Petrographic and shock metamorphic studies of the impact breccia section (1397–1551 m depth) of the Eyreville drill core, Chesapeake Bay impact structure, USA

Katerina Bartosova*
Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

Ludovic Ferrière
Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria, and Department of Earth Sciences, University of Western Ontario, 1151 Richmond Street, London, ON, N6A 5B7, Canada

Christian Koeberl
Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

W. Uwe Reimold
Museum für Naturkunde–Leibniz Institute at Humboldt University Berlin, Invalidenstrasse 43, 10115 Berlin, Germany

Susanne Gier
Department of Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

ABSTRACT

The moat of the 85-km-diameter and 35.3-Ma-old Chesapeake Bay impact structure (USA) was drilled at Eyreville Farm in 2005–2006 as part of an International Continental Scientific Drilling Program (ICDP)–U.S. Geological Survey (USGS) drilling project. The Eyreville drilling penetrated postimpact sediments and impactites, as well as crystalline basement-derived material, to a total depth of 1766 m. We present petrographic observations on 43 samples of suevite, impact melt rock, polymict lithic impact breccia, cataclastic gneiss, and clasts in suevite, from the impact breccia section from 1397 to 1551 m depth in the Eyreville B drill core. Suevite samples have a fine-grained clastic matrix and contain a variety of mineral and rock clasts, including sedimentary, metamorphic, and igneous lithologies.

Six subunits (U1–U6, from top to bottom) are distinguished in the impact breccia section based on abundance of different clasts, melt particles, and matrix; the boundaries between the subunits are generally gradational. Sedimentary clasts are dominant in most subunits (especially in U1, but also in U3, U4, and U6). There

INTRODUCTION

The 85-km-diameter Chesapeake Bay impact structure (Fig. 1) is ~35.3 Ma old (e.g., Poag et al., 1994, 2004; Horton and Izett, 2005; Gohn et al., 2006a). It is a large and well-preserved marine impact structure that displays a complex crater geometry (known as “inverted sombrero”; Gohn et al., 2006a). It has a deep inner crater and a small central uplift structure (Poag et al., 1999) surrounded by a shallower outer basin. The 85-km-diameter outer basin was formed during the crater modification stage. Collins and Wünnemann (2005) suggested that the diameter of the inner basin, ~40 km (Poag et al., 2002), might better represent the energy involved in the impact event. The location of the impact structure on a passive continental margin and the immediate resumption of marine deposition after impact protected the crater from subsequent erosion (Poag et al., 2004, p. 4). Today, the impact crater is buried beneath southern Chesapeake Bay, its surrounding peninsulas, and the continental shelf east of the Delmarva Peninsula (Poag et al., 1994; Poag, 1997). Previous work, based on geographic position, age, and chemical as well as isotopic data, indicates that the Chesapeake Bay impact structure is the source of the North American tektites (Koeberl et al., 1996; Deutsch and Koeberl, 2006).
Geology of the Atlantic Coastal Plain and Discovery of the Chesapeake Bay Impact Structure

The Atlantic Coastal Plain is a subsiding passive continental margin. Marine transgressions have alternated with regressions, and the succession has been modified by isostatic adjustment, Appalachian tectonics, and paleoclimatic changes (Poag, 1997). Crystalline basement rocks beneath the Virginia coastal plain include a variety of plutonic, volcanic, and metamorphic rocks that constitute distal parts of the Appalachian orogen (Thomas et al., 1989). Sedimentary deposits of the Atlantic Coastal Plain constitute a seaward-thickening wedge of poorly consolidated siliciclastic sands, silts, and clays of both marine and nonmarine origin (Poag et al., 2004, p. 47). The ages of these deposits range from Early Cretaceous to Holocene. The pre-impact sediments of the Virginia coastal plain are Early Cretaceous to early late Eocene in age, and they are 1–1.5 km thick. The following pre-impact formations are distinguished (from the oldest to the most recent): Potomac Formation, unnamed Formation, Brightseat Formation, Aquia Formation, Marlboro Clay, Nanjemoy Formation, and Piney Point Formation (Fig. 2; e.g., Poag et al., 2004, p. 49; Gohn et al., 2005). Marine sedimentation resumed immediately after the impact, and today the crater is covered by ~200–550 m of sediments (Poag et al., 2004, p. 51).

Initial evidence of an impact structure in this region came from the discovery of impact ejecta, which are part of the North American tektite strewn field. Approximate inferred locations of the impact site, based on the nature and thickness of impact ejecta at Deep Sea Drilling Project (DSDP) Site 612, were suggested by Thein (1987) and Koeberl (1989). Site 612 was drilled on the upper continental slope off New Jersey, ~330 km northeast of the center of the Chesapeake Bay impact structure (Koeberl, 1989; Koeberl et al., 1996). Poag et al. (1992) interpreted the Exmore boulder bed in southeastern Virginia to have been deposited by a tsunami-like wave generated by an impact event. The existence of the Chesapeake Bay impact structure was proposed by Poag et al. (1994) based on analyses of core samples and seismic profiles. Koeberl et al. (1996) found the first evidence of shocked minerals within the crater fill (the Exmore breccia) at the Chesapeake Bay structure and thus confirmed that the structure is of impact origin. These authors also presented chemical analyses of breccia and clast samples from the Exmore breccia and noted a similarity with the composition of North American tektites, thus providing further evidence that the Chesapeake Bay structure was the source crater of those tektites. Koeberl et al. (1996) also showed that the distribution of gravity anomalies is typical of a complex impact structure and is in good agreement with the structural interpretations derived from seismostratigraphic analyses, i.e., subcircular negative anomaly above the inner basin and a ring of positive anomalies corresponding with the peak ring (Poag et al., 2004, p. 88–89). Shah et al. (2005, this volume) collected more gravity and magnetic field data, refined the geophysical signatures of the structure, and discussed possible volume and occurrence of impact melt.

Previous Deep Drilling at the Chesapeake Bay Impact Structure and Main Observations

Impact breccias were recovered from core holes into the Chesapeake Bay impact structure already in the 1940s, although their impact origin was not suspected until 1992 (Poag et al., 1992, 2004, p. 17–39; Koeberl et al., 1996). The Exmore boulder bed was cored in 1986 in the Exmore core hole (Poag et al., 2004, p. 216).

In 2000–2002, four major core holes were drilled: North, Bayside, and National Aeronautics and Space Administration (NASA) Langley in the annular trough, and Watkins School at the outer margin of the impact structure. The Bayside core hole penetrated the full thickness of postimpact, impact-generated, and impact-modified sediments and reached the underlying

Figure 2. Stratigraphy of mainly pre-impact sedimentary formations in southeastern Virginia (modified from Poag et al., 2004).
Precambrian crystalline rocks (Horton et al., 2008). The continuously cored NASA Langley core was drilled on the York-James Peninsula in Hampton in 2000. It penetrated 236 m of Upper Eocene–Pleistocene deposits, 390 m of impact-generated deposits, and reached 9 m of underlying pale red, medium-grained Precambrian monzogranite. Three units were defined within impact-generated deposits in the NASA Langley core on the basis of lithology, sedimentary structure, clast-matrix ratio, and deformation style (Gohn et al., 2001). The lowermost so-called crater unit A typically consists of feldspathic, medium-grained to gravelly quartz sands containing minor amounts of dark-colored clay-silt clasts and quartz, quartzite, and chert pebbles in addition to the granodiorite pebbles. Crater unit B is a clast-supported sedimentary-clast breccia, and the vast majority of its material appears to have been derived from the Cretaceous Potomac Formation. The uppermost crater unit C corresponds to a different sedimentary breccia: it is matrix-supported and contains a mixture of clasts derived from the Lower Tertiary formations as well as from the Cretaceous Potomac Formation (Gohn et al., 2001). Very rare quartz grains and cataclastic crystalline clasts with planar deformation features (PDFs) were reported in the samples from the NASA Langley core by Horton and Izett (2005) and Horton et al. (2005a). No shock metamorphic features were found in the autochthonous granites cored in the NASA Langley and Bayside cores (Horton et al., 2005a).

In 2003, a deep drilling proposal was put to ICDP for a continuous core hole through the interior of the Chesapeake Bay impact structure. Subsequently, in 2004, the USGS drilled a test hole near Cape Charles. This 823-m-deep, partially cored (with a core diameter of 64 mm), Sustainable Technology Park (STP) test hole consists of 355 m of marine, Upper Eocene to Pleistocene sediments, 300 m of sedimentary-clast breccia, and 167 m of crystalline-clast breccias (largely suevitic) and cataclastic gneiss (Horton et al., 2005b; Gohn et al., 2007). According to Horton et al. (2005b), the melt particles in suevite are glassy to aphanitic, and some have flow laminations. Shapes and textures of some melt particles suggest that they were compacted while they were still hot and plastic. Multiple sets of decorated PDFs in quartz and feldspar were observed in clasts in suevite and in brecciated gneiss (Horton et al., 2005b). The suevite was found to be pervasively albited and chloritized at lower-greenschist-facies conditions. The suevite contains amygdules filled with clay minerals and carbonates (Horton et al., 2005b). A minor meteoritic component was identified by Lee et al. (2006) in impact melt rock clasts in suevite from the STP test hole using osmium isotope ratios and platinum group element analysis (for detailed discussion, see McDonald et al., this volume). Previous drilling operations at the Chesapeake Bay impact structure have been summarized in detail by Poag et al. (2004, p. 17–39) and Horton et al. (2005c).

