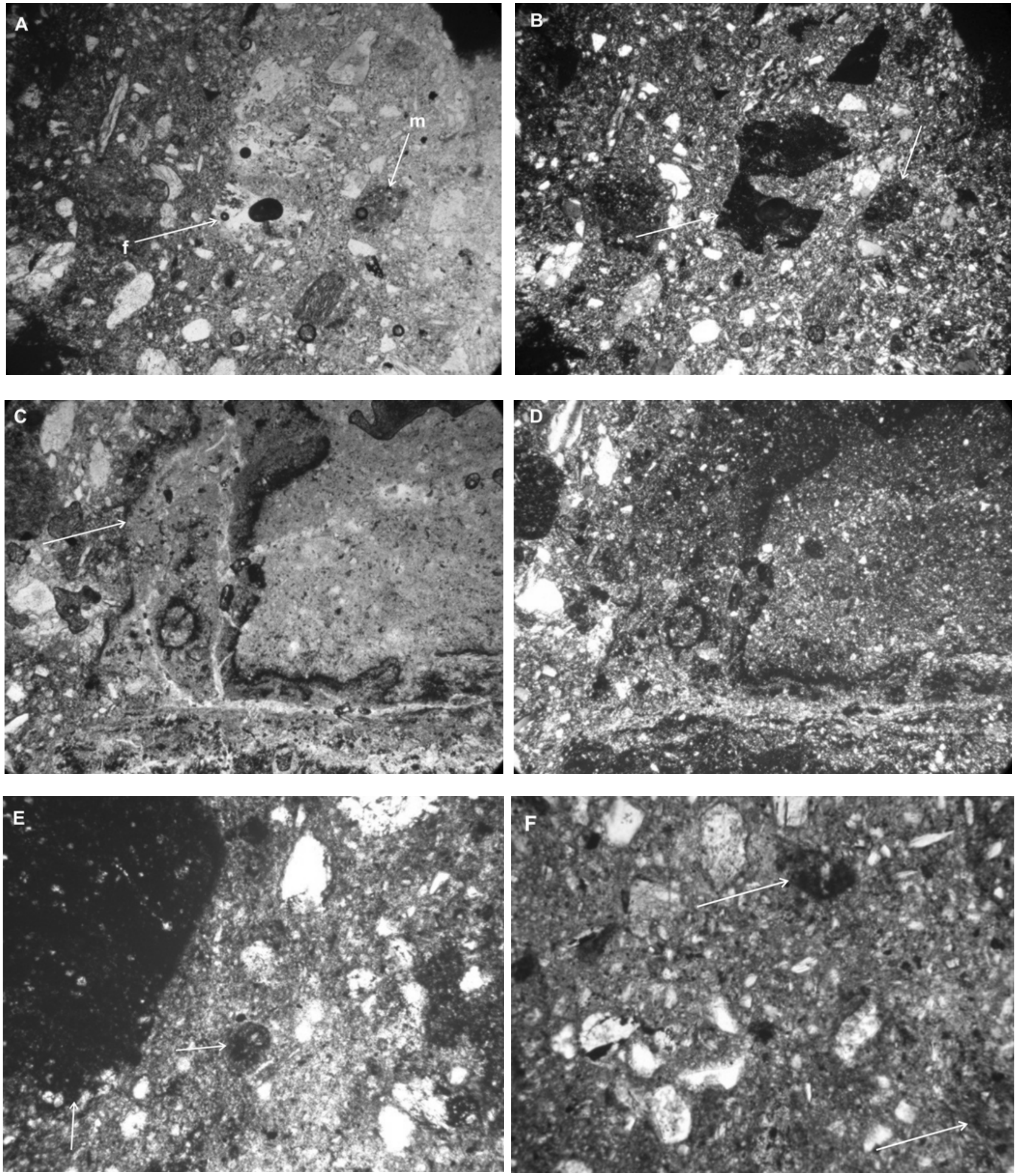


Fig. 13. Photomicrographs of various suevites from the upper and lower impactites and the basement material. a) PPL and b) CPL photomicrographs of upper impactite suevite with felsic (f) and mafic (m) melt particles; image width = 3 mm, sample depth = 364.45 m. c) PPL and d) CPL photomicrographs of melt particle in lower impactite suevite injection, with flow structures; image width = 3 mm, sample depth = 430.13 m. e) Suevite intercalation in basement with melt particle located on left hand side and center of image; image width = 1.75 mm, PPL, sample depth = 483.00 m. f) Suevite intercalation in basement; image width = 1.75 mm, PPL, sample depth = 513.90 m.