**Eyreville Drill Core**

In 2005–2006, three cores were drilled as part of the international ICDP-USGS Chesapeake Bay impact structure drilling project at Eyreville farm, in Northampton County (Virginia). Core hole Eyreville A was cored between 125 and 941 m depths (with core diameters of 85 mm and 63.5 mm in the intervals 125.6–591.0 m and 591.0–940.9 m, respectively). Eyreville B was cored from 738 m to a final depth of 1766 m (with core diameters of 63.5 mm and 47.6 mm in the intervals 737.6–1100.9 m and 1100.9–1766.3 m, respectively). In Eyreville C, postimpact sediments were cored from the land surface to a depth of 140 m (with a core diameter of 63.5 mm; Gohn et al., 2006a, 2006b, 2006c). At Eyreville, the crater fill consists of sedimentary-clast breccia and sedimentary megablocks of the Exmore beds, a granitic and an amphibolitic megablock, gravelly sand, impact breccia, and granite/pegmatite and mica schist (Fig. 3; Gohn et al., 2006a, 2006b). The core is now stored at the USGS in Reston, Virginia. More details about the coring operations at Eyreville have been reported in Gohn et al. (2006c) and Koeberl et al. (2007). A detailed geologic column of the Eyreville drill core was established by Horton et al. (this volume, Chapter 2) for the depth interval 1766–1095 m, by Edwards et al. (this volume, Chapter 3) for the depth interval 1096–444 m, and by Edwards et al. (this volume, Chapter 4) for the postimpact sediments (depth interval 444–0 m).

The deep Eyreville drill core provides a unique opportunity to compare the Chesapeake Bay impact structure with observations reported from other impact structures formed in a shallow-marine environment, such as the Montagnais, Mjølnir, and Lockne impact structures (Dypvik and Jansa, 2003; Lindström et al., 2005, and references therein). As one of the largest craters on Earth, the Chesapeake Bay impact structure can be compared with the Chicxulub impact structure, which also formed on a continental shelf (Kring, 2005).

The impact breccia section constitutes 154 m of the Eyreville B drill core, from 1397.2 to 1551.2 m. There are several suevite units in the impact breccia section, as well as two intervals of impact melt rock in the upper part (Wittmann et al., this volume, Chapter 16) and blocks of cataclastic gneiss in the lower part of the section (Horton et al., this volume). A small suevite boulder occurs in gravelly sand between 1393.0 and 1393.4 m depth above the impactite section, and some melt particles (thought to be derived from reworked suevite) are present within the gravelly sand between 1396.4 and 1397.2 m (Horton et al., this volume). Suevite occurs also in the form of several dike breccia veins in the crystalline basement (Reimold et al., 2007).

This study is based on macroscopic observation of the Eyreville B core and optical microscopic investigation of 43 samples from the impact breccia interval. Detailed petrographic (mineral composition and modal proportions of lithic clasts) and shock metamorphic studies (shock effects in minerals; shapes, textures, and types of melt particles) were carried out to constrain conditions and processes involved in the formation of the impact breccias. Preliminary results were reported in abstracts by Bartosova et al. (2007a, 2007b, 2008).
SAMPLES AND ANALYTICAL METHODS

Forty-three samples were taken from the impact breccia section between 1399.2 m (sample CB6-093) and 1547.4 m (sample CB6-130) depth. These samples include 30 samples of suevite, three samples of impact melt rock, one polymict lithic impact breccia (CB6-128), six samples of cataclasite (CB6-119, CB6-122, CB6-123, CB6-124, CB6-129, and CB6-130), and three conglomerate clasts from suevite (CB6-112, CB6-115, and KB-6). All samples are described in detail in the Appendix.

The samples are mostly half core, with a diameter of 47.6 mm and lengths of ~100 mm. Samples were selected to encompass the variety of different lithologies occurring in the studied core interval. The spacing between the samples varies according to the lithology of the core. In relatively homogeneous parts, e.g., the cataclastic gneiss blocks, the spacing of the samples is larger (~5 m). In those sections, in which the nature of the impact breccias changes over small distances, or which are petrographically interesting (e.g., melt-rich parts), the distances between samples are smaller (~2 m). Thin sections of all samples were investigated using optical microscopy. In addition, 16 polished thin sections were prepared for electron microscopy.

Electron microscopy, including melt particle analyses by energy-dispersive spectrometry (EDX), was done with a JEOL JSM 6400 instrument at the Naturhistorisches Museum, Vienna. Energy-dispersive microchemical analysis was performed using a KEVEX SuperDry Si(Li) detector linked to a VANTAGE EDX system at 15 kV acceleration voltage and a beam current of ~1–2 nA. The standardless EDX analyses have a precision of ~3 rel% and a detection limit of ~0.2–0.5 wt% for major elements. An electron beam with a diameter of ~2 μm was used for identification of minerals. For determining the composition of the melt particles, a defocused beam was used, and larger areas (~50 × 50 μm to 200 × 200 μm) were analyzed.

Modal analysis by point counting was performed on 28 suevite samples to estimate the proportions of the different clast types (i.e., mineral and rock clasts); 155 points per thin section were counted on average. The whole area of a thin section was investigated with 2 mm spacing between each point counted; mineral grains (single grains in matrix) and rock clasts (without distinguishing individual minerals within rock clasts), as well as melt particles, were characterized; grains/clasts of less than 0.2 mm apparent diameter were counted as matrix.

Systematic analysis of the properties of quartz grains in suevite was carried out to determine the following properties: proportion of unshocked and shocked grains, i.e., grains with planar fractures (PFs) and/or with PDFs; number of sets of PDFs per grain; and percentage of grains with “toasted” appearance (brownish cloudy appearance; see, e.g., Short and Gold, 1996; Whitehead et al., 2002; Ferrière et al., 2009a). For this statistical analysis, information for single quartz grains enclosed in matrix and grains occurring within different rock clasts was recorded separately. About 360 quartz grains were analyzed per thin section, on average.

The mineral compositions of seven bulk samples were determined by X-ray diffraction (XRD) at the University of Vienna. This suite included one mafic cataclasite and six suevites, from which clasts larger than ~1.5 cm had been extracted. Diffraction data were collected with a Philips diffractometer (PW 3710, goniometer PW 1820), CuKα radiation (45 kV, 35 mA), step size of 0.02 degrees, and a counting time of 1 s per step. Minerals were identified using the Joint Committee on Powder Diffraction Standards database (JCPDS, 1980). The samples were milled to a fine powder, pressed into the sample holder, and analyzed. Two phyllosilicate-rich samples were also analyzed after treatment with ethylene.
glycol to detect expandable clay minerals (see Moore and Reynolds [1997] for more information on the technique).

The focused ion beam (FIB) technique was used for the preparation of a transmission electron microscope (TEM) foil of a quartz grain with PDFs from suevite sample CB6-097 (depth = 1412.8 m) at the GeoForschungsZentrum (GFZ) Potsdam (Germany). A FIB foil of 15 × 7 µm extent and ~100–200 nm thickness was prepared following the method presented by Wirth (2004). TEM studies were performed using a 200 kV Philips CM 20 STEM equipped with a TRACOR Northern energy-dispersive X-ray detector at the Museum of Natural History, Humboldt University, Berlin (Germany). Conventional bright-field imaging techniques were used to observe and characterize microstructural characteristics of PDFs.

In addition, a Renishaw RM1000 confocal edge filter-based microRaman spectrometer with a 20 mW, 632.8 nm He-Ne laser excitation system, and a thermoelectrically cooled charge-coupled device array detector was used at the Institute of Mineralogy and Crystallography, University of Vienna, for identification of some mineral phases.

RESULTS

The impact breccia section, ~154 m thick, consists of ~110 m of suevite and lithic impact breccia and 44 m of cataclastic gneiss (Fig. 3). Detailed petrographic descriptions of the samples are given in the Appendix.

Suevite and Impact Melt Rock

According to Stöffler and Grieve (2007, p. 198), suevite is “a polymict impact breccia with particulate matrix containing lithic and mineral clasts in all stages of shock metamorphism including cogenetic impact melt particles which are in a glassy or crystallised state.” Impact melt rock is “a crystalline, semihyaline or hyaline rock solidified from impact melt and containing variable amounts of clastic debris of different degree of shock metamorphism” (Stöffler and Grieve, 2007, p. 162). In the Eyreville B core, suevite occurs in the 1397.2–1551.2 m depth interval (Fig. 4; Horton et al., this volume). At the top of the impact breccia section, the suevite is melt-rich and grades locally into impact melt rock (Wittmann et al., 2008, this volume, Chapters 16 and 17). The term “melt-rich suevite” is used here when melt constitutes more than ~20 vol% of the rock. In the lower parts of the section, lithic clasts in the suevite become more abundant and larger, and the suevite contains blocks of cataclastically deformed gneiss/schist. Most suevite samples have a grayish, fine-grained, clastic matrix that contains a variety of rock and mineral clasts, melt particles, and secondary minerals (e.g., phyllosilicates and calcite).

Cataclastic Gneiss

Cataclasite is “a fault rock that is cohesive with a poorly developed or absent schistosity, or that is incohesive, charac-

terized by generally angular porphyroclasts and lithic fragments in a finer-grained matrix of similar composition” (Brodie et al., 2007, p. 138). Cataclastic gneiss occurs mostly in the lower part of the studied interval (below 1474 m), as large, monomict, brecciated crystalline basement-derived blocks incorporated into the suevite (Fig. 4). The cataclasite blocks consist of millimeter- to centimeter-sized clasts of fine-grained gneiss or more rarely schist, with some flour-like groundmass of the same material. The main minerals recognized microscopically are quartz, chlorite, muscovite, biotite, K-feldspar, and plagioclase. Additionally, carbonate occurs as irregular patches or filling in fractures. Opaque minerals and other accessories (e.g., sphene, epidote, garnet, and tourmaline) were also noted. Cataclastic gneiss shows both PFs and PDFs in quartz grains, and some of the quartz grains display a toasted appearance. In the cataclasite samples from the lower part of the core (below ~1530 m), shock metamorphic effects are less abundant, and in sample CB6-129 (depth = 1542.7 m), neither PFs nor PDFs were detected. In one portion of the core (1514.5–1521.5 m), the cataclasite appears dark greenish and contains abundant chlorite and amphibole (sample CB6-123; depth = 1514.3 m). The upper part of the impact breccia section (above 1474 m) contains only one larger (~1.5 m) boulder of cataclastic gneiss at ~1433 m depth (Fig. 4).

Stratigraphy of the Impactite Section and Petrographic Description of the Subunits

The detailed stratigraphic column of the impact breccia section presented by Horton et al. (this volume) is shown in Figure 4, where short macroscopic descriptions of the core are also added. Based on macroscopic and microscopic observations of our samples, in addition to our macroscopic study of the drill core, we recognized six subunits of suevite (Fig. 4; Table 1). Our subdivision is not in conflict with that by Horton et al. (this volume), but it is somewhat different, because we have focused our subdivision on distinguishing different types of suevite based on differences in proportions and types of melt particles, clasts, and matrix present. Transitions between subunits are gradational. For detailed information on the different types of melt particles distinguished in suevite and used in the distinction of subunits, see the section “Melt Particles and Melt Matrix” and Table 2.

Figure 4. Geologic column of the impact breccia section from the Eyreville B drill core. The geologic column is modified from Horton et al. (this volume). Positions of the samples for the present study are indicated by lines on the left side; sections U1–U6 are the subunits of suevite identified during our investigations (Table 1). The detailed core descriptions on the right are based mostly on macroscopic observations, and only details based on microscopic studies were added.
<table>
<thead>
<tr>
<th>Samples</th>
<th>Subunits</th>
<th>Geologic column</th>
<th>Core description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB6-093</td>
<td>KB-2</td>
<td>SU Upper suevite</td>
<td>suevite with gray matrix and abundant small clasts (dark-gray fine-grained sedimentary clasts, sandstone, schist, and dark olive green altered shale)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M2 Clast-rich impact melt rock</td>
<td>abundant melt particles, elongated and amoeboid, dark olive green to 6 cm below 1398.7 m smaller yellowish melt particles, &lt;3 cm, rare dark pinkish melt particles (~4 cm) below 1401.8 m the rock is partly melted, has a melt matrix, and shows flow structures mostly sedimentary, but also large (up to 9 cm) clasts of crystalline basement, often fractured abundant gray-pinkish melt at ~1405.1 m large vesicles and fractures with yellowish coating, pyrite and zeolites clasts of crystalline basement and shale clasts are most common</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S3 Suevite</td>
<td>melt-rich suevite, angular to subrounded clasts, both crystalline and sedimentary (schist, shale), a bit smaller than in the parts above abundant small yellowish melt particles, at ~1411.2 m the suevite has yellowish color below 1411.2 m some large clasts up to 15 cm (schist, shale, conglomerate), but small clasts are very abundant as well melt particles elongated, yellowish or olive green, up to 5 cm at ~1414.3 m and 6 cm at ~1422.2 m below 1422.8 m melt particles become smaller, below 1425 m crystalline clasts become more abundant at ~1428 m the suevite is altered, some vesicles at ~1431.3 m very porous suevite, altered, melt particles not so abundant small yellowish melt particles, at ~1411.2 m the suevite has yellowish color below 1411.2 m some large clasts up to 15 cm (schist, shale, conglomerate), but small clasts are very abundant as well melt particles elongated, yellowish or olive green, up to 5 cm at ~1414.3 m and 6 cm at ~1422.2 m below 1422.8 m melt particles become smaller, below 1425 m crystalline clasts become more abundant at ~1428 m the suevite is altered, some vesicles at ~1431.3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2 Cataclastic gneiss</td>
<td>light-gray monomict cataclastic gneiss light-gray suevite, clast-rich and porous, with melt particles up to 1.5 cm some sedimentary clasts, but crystalline clasts are dominant below 1438.4 m some larger sedimentary clasts (conglomerate, shale) up to 6 cm and crystalline clasts with pre-impact veins, rare melt particles, more abundant melt particles at ~1441.4 m below 1441 m the suevite is very porous and rich in mostly crystalline clasts, cavities after altered melt at ~1442 m shale clasts up to 6 cm and some clay particles at ~1443.5 m crystalline clasts still prevail, clasts up to 10 cm, but also small clasts 1-5 mm abundant below 1448.4 m the suevite starts to be melt-rich and greenish below 1449.9 m all the rock is partly melted at ~1450.8 m some big vesicles filled with quartz at ~1451.4 m pinkish melt particles, below 1451.4 m sedimentary clasts are dominant clast-rich suevite, granite clasts, larger clasts of shale up to 10 cm and schist up to 40 cm at ~1455.2 m sedimentary clasts and rare altered crystalline clasts, below ~1455.2 m conglomerate clasts up to 10 cm occur below 1456.9 m abundant large clasts of siltstone, sandstone, and conglomerate up to 15 cm diameter some crystalline clasts, but sedimentary clasts are dominant down to 1474.1 m below 1471.3 m a lot of clay, fine-grained sedimentary clasts, clasts of schist up to 20 cm, and abundant shale clasts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1 Cataclastic gneiss</td>
<td>gray cataclastic gneiss, fractures filled with white mineral at ~1475.7 m some minor parts of polymict breccia very porous suevite, altered, melt particles not so abundant, mostly very altered at ~1484.4 m some sedimentary clasts, but gneiss clasts are dominant gray cataclastic gneiss with some quartz veins sedimentary clast occur at ~1491.4 m, 1495.0 m and rarely at ~1501.1 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P4 Suevite/polymict lithic impact breccia</td>
<td>lithic clast-rich suevite with fine-grained sedimentary clasts, crystalline clasts, large clay clasts, and arkose clasts up to 10 cm in size below 1506.3 m melt particles, larger siltstone clasts, and crystalline clasts sedimentary clasts very abundant from 1508.7 m to 1510.8 m below 1510.8 m cataclastic gneiss is dominant; contains some secondary quartz and pyrite sedimentary clasts abundant again below 1512.0 m cataclastic gneiss, very altered, secondary pyrite in fractures below 1514.5 m the color changes to dark green with some white veins lithic clast-rich suevite, with abundant sedimentary clasts and clay abundant larger clasts up to 15 cm include conglomerate, sandstone, siltstone, graphitic shale, granite, and rare schist some melt particles at ~1528.6 m below 1528.6 m the suevite is clast rich with mostly sedimentary clasts large meter-size boulders of cataclastic gneiss occur at ~1530.9 m and at ~1534.7 m below 1534.7 m clast-rich suevite, sedimentary clasts prevail rare melt particles recognized only microscopically in the lower parts of this unit cataclastic gneiss/chert with alteration in fractures below 1538.5 m very rich in mica, some quartz-rich parts and pyrite grains graphite-rich cataclasite with small parts of polymict breccia cataclastic gneiss/chert, folded, not very fractured polymict impact breccia with graphitic matrix, sedimentary and crystalline clasts (schist, sandstone) no melt particles recognized macroscopically, but reported by W.U. Reimold, alternation with cataclastic schist</td>
</tr>
</tbody>
</table>
Subunit 1 (U1, 1397.2–1430 m)

Subunit U1 is the most homogeneous subunit with respect to smallest clast sizes. Clasts are smaller in size and the proportion of matrix is larger than in the other subunits. Sedimentary clasts (e.g., siltstone, sandstone, and conglomerate) are dominant, but clasts of schist/gneiss are also present. Large melt particles (up to 5 cm) occur. This suevite is melt-rich and grades into impact melt rock in the interval 1402.2–1407.5 m, where melt with micro-lites (type 4) is abundant. Clear glass particles (unaltered glass; type 1) are common and are typical of this subunit, but the occurrence of clear glass is much more limited in lower subunits. A sample from subunit U1 (CB6-097; depth = 1412.8 m) with small clasts and abundant particles of melt type 1 is shown in Figure 5A.

Subunit 2 (U2, 1430–1448.4 m)

This suevite unit is clast-rich, and the clasts mostly originate from crystalline basement lithologies (gneiss, schist, and granite). Rare sedimentary clasts (e.g., siltstone, shale, and conglomerate) occur. Melt particles (mostly of type 2) are rare and constitute less than 3 vol% in the samples from this subunit. PDFs in quartz grains from polycrystalline quartz clasts and kink-banding in muscovite were observed in samples of this subunit. A sample from subunit U2 (CB6-103; depth = 1440.0 m) with abundant crystalline clasts and rare melt particles is shown in Figure 5B.