and Mason 1967) and, thus, appear to be the result of a pre-impact event. Sericitization of plagioclase is confined, on the whole, to euhedral plagioclase grains, along cleavage directions, and is observed in a number of target lithologies, as is the secondary chlorite. Secondary effects include both macroscopic and microscopic fine-grained carbonate segregations, calcite veins and pods, cross-cutting quartz veins and sulfide occurrences.

Kontny and Just (2006) showed evidence for <10 μm pyrrhotite relics within pyrite as the main carriers of the rock magnetic signature, which they suggested had formed before the impact event, together with the replacement of ilmenite by rutile. Kontny and Just (2006) found little evidence for a post-impact hydrothermal system. However, the fact that sulfides (and rutile in shale; see the Upper Impactite Unit [333.38–415.67 m] section) occur within clasts within breccias as well as around the clasts (Fig. 10) in different stratigraphic positions indicates that several mineralization events took place. It appears that the oxidation and one generation of pre-impact sulfide mineralization (euhedral crystals) was followed by a second, post-impact sulfide-forming event, with no new oxide enrichment. Both generations of sulfide mineralization formed pyrite and chalcopyrite (with pyrite > chalcopyrite). No arsenopyrite has been observed, even though this has been noted in the Birimian country rocks (Yao and Robb 2000).

Comparison with Results from the LB-08A Borehole

The LB-08A borehole was drilled into the flank of the central uplift (Fig. 2), approximately 750 m southeast of the LB-07A borehole. The lithostratigraphies are substantially different for the two boreholes (cf. Ferrière et al. 2007; Deutsch et al. 2007). The LB-07A borehole can be divided into three defined sequences (this work), whereas LB-08A consists of ~25 m of polymict lithic breccia intercalated with suevite, underlain by metasediments (Fig. 4) with suevitic breccia intercalations. Very little monomict impact breccia has been found in LB-08A (~1 m) (Ferrière et al. 2007), whereas nearly 55 m of monomict breccia have been noted in LB-07A. The total thickness of the melt-bearing suevites of the uppermost part of LB-08A (<10 m) is substantially different from LB-07A (nearly 50 m). Despite these differences, similar petrographic observations have been made for both cores (see Ferrière et al. 2006a, 2006b, 2007) in terms of overall shock petrography, although a slightly higher level of shock is seen in the LB-08A core in terms of average number of PDFs per quartz grain. Ferrière et al. (2007) found different percentages of shocked quartz grains in different rocks, and the maximum percentage of shocked quartz grains was observed in “gritty graywackes.” No gritty graywackes were observed in the LB-07A core. The observation of different shock degrees may be the result of the different response of certain lithologies to shock. The maximum percentage of shocked grains quoted for the LB-08A core is 38 vol% (Ferrière et al. 2007), which is substantially higher than values observed in the LB-07A core (12 vol%). Ferrière et al. (2007) noted a distinct decrease in shock with depth in LB-08A. In LB-07A, an apparent increase in the shock intensity with depth is seen in the upper impactites, but in the lower impactites and suevite injections in the basement rocks, relatively lower levels of shock have been observed.

Comparison with the Fallout Suevites around the Bosumtwi Crater

Petrographic and geochemical characterization of the suevites from outside the crater has been provided by Boamah and Koeberl (2002, 2003, 2006). Additionally, two samples from the northern crater rim (LB-39a,c) were point-counted (Table 2). A number of interesting differences between the fallback and the fallout suevite facies, in terms of precursor lithologies and shock deformation, have been noted. Outside the crater, a significant granite clast component (up to 3 vol%; graywacke at up to 8 vol%, metapelite at up to 5 vol%, impact melt/glass at up to 20 vol%, and matrix to 70 vol%) has been indicated by Boamah and Koeberl (2006). This was also confirmed by point-counting during the current study, in which up to 17 vol% granite fragments were counted. Similar proportions of graywacke, shale, phyllite, and schist were noted to the studies of Boamah and Koeberl (2003, 2006). Granite is not a significant component of the within-crater breccias (see Table 2) and has been found irregularly in trace amounts only (also in the LB-08A borehole; Deutsch et al. 2006; Ferrière et al. 2007). This suggests that at least parts of the transient cavity volume did not contain significant granite. A significant carbonate target component has also been identified in the suevites in LB-07A that was unknown from study of suevites and country rocks from outside the crater rim (also confirmed by this study), prior to the recovery of these ICDP cores (see Reimold et al. 1998; Koeberl et al. 1998; Boamah and Koeberl 2003, 2006).

Boamah and Koeberl (2006) concluded that the shock pressures varied from less than 5 GPa to at least 50 GPa in the suevites to the north of the crater rim. The same range of shock levels is seen within the LB-07A borehole, but proportionally there is relatively more highly shocked (>30 GPa) material in the fallout suevites than in the fallback suevites within the crater. The presence of up to 5 sets of PDFs has been noted outside the crater, and there is much quartz diaplectic glass, and ballen quartz (Boamah and Koeberl 2006). Up to 20 vol% of melt fragments is noted consistently in the fallout suevite (Boamah and Koeberl 2006), whereas in the LB-07A borehole, a highly variable and mostly significantly lower amount of melt is seen (range from 1.66 to 6.78 vol%; average of ~3.6 vol% in the upper impactite). Additionally, the average number of PDF sets per shocked quartz grain is much lower in core LB-07A.

Bosumtwi Impact Crater and Lessons from the LB-07A Borehole

The LB-07A core has provided a section through the thick crater fill of a small, well-preserved impact crater. Some new insights into the formation and characteristics of the crater were obtained from this study.

The drilling into the crater has identified a previously unknown carbonate (calcite) component of the target rocks. Granite, which is abundant in the fallout suevites, forms only a minor component of the fallback breccias and basement rocks of the LB-07A core. This emphasizes the heterogeneity of the target rocks and allows for the possibility of excavation of a granite intrusion within the predominantly metasedimentary rocks, many of which are steeply dipping. As granitoid bodies are especially known to occur in the sector around the northern half of Lake Bosumtwi, it appears possible that ejecta from this half of the crater may contain more granitic clasts than suevite accumulated preferentially from material derived from other parts of the transient cavity. This possibility has interesting implications regarding limited mixing between different sectors of the ejecta plume.

The shock pressures recorded in the fallout suevites are similar to those of the fallback suevites. However, a number of shock features, which are abundant in the fallout suevites, were not noted in the in-crater suevites (e.g., ballen quartz). Also, the respective proportions of different shock features varies between the fallback and fallout suevites, with the fallout suevites having more strongly shocked clasts (e.g., quartz with up to 5 PDF sets in fallout suevite versus quartz with 3 or fewer PDF sets in fallback suevite from core LB-07A). A similar comparison of fallout suevite and fallback suevite from core LB-08A was made by Ferrière et al. (2007). Another major contrast between the fallout and fallback suevites is the amount of melt; proportionally, more melt appears to have been ejected from the crater. This implies that most shocked, and especially highly shocked, material was ejected. The target for the Bosumtwi crater must have been porous and wet (e.g., presence of decorated PDFs) (Fig. 12b; see also discussion in Ferrière et al. 2007), and this will have affected the distribution and respective amounts of variably shocked target rock.

Shock petrographic studies from the two cores suggest lower pressures than predicted from numerical modeling studies (e.g., Artemieva et al. 2004). Artemieva et al. (2004) used the results of numerical modeling to predict the level of shock for the Bosumtwi crater. They expected to see 100–200 m of impact melt above the central uplift, as well as evidence for shock pressures in excess of 40 GPa. Deutsch (2006) noted that the shock levels actually found in rocks of both cores are lower than the predictions, and reported on shock experiments made to elucidate the reason(s) for this observation. Deutsch (2006) suggested that this discrepancy may be related to the obliquity of the impact rather than any intrinsic properties of the target materials. Further possibilities to explain the discrepancy are discussed by Artemieva (2007).