Subunit 3 (U3, 1448.4–1457 m)

Subunit U3 consists of melt-rich suevite and contains a thin interval of impact melt rock between 1450.2 and 1451.2 m; the contact with the suevite is gradational. Clasts are difficult to resolve due to partial melting. There are abundant sedimentary clasts (e.g., siltstone, mudstone, sandstone, graywacke) and some crystalline clasts (e.g., schist and granite). At ~1455 m depth, there are abundant larger clasts, ~10 cm in size (shale, conglomerate, schist/gneiss). Quartz grains show abundant PFs and PDFs, and ballen quartz also occurs. Melt particles of types 3 and 5 are the most common ones in this unit. A suevite from subunit U3 with abundant melt particles and sedimentary clasts (CB6-109; depth = 1452.3 m) is presented in Figure 5C. A sample transitional between suevite and impact melt rock (CB6-108; depth = 1451.0 m) is shown in Figure 5D.

Subunit 4 (U4, 1457–1474.1 m)

Suevite in subunit U4 contains abundant melt particles, but the proportion of melt is lower and the proportion of matrix is higher than in subunit U3 above (Fig. 6). There are various types of lithic clasts (e.g., siltstone, sandstone, conglomerate, and...
<table>
<thead>
<tr>
<th>Type</th>
<th>Color*</th>
<th>Shape</th>
<th>Texture, vesicles, inclusions, grains</th>
<th>Alteration</th>
<th>Interval of most abundant occurrence† (m)</th>
<th>Interval of occurrence† (m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear glass</td>
<td>Mostly light brown, rarely colorless or greenish</td>
<td>Amoeboid, &quot;flame&quot;-shaped, many are shard-like, with sharp contacts with the matrix</td>
<td>Many have darker brown schlieren, rarely undigested grains or vesicles occur</td>
<td>Fresh, can be partly altered, interestingly, some particles are altered in the middle of the particle</td>
<td>1412.8–1421.7 (CB6-097:CB6-099)</td>
<td>1399.2–1508.5 (CB6-093:CB6-109)</td>
<td>Shapes suggest solidification before incorporation</td>
</tr>
<tr>
<td>Altered melt</td>
<td>Brown, beige</td>
<td>Oval to amoeboid</td>
<td>Commonly fluidal texture, many cracks, contains undigested grains (as quartz)</td>
<td>Altered to clay minerals (e.g., smectite), commonly parts removed during thin-section preparation</td>
<td>1399.2–1409.3 (CB6-093:CB6-096)</td>
<td>1399.2–1508.5 (CB6-093:CB6-121)</td>
<td>Most abundant melt type</td>
</tr>
<tr>
<td>Recrystallized silica melt</td>
<td>Colorless, some show brownish patches</td>
<td>Amoeboid, some preserve shapes of the clasts, globules</td>
<td>Some recrystallized into cherty texture, in melt-rich intervals can be recrystallized to ballen quartz</td>
<td>Some parts altered, brownish</td>
<td>1402.9–1405.7 (KB-2:KB-4)</td>
<td>1399.7–1452.3 (CB6-094:CB6-109)</td>
<td>Probably recrystallized clasts of quartz and quartz-rich rocks</td>
</tr>
<tr>
<td>Melt with microlites</td>
<td>Brownish to dark gray</td>
<td>Irregular shapes, forms matrix in impact melt rock intervals or rare single particles</td>
<td>Laths of feldspars and/or pyroxenes, interstitial or microporphyritic texture</td>
<td>Fresh or slightly altered</td>
<td>1402.9–1405.7 (KB-2:KB-4)</td>
<td>1422.9–1455.2 (KB-2:CB6-110)</td>
<td>In some cases, clasts of impact melt and clasts of dolerite are difficult to distinguish from each other</td>
</tr>
<tr>
<td>Dark-brown melt</td>
<td>Dark brown to black</td>
<td>Oval to amoeboid</td>
<td>Commonly contains undigested grains, mostly quartz grains, some isotropic</td>
<td>Altered, commonly parts removed during thin-section preparation</td>
<td>1451.01 (CB6-108)</td>
<td>1443.65–1535.40 (CB6-104:CB6-127)</td>
<td>Probably melt of carbon-rich shale or other fine-grained sediment</td>
</tr>
</tbody>
</table>

*Color in plane-polarized light using optical microscope.
†In our samples.
Figure 5. Macrophotographs of samples from the impact breccia section from the Eyreville B drill core, Chesapeake Bay impact structure. (A) Melt-rich suevite sample of subunit U1 with abundant small yellowish melt particles (M—melt type 1) and small fine-grained sedimentary clasts (e.g., S—siltstone) and crystalline clasts (e.g., G—granite; sample CB6-097; depth = 1412.8 m). (B) Suevite sample of subunit U2 with large, mostly crystalline, clasts (e.g., G—granite) and rare melt particles (e.g., M—elongated greenish-gray melt particle; sample CB6-103; depth = 1440.0 m). (C) Suevite sample of subunit U3 with abundant melt particles and sedimentary clasts (e.g., M—melt particles, F—fine-grained sedimentary clasts, such as siltstone and mudstone; sample CB6-109; depth = 1452.3 m). (D) Sample of subunit U3, transitional between suevite and impact melt rock with local melt matrix (e.g., areas marked with arrows), but also with some clastic matrix. All clasts are deformed and partly melted; thus, it is difficult to resolve their nature (sample CB6-108; depth = 1451.0 m). (E) Suevite sample from subunit U4 with large, mostly sedimentary clasts (e.g., GW—large clast of graywacke, F—clasts of fine-grained sediments [siltstone, mudstone]) and relatively abundant melt particles (e.g., M—altered melt particle; sample CB6-114; depth = 1467.4 m). (F) Suevite from subunit U5 with small, mostly crystalline (GS—gneiss), and rare fine-grained sedimentary (F), clasts. The suevite is very porous; some vesicles are filled with secondary quartz (Q; sample CB6-117; depth = 1481.7 m). (G) Suevite sample from subunit U6 with large, mostly sedimentary clasts (e.g., S—large white clast of sandstone, F—small gray fine-grained sedimentary clast) and rare melt particles (e.g., M—altered melt particle; sample CB6-126; depth = 1529.3 m). (H) Sample of cataclastic gneiss (sample CB6-124; depth = 1516.2 m). An intense fracture network is developed, visible as light lines in the picture. The NE-SW lines in the left part of the photograph are only saw cuts.
Petrographic and shock metamorphic studies of the Eyreville drill core

The color of the suevite matrix varies from light to dark gray throughout the impact breccia section. The matrix is mostly fragmental; the suevite grades into impact melt rock with a melt matrix only in two intervals (1402.0–1407.5 m and 1450.2–1451.2 m; Fig. 4). In the lower impact melt rock interval, the melt rock contains microlites of plagioclase (sample CB6-108; depth = 1451.0 m). In the upper impact melt rock interval, tiny pyroxene microlites occur in the melt matrix; (e.g., sample KB-2; depth = 1402.9 m). The proportion of matrix in the suevite is, on average, ~34 vol% (based on our modal point counting). Matrix is most abundant in the upper part (maximum value of 67 vol% observed in sample CB6-094, depth = 1399.7 m; Table 3), but no simple trend was observed.