At the 14.3 Myr old Ries crater in Germany (24 km in diameter), a number of different types of breccia have been identified: monomict breccias and megablocks, Bunte breccia, fallout and crater suevites. This variety of breccias at Ries is more extensive that at Bosumtwi. It is not sure if there is an equivalent to Bunte breccia (a polymict breccia composed largely of sedimentary rock that experienced low levels of shock, located outside the crater center; see Kring 2005) at Bosumtwi (but see discussion in Koeberl and Reimold [2005] regarding a possible occurrence to the north of the crater rim). Additionally, the amount of melt in the Ries suevites is far greater than that observed at Bosumtwi, at least in the fallback suevites. The Ries fallback suevites are more complex than those in Bosumtwi core LB-07A: subdivisions based on melt and clast content, texture, and degree of remanent magnetization (see Stöffler et al. 1977; Engelhardt and Graup 1984; Kring 2005) have been described. This is in contrast to the results from the Bosumtwi crater, in which seemingly little change with depth takes place in the suevites (other than alteration). These differences are probably related to the larger diameter of the Ries crater, and even though both craters were excavated in a target that included a variety of lithologies, distinct differences in target rock properties are apparent. Such detailed studies of impact breccias, in comparison of different crater structures, have the potential to provide insight into the ejecta plume processes and controls on deposition of impact breccias inside and outside of an impact structure.

Thus, it is likely that target rock lithology and structure together with the obliquity of the impact are controlling factors in the creation of melt and shock effects. In order to constrain the mixing processes at Bosumtwi, analysis of the melt particles in the suevites and comparison to the outer-crater melt particle composition is in progress.

CONCLUSIONS

The LB-07A borehole comprises 211.7 m of meta-graywacke- and shale-dominated breccias and metasediments. The drill core has been divided into so-called upper and lower impactite sequences as well as the crater floor. Compared with numerical modeling of the crater by Artemieva et al. (2004), the paucity of melt is surprising. The petrographic signatures of lithic and suevitic breccias of the upper impactites are similar, with the exception of the presence of discrete melt particles in the suevites. Both types of polymict impact breccia are dominated by meta-graywacke clasts, followed by shale, quartz, and phyllite. The lower impactites consist of monomict breccias, mostly after meta-graywacke, and the lowermost basement floor consists of alternating altered shale and meta-graywacke, which seemingly are extensively fractured (no coherent core was recovered). Both the lower impactites and the basement rocks, which likely represent crater floor, contain several suevite injections, which differ from each other and from those of the upper impactites with respect to color, degree of shock and, to a lesser extent, clast size (Table 4).

The LB-07A impactites are dominated by meta-graywacke clasts followed by altered shales, in contrast to the pulverized basement metasediments, which are dominated by altered shales. This is clearly related to the heterogeneity of the target rocks.

A previously unknown carbonate target component has been identified in the LB-07A core. In contrast to the relative abundance of granite clasts in the fallout suevites (Boamah and Koeberl 2006), only trace amounts of granite clasts are found in the lithic breccias and basement rocks of the LB-07A core.

Shock petrographic features indicate varied but mostly low to moderate levels of shock pressure (<35 GPa) for the mineral/lithic components in suevite, with the bulk of the clastic material derived from the <15 GPa shock zone. An overall slight increase in shock pressures is inferred from the top to the bottom of the impactite sequence based on proportions of diaplectic glass. Below this level, fewer shock effects in quartz are observed, which agrees with observations made for samples from the LB-08A borehole (Ferrière et al. 2007).

Degrees of shock metamorphism in samples from the LB-07A core are lower than those in the LB-08A borehole (sited on the flank of the central uplift) and suevites outside the northern crater rim. Melt proportions are higher outside the crater rim, and this implies that much of the most heavily shocked material has been ejected from the crater. Further studies of the effects of an impact into porous, heterogeneous metasediments are required to obtain new insight into the cratering process.

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