**Figure 6. Bar diagram showing the proportions of (in each horizontal bar from left to right) matrix, crystalline clasts, sedimentary clasts, and melt (the rest being mineral clasts and unidentifiable lithic clasts) in 28 suevite samples from Eyreville B drill core (based on modal point counting; see also Table 3). In the right part, stratigraphic columns are shown for comparison: left column—subunits (this study), right column—geologic column from Horton et al. (this volume; see Fig. 4 for general information and more details).**
<table>
<thead>
<tr>
<th>Sample:</th>
<th>CB6-093</th>
<th>CB6-094</th>
<th>CB6-095</th>
<th>CB6-096</th>
<th>CB6-097</th>
<th>CB6-098</th>
<th>CB6-099</th>
<th>CB6-100</th>
<th>CB6-101</th>
<th>CB6-102</th>
<th>CB6-103</th>
<th>CB6-104</th>
<th>CB6-105</th>
<th>CB6-106</th>
<th>CB6-107</th>
<th>CB6-108</th>
<th>CB6-109</th>
<th>CB6-110</th>
<th>CB6-111</th>
<th>CB6-112</th>
<th>CB6-113</th>
<th>CB6-114</th>
<th>CB6-115</th>
<th>CB6-116</th>
<th>CB6-117</th>
<th>CB6-118</th>
<th>CB6-119</th>
<th>CB6-120</th>
<th>CB6-121</th>
<th>CB6-122</th>
<th>CB6-123</th>
<th>CB6-124</th>
<th>CB6-125</th>
<th>CB6-126</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m):</td>
<td>1399.2</td>
<td>1399.7</td>
<td>1401.3</td>
<td>1409.3</td>
<td>1412.8</td>
<td>1418.8</td>
<td>1421.7</td>
<td>1427.0</td>
<td>1431.1</td>
<td>1436.6</td>
<td>1440.0</td>
<td>1443.7</td>
<td>1445.8</td>
<td>1447.0</td>
<td>1449.8</td>
<td>1451.0</td>
<td>1452.3</td>
<td>1455.2</td>
<td>1458.2</td>
<td>1464.0</td>
<td>1467.4</td>
<td>1473.5</td>
<td>1480.8</td>
<td>1481.7</td>
<td>1484.1</td>
<td>1504.3</td>
<td>1508.5</td>
<td>1529.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53.4</td>
<td>66.7</td>
<td>45.7</td>
<td>39.4</td>
<td>48.1</td>
<td>33.9</td>
<td>32.0</td>
<td>41.5</td>
<td>42.9</td>
<td>25.8</td>
<td>27.0</td>
<td>32.4</td>
<td>54.9</td>
<td>44.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral clasts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz clasts</td>
<td>2.3</td>
<td>3.2</td>
<td>3.9</td>
<td>1.7</td>
<td>2.2</td>
<td>1.1</td>
<td>2.3</td>
<td>n.d.*</td>
<td>1.8</td>
<td>1.5</td>
<td>9.0</td>
<td>0.7</td>
<td>2.0</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other mineral clasts</td>
<td>0.5</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.6</td>
<td>n.d.</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
<td>1.0</td>
<td>0.9</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt particles</td>
<td>20.4</td>
<td>7.7</td>
<td>n.d.</td>
<td>12.0</td>
<td>14.6</td>
<td>31.7</td>
<td>17.4</td>
<td>5.6</td>
<td>0.6</td>
<td>1.0</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partially melted clasts</td>
<td>2.4</td>
<td>3.8</td>
<td>6.2</td>
<td>9.1</td>
<td>2.7</td>
<td>2.2</td>
<td>2.3</td>
<td>1.4</td>
<td>n.d.</td>
<td>0.5</td>
<td>1.8</td>
<td>0.7</td>
<td>2.9</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithic clasts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schist/gneiss</td>
<td>0.3</td>
<td>n.d.</td>
<td>1.6</td>
<td>n.d.</td>
<td>0.5</td>
<td>2.2</td>
<td>12.2</td>
<td>6.3</td>
<td>4.7</td>
<td>12.4</td>
<td>0.9</td>
<td>10.8</td>
<td>n.d.</td>
<td>6.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phyllite</td>
<td>0.3</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>6.5</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.0</td>
<td>1.8</td>
<td>0.7</td>
<td>5.9</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other crystalline clasts</td>
<td>1.0</td>
<td>5.1</td>
<td>5.4</td>
<td>0.6</td>
<td>2.2</td>
<td>n.d.</td>
<td>7.0</td>
<td>35.2</td>
<td>40.0</td>
<td>24.7</td>
<td>49.5</td>
<td>38.8</td>
<td>2.9</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine-grained sediments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt particles</td>
<td>5.7</td>
<td>7.7</td>
<td>3.1</td>
<td>4.6</td>
<td>2.2</td>
<td>1.6</td>
<td>11.0</td>
<td>0.7</td>
<td>0.6</td>
<td>2.6</td>
<td>n.d.</td>
<td>0.7</td>
<td>3.9</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partially melted clasts</td>
<td>2.6</td>
<td>2.6</td>
<td>1.6</td>
<td>1.1</td>
<td>5.4</td>
<td>2.2</td>
<td>9.3</td>
<td>n.d.</td>
<td>4.1</td>
<td>n.d.</td>
<td>1.8</td>
<td>1.4</td>
<td>2.9</td>
<td>35.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>2.6</td>
<td>1.7</td>
<td>17.1</td>
<td>4.9</td>
<td>21.5</td>
<td>0.6</td>
<td>0.7</td>
<td>n.d.</td>
<td>0.5</td>
<td>2.7</td>
<td>n.d.</td>
<td>20.6</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other sedimentary</td>
<td>1.5</td>
<td>n.d.</td>
<td>32.6</td>
<td>2.3</td>
<td>1.1</td>
<td>0.5</td>
<td>1.2</td>
<td>3.5</td>
<td>1.2</td>
<td>0.5</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polycrystalline quartz</td>
<td>2.3</td>
<td>n.d.</td>
<td>1.1</td>
<td>4.3</td>
<td>1.6</td>
<td>2.9</td>
<td>n.d.</td>
<td>2.9</td>
<td>1.5</td>
<td>3.6</td>
<td>12.9</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other/unidentified</td>
<td>1.3</td>
<td>0.6</td>
<td>n.d.</td>
<td>1.7</td>
<td>3.8</td>
<td>1.6</td>
<td>1.2</td>
<td>1.4</td>
<td>0.6</td>
<td>26.8</td>
<td>0.9</td>
<td>0.7</td>
<td>3.9</td>
<td>n.d.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Note: Clasts and grains smaller than 0.2 mm were counted as matrix. Totals are 100 vol%.
*Not detected.
with regard to matrix abundance with depth (Fig. 6). Matrix consists mainly of mineral and rock clasts similar to the larger clasts (abundant quartz and mica).

**Mineral Composition**

Mineral clasts include (in order of estimated decreasing abundance) quartz, K-feldspar, plagioclase, muscovite, biotite, chlorite, and opaque minerals (mostly pyrite). Accessory minerals, present either as single grains in matrix or within rock clasts, include epidote (frequently observed in graywacke clasts), zircon, garnet (in crystalline clasts), apatite, and tourmaline. Calcite rarely forms patches in matrix and fills cracks in the suevite. Calcite is more common in lithic clasts, mostly filling fractures. Some amygdules in melt-rich samples are abundant near the top of the impact breccia section, between ~1430 and 1448.4 m (subunit U2), the melt particles are rare and make up less than 3 vol% (i.e., in samples CB6-101 to CB6-112, CB6-125, and KB-6; depth = 1459.2 m, 1522.7 m, and 1468.7 m, respectively). The crystalline-clast population includes gneiss and schist (~6 vol%); the gneiss clasts have similar lithology to that of the cataclastic gneiss blocks and boulders that occur in the impact breccia section. In addition, the crystalline-clast population includes granite and pegmatite clasts. Clasts of dolerite are extremely rare and somewhat difficult to distinguish from impact melt with microlites.

**Lithic Clast Populations**

Lithic fragments include sedimentary (siltstone, mudstone, shale, sandstone, graywacke, and conglomerate), metamorphic (schist, phyllite, gneiss, and quartzite), and igneous (granite, pegmatite, and dolerite) lithologies. Clasts are angular to sub-rounded, and sizes range from less than a millimeter, through centimeter sizes, to meter-sized cataclastic blocks occurring especially in the bottom part of the impact breccia section. The proportions of the different types of clasts and of melt particles in the suevite vary from 0.2 to ~10 mm, as estimated from point counting analysis, are reported in Table 3 and Figure 6. On average, sedimentary clasts are slightly more abundant (~26 vol%) than crystalline clasts (~18 vol%). Within the sedimentary clast population, fine-grained sediments, such as siltstone and mudstone, are most abundant, representing ~13 vol%, on average; graywacke (~4 vol%, on average) and sandstone (~5 vol%, on average) are also represented. Conglomerate clasts in suevite are comparatively rarer at thin-section scale, but they occur as relatively large clasts in the core (e.g., samples CB6-112, CB6-125, and KB-6; depth = 1459.2 m, 1522.7 m, and 1468.7 m, respectively). The crystalline-clast population includes gneiss and schist (~6 vol%); the gneiss clasts have similar lithology to that of the cataclastic gneiss blocks and boulders that occur in the impact breccia section. In addition, the crystalline-clast population includes granite and pegmatite clasts. Clasts of dolerite are extremely rare and somewhat difficult to distinguish from impact melt with microlites.

**Melt Particles and Melt Matrix**

The term “melt particle” is used for all forms of melt, of different types and shapes, as described in detail later herein, and sizes range from a few hundred micrometers to a few centimeters. Macrophotographs, microphotographs, and scanning electron microscope (SEM) images of melt particles are shown in Figures 8, 9, and 10, respectively. Melt particles are most abundant near the top of the impact breccia section, between 1397 and ~1430 m (subunit U1), where the suevite contains ~35 vol% of melt particles (see Fig. 6) and grades into impact melt rock between 1402 and 1407.5 m (Horton et al., this volume; Wittmann et al., this volume, Chapter 16). Between ~1430 and 1448.4 m (subunit U2), the melt particles are rare and make up less than 3 vol% (i.e., in samples CB6-101 to CB6-106; depth = 1431.1 and 1447.0 m, respectively). The suevite becomes melt-rich again in the interval 1448.4–1457 m (subunit U3), where it grades into impact melt rock between 1450.2 and 1451.2 m (Horton et al., this volume; Wittmann et al., this volume, Chapter 16). Our sample CB6-108 (depth = 1451.0 m), from this interval, contains ~74 vol% of melt and partly melted clasts, but still has some clastic groundmass. Below 1457 m, the melt abundance is very variable, from <0.6 to 35 vol%. The percentage of melt particles in this lower part is typically below 13 vol%, but some samples with higher melt abundances occur as well, e.g., ~35 vol% in sample CB6-115 (depth = 1473.5 m).

![Figure 7. X-ray diffraction spectra for suevite sample CB6-115 (depth = 1473.5 m) particularly rich in phyllosilicate minerals. N—normal spectrum, EG—spectrum (shifted up the y-axis by 200 counts for easier comparison) obtained from the same sample after treatment with ethylene glycol, where the first peak belongs to the expanded smectite (in which the crystal lattice is expanded as a result of the glycol treatment). Q—quartz, Sm—smectite, Mu—muscovite, Kf—K-feldspar, Ca—calcite. Minerals were identified using the Joint Committee on Powder Diffraction Standards database (JCPDS, 1980). Identification of smectite is according to Moore and Reynolds (1997).](image-url)
Millimeter- to centimeter-sized melt particles (up to 5 cm in size; Figs. 8A and 8B) are mostly ovoid to amoeboid in shape (Fig. 8B) and commonly show flow structures (Figs. 9A, 9C, and 9D). Several major types of melt particles have been distinguished, on the basis of color, microtexture, and chemical composition: (1) clear, brownish, or greenish, unaltered glass with high silica content, often with flow texture (dark- and light-colored schlieren; Figs. 9A, 9B, 9C, and 10A); (2) brown melt, entirely altered to fine-grained phyllosilicate minerals, often with undigested clasts (Fig. 9D); (3) recrystallized silica melt (Figs. 9E and 9F); (4) melt with feldspar (Fig. 9G) and/or pyroxene microlites (Fig. 9H); and (5) dark brown melt (melted shale or carbon-rich clasts; Fig. 9I). The most important features of the different types of melt particles are summarized in Table 2.

Most of the melt fragments are devitrified and altered; fragments of unaltered, colorless to brownish glass (type 1) were observed mainly in subunit U1, at depths around 1415 m. This type of glass shows abundant schlieren, and some particles display shard-like (Fig. 9C) and “flame” shapes (Fig. 9B). The melt type 2 is the most abundant type and is present in all subunits. The dark-brown melt particles (type 5) occurs. The dark-brown melt (type 5) occurs in amoeboid shapes and is probably a melt of shale or other fine-grained sediment. The different types of melt particles have been characterized by SEM-EDX, and details on the chemical composition of these melt particles are reported in the companion paper by Bartosova et al. (this volume).

Shock Metamorphic Features in Minerals

Shock metamorphic effects in minerals represent the most important evidence for the recognition of an impact origin of a geological structure (e.g., Stöfler and Langenhorst, 1994). Shock metamorphic and shock-related features (such as ballen quartz and quartz toasting) observed in the impact breccia section are illustrated in Figures 11 and 12. A great diversity of shock effects in minerals is known, and these have been abundantly described, mostly for quartz, in the literature over the last 40 years (see, e.g., Stöfler and Langenhorst, 1994; Huffman and Reimold, 1996; French, 1998; Reimold and Koeberl, 2008, and references therein). Upon shock compression, quartz develops irregular fractures (which are not diagnostic shock effects) at very low shock pressures (<5 GPa), and planar fractures (PFs) and planar deformation features (PDFs) at higher pressures. Both PFs and PDFs have orientations that are crystallographically controlled, parallel to rational crystallographic planes (e.g., Stötfler and Langenhorst, 1994, and references therein).

Quartz grains in Chesapeake Bay impact breccia samples, occurring either as single grains in the matrices or as grains within rock clasts, show a variety of shock effects. Planar fractures are less common than PDFs; mostly one set and rarely two sets of PFs were noted. The PFs generally cross the entire quartz grains and are spaced more than 15 µm apart. Occasionally, PFs and PDFs occur together in the same quartz grain. Quartz grains with PDFs have been noted in all investigated suevite samples. Mostly one or two sets of PDFs in quartz (Fig. 11A) occur, and rarely three or four sets were observed. Frequently, PDFs are decorated with tiny fluid inclusions. Individual PDF sets mostly cross the whole host grain, but there are also sets occurring only in a part of a quartz grain. The PDFs are <2 µm wide, and parallel sets are spaced ~2–7 µm apart. The PDFs are best developed in polycrystalline quartz clasts (Fig. 11B), where decorated PDFs penetrating entire grains are common. In some quartz grains, the PDFs are difficult to resolve, for example, in clasts of fine-grained gneiss. Most of the sedimentary clasts are too fine-grained (siltstone, mudstone).
Figure 9 (continued on following page). Microphotographs of the different types of melt particles in the suevite and impact melt rock of the Eyreville B drill core. (A) Clear glass particle (type 1), colorless with brown schlieren, amoeboid (sample CB6-098; depth = 1418.8 m), plane-polarized light. (B) Clear glass particle (type 1), light brownish with brown schlieren and “flame-shaped” structures (sample CB6-098; depth = 1418.8 m), plane-polarized light. (C) Clear glass particle (type 1), colorless with brown schlieren, shard-like; the arrows mark sharp edges, which suggest that the particle had been broken before or during deposition (sample CB6-098; depth = 1418.8 m), plane-polarized light. (D) Altered melt particle (type 2) recrystallized to phyllosilicate minerals and with abundant undigested grains (sample CB6-093; depth = 1399.2 m), plane-polarized light. The outline of the melt particle is marked with a dashed line. (E) Recrystallized silica melt (type 3), clear with some brownish parts, botryoidal shape (sample KB-2; depth = 1402.87 m), plane-polarized light. (F) Recrystallized silica melt (type 3) with botryoidal shape (sample KB-2; depth = 1402.87 m); the same particle as in Figure 9E, but in cross-polarized light. (G) Impact melt with intersertal texture, with crystallites of plagioclase (type 4; sample CB6-108; depth = 1451.0 m), cross-polarized light. (H) Impact melt with microporphyrritic texture, with crystallites of pyroxene (type 4; sample KB-2; depth = 1402.9 m), plane-polarized light. (I) Dark brown, altered melt particle (type 5), probably derived from shale or a fine-grained sediment, with abundant tiny undigested grains (sample CB6-107; depth = 1449.8 m), plane-polarized light. (J) Melt particle altered to phyllosilicate minerals and partially replaced with secondary carbonate (sample CB6-109; depth = 1452.3 m), cross-polarized light.
to determine whether quartz grains have been affected by shock metamorphic transformation.

Because PDFs cannot be clearly resolved under the optical microscope, the TEM was used for characterization of their microstructure. Observations were made on a FIB foil cut across a quartz grain with one PDF set (sample CB6-097; depth = 1412.8 m). The PDFs are represented by planes of high dislocation density and are decorated with tiny fluid inclusions (Fig. 12). The inclusions typically display negative crystal shapes with a maximum size of ~0.5 µm. The PDFs in the investigated quartz grain did not show any amorphous silica phase along the rhombohedral planes; the original amorphous phase is totally recrystallized.

Shock effects are rarely observed in minerals other than quartz in our Eyreville core samples. Rare K-feldspar grains with PDFs were noted, e.g., in a granite-derived clast in sample CB6-099 (depth = 1421.7 m). Overall, PDFs are difficult to resolve in feldspar, possibly because of postimpact alteration.

Results of our systematic analysis of the shock metamorphic effects in quartz grains, carried out on 14 suevite samples, are reported in Table 4. The investigated samples cover nearly the entire depth interval of the impact breccia section. Shock effects were evaluated separately for single quartz grains and for each type of rock clasts; however, the results could be statistically evaluated only for the most abundant clast types. In each thin section, quartz grains in one type of rock clast (e.g., graywacke) were counted together, not separately in each individual clast. Next, an average value from all the investigated thin sections was calculated for a particular clast type. Generally, the clasts of the same lithology have similar proportions of shocked clasts. On average, ~16 rel% of all the quartz grains are shocked (i.e., show PFs and/or PDFs). Single grains in the matrix, which represent a substantial part of all the grains counted, are shocked to a similar percentage (~15 rel%, on average). The proportion of shocked quartz grains in sedimentary clasts is higher than the average proportion of shocked grains from all analyzed quartz grains. Graywacke clasts contain ~19 rel% of shocked quartz grains, and sandstone clasts contain ~47 rel% of shocked quartz grains, on average. However, the sandstone clasts were not abundant enough to provide reliable statistics. About 21.5 rel%, on average, of the quartz grains in polycrystalline quartz clasts are shocked. PFs and PDFs are rarely observed in gneiss/schist clasts (~1 rel% of the quartz grains are shocked).

No obvious trend in the distribution of shocked quartz grains with depth through the impactite sequence is observed (Fig. 13). When only single quartz grains in matrix are taken into account, the results for individual samples are slightly different (Fig. 13), but they do not show any trend with depth either. We also compared the proportion of shocked quartz grains with the abundance of matrix, melt, crystalline clasts, and sedimentary clasts, but no correlation was observed. The only observed, though weak, trend is the increase in abundance of single shocked quartz grains in matrix with the

Figure 10. Backscattered electron images of melt particles in suevite. (A) Microtexture of a clear glass particle (type 1). The glass obviously has a fluidal texture. The particle is mostly composed of silica (>95% of SiO₂). Microfractures are filled with phyllosilicate minerals (1). An undigested quartz grain is visible in the upper part of the image (2). In addition, there is a small elongate grain of rutile (3). Sample CB6-098; depth = 1418.81 m. (B) Melt particle partially altered to phyllosilicate minerals (intermediate type, between type 1 and 2, according to our classification). The lighter areas are silica-rich (up to 98 wt% of SiO₂), whereas the darker areas are altered to phyllosilicate minerals. A small grain of calcite (1) and two tiny grains of rutile (2) occur. Sample CB6-110, depth = 1455.22 m.
increasing proportion of sedimentary clasts (correlation coefficient $r = 0.69$).

Impact-Diagnostic Features and Other Microscopic Features in Minerals

Besides PFs and PDFs in quartz and in feldspars, ballen quartz, toasting of quartz grains, undulose extinction in quartz, and kink-banding of mica were observed. Ballen quartz was identified exclusively in melt-rich suevites and in impact melt rocks (e.g., KB-4, CB6-107, CB6-108; depth = 1405.7 m, 1449.8 m, and 1451.0 m, respectively; Figs. 11C and 11D). Ballen with a mean size of ~80–100 µm occur in silica clasts, generally within melt particles (melt type 3). Ballen quartz with heterogeneous extinction (type III), ballen quartz with intraballen polycrystallinity (type IV), and rare ballen quartz with homogeneous extinction (type II) were noted, according to the classification by Ferrière et al. (2009b). No ballen cristobalite (type I) and ballen quartz of type V (according to Ferrière et al., 2009b) were observed in our samples. Ballen quartz and ballen cristobalite are considered to be impact-diagnostic features (Ferrière et al., 2009b); however, it is not clear yet if the different types of ballen are the result of postimpact alteration processes and/or due to the pressure-temperature ($P$-$T$) conditions during the back-transformation of cristobalite to $\alpha$-quartz.

Quartz grains in the suevite from the Eyreville B drill core commonly have toasted appearance (Fig. 11E). About 8 rel% of all quartz grains in suevite display a toasted appearance; the toasted quartz grains do not necessarily show PDFs. The quartz grains in the impact melt rock from the depth interval 1402–1407.5 m (M2) show only slight toasting together with PDFs. The sample of suevite/impact melt rock (CB6-108; depth = 1451.0 m) from the lower impact melt rock interval (M1, 1450.2–1451.2 m) shows quartz grains with very strong toasting and decorated PDFs.

Undulose extinction, which is by itself not of impact-diagnostic value, is observed for the majority of the quartz grains, including grains without PFs or PDFs. Kink bands occasionally occur in mica (mostly in muscovite; e.g., in sample CB6-100; depth = 1427.01 m; Fig. 11F); however, since kink-banding is also observed in mica from nonimpact settings, such as in tectonically deformed rocks, it cannot be considered to be a diagnostic shock effect (e.g., French, 1998, p. 33).

Alteration of the Impactites

The impact breccia section shows a large variety of alteration effects that have significantly modified the mineralogy and affected the chemical composition of the rocks (see Bartosova et al., this volume); some minerals are partially or totally replaced by secondary minerals, such as biotite by chlorite or feldspar by sericite. Especially in the rock clasts, this alteration can be pre-impact because the same alteration effects are noted in the lower basement-derived section (Townsend et al., this volume). In suevite and cataclasite, veins or patches of carbonate occur, mostly in the lower part of the impact breccia section (below 1500 m). However, in cataclasite blocks, some of the veins might be of pre-impact age. Secondary opaque minerals (e.g., pyrite) occur in clusters and patches, many at the boundaries between clasts and matrix. Commonly, melt particles (especially type 2) are altered to phyllosilicate minerals. Phyllosilicate minerals are also abundant in matrix. The occurrence of smectite was
confirmed by XRD analyses in suevite samples from the lower parts of the impact breccia section (in samples CB6-115 and CB6-121; depth = 1473.5 and 1508.5 m, respectively). Chamosite, an alteration mineral of the chlorite group, was identified in suevite and cataclastic gneiss by microRaman spectroscopy; chamosite occurs abundantly in the form of patches and fracture fillings, mostly in the lower part of the impact breccia section (typically around 1500 m depth). Amygdules filled with zeolites (faujasite and phillipsite) were noted in the melt-rich parts of the suevite (e.g., sample CB6-108; depth = 1451.0 m).

**DISCUSSION AND INTERPRETATION**

**Implications for the Formation of the Impact Breccia**

Generally, clast size increases with increasing depth in the impact breccia section; additionally, matrix proportions are much higher in the uppermost part of the section. In the lower part of the impact breccia section, clasts are more abundant and large blocks of cataclastic gneiss occur. Large clasts and blocks, similar to cataclastic gneiss blocks that occur in the lower part of the impact breccia (below 1474 m), were also observed in the STP test hole (e.g., Horton et al., 2005b). Some blocks of cataclastic gneiss may have been incorporated into the suevite during the collapse of the central uplift, as previously suggested by Horton et al. (2005b) for the STP test hole. The lowermost parts of the impact breccia section (subunits U5 and U6), which contain large blocks of cataclastic gneiss, are relatively melt-poor. These two subunits probably represent ground-surge material. A ground-surge origin for the lower part of the impact breccia section (1468–1551 m) was also suggested by Wittmann et al. (2008), based on the scarcity of melt fragments and clast-size distribution. The presence of large gneiss blocks and the overall increasing proportion of crystalline basement-derived rock suggest a more autochthonous character of the materials in these lower parts of the impact breccia section (Jolly et al., 2008). In our point counting, we observed abundant sedimentary clasts in subunit U6 (1486.1–1551.2 m). However, we counted proportions of relatively small clasts (<1 cm); the observations by Jolly et al. (2008) suggest that in the smaller clasts, the proportion of sedimentary clasts is higher than in larger clasts (clasts >4 cm).

Regarding shape and texture of the different melt particles, it seems that the shard-like melt particles (clear glass, type 1; Fig. 9C), which have sharp edges and sharp contacts to matrix, were solidified before incorporation into the impact breccia. In addition, this type of melt fragment (type 1) was found only in the upper part of the suevite sequence (above 1430 m). These observations suggest that subunit U1 (1397.2–1430 m) represents fallback impact breccia. Further, the upper part of the impact breccia section contains more matrix and small clasts derived from different types of target rocks (see also Jolly et al., 2008). The melt rock intervals (M1 and M2) are very clast-rich and heterogeneous. The melt rocks included in the suevite clearly
do not represent a coherent melt sheet, but rather individual melt bodies incorporated into the fallback material.

Below 1430 m, some parts of the investigated section (i.e., U3; 1448.4–1457 m) contain abundant melt particles and small clasts, and these probably also represent fallback material. The melt-poor, crystalline clast–rich subunit (U2; 1430–1448.4 m) might represent ground-surge material or material slumped either from the central uplift or from the margin of the transient crater. Wittmann et al. (2008, this volume, Chapter 17) have observed some shard-like particles also in the lower parts of the section (e.g., in the interval 1451–1468 m), and they interpret the impactites above 1468 m as a mixture of fallback and ground-surge material, with fallback material becoming more important toward the top of the section. Shard-like melt particles were also found in Exmore breccia from the Eyreville drill core and are interpreted as fallout from the ejecta plume (Reimold et al., this volume).

The petrographic and geochemical diversity of the melt particles from the impact breccia section suggests that the particles were derived from different precursors. More information about chemical composition of the different types of melt particles from the impact breccia, including discussion about possible precursors, can be found in Bartosova et al. (this volume).

**Comparison with Suevite from the STP Test Hole**

Before the drilling at Eyreville, suevite was cored at Chesapeake Bay only in the STP test hole, but, unfortunately, only limited observations of the suevite from this test hole are reported in the literature (Horton et al., 2005b, 2006, 2008; Lee et al., 2005, 2006; Gohn et al., 2007). In Gohn et al. (2007), the suevite from the STP test hole is described as part of a crystalline-clast breccia, where clasts of gneiss and chloritized mafic rock dominate. In the Eyreville drill core, a mafic lithology containing abundant amphibole and chlorite occurs (e.g., sample CB6-123; depth = 1514.3 m), but it is not among the most abundant components of the suevite, according to our petrographic observations and further confirmation from our chemistry-based HMX (Harmonic least-squares MiXing) mixing calculations (Bartosova et al., this volume). According to Horton et al. (2005b), the suevite from the STP test hole is crumbly to moderately cohesive and contains metamorphic and igneous rock fragments and less abundant particles of impact melt rock. Only rare sedimentary clasts occur in the suevite from the STP test hole (Horton et al., 2008), whereas sedimentary clasts constitute an important component of suevite from the Eyreville B core. This implies that the suevite from the STP test hole is similar to the lower part of the impact breccia section from the Eyreville B core. However, insufficient core recovery at the STP test hole makes further comparison of the two cores difficult (J.W. Horton Jr., 2008, personal commun.). Suevite from the STP test hole (polymict, poorly sorted, and not bedded) was first interpreted as fallback material (Horton et al., 2005b), but later, an origin similar to that of the “crater suevite” in the Ries crater, i.e., suevite that never left the crater cavity (von Engelhardt and Graup, 1984), was proposed by Horton et al. (2008). The crater suevite from the Ries crater has a relatively higher clast/melt ratio compared to the Ries fallout suevite, contains clasts that are on average shocked to a lower stage, and lacks aerodynamically shaped glass bodies (von Engelhardt, 1997). The melt particles in the suevite from the STP test hole are glassy or partly aphanitic, with some flow lamination (Horton et al., 2005b). Our observations of melt particles are somewhat comparable to the descriptions by these authors.

![Figure 13](image-url)
Comparison with Exmore Breccia

The Exmore beds represent washback material deposited by a collapsing marine water column and associated tsunami waves (e.g., Poag et al., 2004, p. 185). It has also been proposed that the lower parts of this sequence, which contain abundant and partly very large blocks (Gohn et al., this volume), represent avalanche deposits. The finer-grained materials are generally described as “Exmore breccia” (cf. Reimold et al., this volume). The unit consists of a fine matrix containing millimeter-sized mineral clasts, millimeter- to centimeter-sized lithic clasts, and generally rare melt particles. However, melt particles are enriched in some depth intervals in the upper parts of the Exmore breccia (Reimold et al., this volume). In contrast to suevite, Exmore breccia contains abundant glauconite and microfossils, and evidence of shock metamorphism is rare in the microclasts (Reimold et al., this volume).

The Exmore breccia has been cored in several drill holes in the Chesapeake Bay impact structure, and PDFs in quartz in some clasts of crystalline basement rocks have been observed (e.g., Koeberl et al., 1996; Poag et al., 2004, p. 217). More rarely, PDFs have been reported in single quartz grains within Exmore breccia (Poag et al., 2004, p. 217; Horton et al. 2005a). In contrast, in suevite, the shock metamorphic effects are more abundant in single quartz grains and sedimentary clasts than in crystalline clasts. The occurrence of melt particles mostly in the uppermost part of the Exmore beds suggests that fallback material similar to that incorporated into the uppermost suevite of the impact breccia section continued to settle down during the subsequent deposition of the Exmore breccia. Most melt particles that occur in the Exmore breccia are completely altered to secondary phyllosilicate minerals and, in rare cases, replaced by carbonate (Reimold et al., this volume; also see Ferrell and Dypvik, this volume), as are some melt particles in suevite from the Eyreville B core (e.g., in sample CB6-109; depth = 1452.3 m).

Shock Petrographic Characteristics

Investigated suevite samples show a large variety of shock metamorphic effects, particularly PDFs in quartz and melt particles, which attest to the mixing of different target rocks that were previously shocked at different pressures according to their original position (i.e., depth) in the stratigraphic column. There is a weak trend ($r = 0.69$) of increasing proportion of shocked single grains with increasing sedimentary component. This could mean that in the samples with predominantly sedimentary clasts, the single quartz grains in the matrix also originated mostly from sediments. This means that the single quartz grains would be relatively more shocked, as are their parent sediments (e.g., relatively larger proportions of shocked grains in graywacke and sandstone than in the other lithologies). Our observation, that PDFs are more abundant in the sedimentary clasts than in the crystalline basement clasts, is in agreement with the fact that the target sediments were overlying the crystalline basement before the impact and would have been subjected to higher shock pressures because they were located closer to the point of impact. It is well established that the shock wave attenuates rapidly with increasing distance from the point of impact (e.g., Stöffler, 1971; Robertson and Grieve, 1977; Melosh, 1989, p. 60–66; French, 1998, p. 18).

In previous studies of Exmore breccia that involved descriptions of shock metamorphism in clasts, shock effects were observed only in single quartz grains or clasts derived from the crystalline basement (e.g., Koeberl et al., 1996; Poag et al., 2004, p. 217; Horton and Izett, 2005), but no shock metamorphic effects in sedimentary clasts were reported. In contrast, we found abundant PDFs in sedimentary clasts in suevite, e.g., in graywacke and sandstone.

As documented by optical microscopy and supported by TEM work, most of the PDFs in quartz are decorated with tiny fluid inclusions (Fig. 12). No amorphous phase (i.e., glass) was observed along the rhombohedral planes. Initially, PDFs are amorphous lamellae formed during shock compression (e.g., Stöffler and Langenhorst, 1994; Grieve et al., 1996). The occurrence of fluid inclusions and of dislocations, in place of an amorphous phase, indicates that primary PDFs were altered (e.g., Leroux et al., 1994; Stöffler and Langenhorst, 1994; Grieve et al., 1996; Leroux, 2005). The amorphous phase was probably recrystallized due to the hydrothermal alteration of the impact breccia and thermal overprint from the hot suevite host package.

The full range of progressive stages of shock metamorphism (e.g., Stöffler and Langenhorst 1994) has been observed in most of the investigated suevite samples, including PDFs in quartz grains (rarely observed in feldspar), silica glass (rare bollen quartz observed), and more or less abundant melt particles. The quartz grains in the samples from the impactite section commonly show one or two sets, rarely more sets, of PDFs. The formation of PDFs requires pressures of at least 8–10 GPa (e.g., Stöffler and Langenhorst, 1994; Huffman and Reimold, 1996; French, 1998, p. 33). A detailed study of PDFs in some quartz grains from Exmore breccia, including universal stage measurements of PDF orientations, was reported by Koeberl et al. (1996). The occurrence of silica glass, as well as of melt particles, is consistent with shock pressures of at least 50 GPa (e.g., Stöffler and Langenhorst, 1994). The presence of impact melt rocks indicates that at least some target rocks experienced extremely high pressures and temperatures (more than 60 GPa and 1500 °C, respectively; French, 1998, p. 33).
Hydrothermal Alteration

Evidence for postimpact hydrothermal alteration is known for more than 60 impact structures (for reviews, see Naumov, 2002, 2005). Hydrothermal mineral associations in the majority of the terrestrial craters are very similar, and the dominant assemblage consists of phyllosilicate minerals (smectite, chlorite, and mixed-layered smectite-chlorite), various zeolites, calcite, and pyrite. For impact structures in which the target rocks contained significant amount of carbonate, the carbonate-quartz-sulfide association is also widespread (Naumov, 2002, 2005).

In suevite from the Chesapeake Bay impact structure, the original glassy groundmass of most of the melt particles has been altered to secondary minerals, such as smectite (cf. Fig. 7). The presence of smectite is in good agreement with the findings by Dypvik and Jansa (2003), who reported that in a Na-rich marine or brackish environment, impact glass should alter to smectitic clays (also see Ferrell and Dypvik, this volume). The zeolites (phillipsite and faujasite) occurring in the melt-rich suevite indicate low-temperature (<300 °C; Chipera and Apps, 2001) hydrothermal alteration, probably at ~100 °C (cf. Chipera and Apps, 2001; Osinski, 2005).

Additionally, veins and patches of carbonate, as well as secondary pyrite, occur within suevite and cataclastic gneiss samples from the Eyreville B drill core and are interpreted to be of postimpact hydrothermal origin. Horton et al. (2005b) have also suggested that the decoration of PDFs in quartz may be a consequence of the hydrothermal alteration. Our initial TEM observations seem to support this hypothesis of fluid circulation in rocks and minerals. Based on analyses of fluid inclusions, Horton et al. (2006) have shown that hydrothermal fluids associated with sparry calcite veins from the deeper crystalline-clast breccia reached temperatures up to the boiling point of seawater (~220 °C at 300 m water depth). The notable alteration of feldspars, as well as the chloritization of mica observed in our samples, is interpreted to be possibly—at least in part—of preimpact age because similar alteration has been observed in granitoids and schists in the basement rocks (e.g., Townsend et al., this volume).

Comparison with Other Impact Structures

The Chesapeake Bay impact structure was formed in a layered submarine terrain composed of a sedimentary sequence and underlying crystalline basement, similar to that at many other craters, including, e.g., Ries and Chicxulub (Kring, 2005). The location in a shallow-water marine environment makes the Chesapeake Bay impact structure comparable with, e.g., the Montagnais, Mjölnir, and Locke impact structures (Dypvik and Jansa, 2003; Lindström et al., 2005).

Studies of submarine impact craters have demonstrated that the presence of water and the physical properties of target rocks have a major influence on the formation of the impact structure and on the associated sedimentary processes (Dypvik and Jansa, 2003). The shape of the Chesapeake Bay impact structure is similar to the shape of the Mjölnir impact structure (40 km in diameter), both of which have been described as having an “inverted sombrero” geometry (Dypvik and Jansa, 2003; Gohn et al., 2006a). The deposition of the suevite in the case of the Chesapeake Bay structure was probably somewhat similar to that described from the Yaxcopoil-I drill core (located ~62 km from the crater center) at the Chicxulub impact structure (~180 km in diameter). At Yaxcopoil-1, according to Stöffler et al. (2004), after the ground surge and the formation of the ejecta curtain, the main fallback phase occurred, followed by the late fallback phase, which was modified by atmospheric interaction. In the central moat of the Chesapeake Bay impact structure, the deposition of fallback material was disturbed by slumping of material off the central uplift (Horton et al., 2005b) and interrupted by the return of fluidized sediments into the central cavity about 10 min after the impact (according to numerical modeling results discussed by Kenkmann et al., this volume). At Chicxulub, in the Yucatán-6 (Y6) drill core (located in the inner part of the ring depression surrounding the peak ring structure), the clasts in suevite increase in size, and crystalline basement clasts become more abundant with increasing depth (Claeys et al., 2003), similar to what we observed in the impact breccia section from the Eyreville B drill core. However, at Y6, silicate melt fragments become more abundant with increasing depth, and a layer of impact melt underlies the suevite section, which is the reverse of our observations from the Eyreville B drill core. Furthermore, the abundance of carbonates in the upper target sediments from Chicxulub had a large influence on the distribution of the impactites and makes some features of Chicxulub difficult to compare with the Chesapeake Bay structure.

In the Eyreville drill core, only two impact melt rock intervals were cored (5.5 m and 1 m in thickness, depth intervals 1402.0–1407.5 and 1450.2–1451.2 m, respectively; Horton et al., this volume; Wittmann et al., this volume, Chapters 16 and 17), whereas a continuous melt sheet is expected in an impact structure of this size (Shah et al., 2005, this volume). However, the lower amount of melt, as observed during our investigations, corresponds to what is expected for an impact structure with a diameter of ~20–40 km (i.e., the estimated size of the transient crater) and for an impact into a target made up of weak, wet sediments and water (Shah et al., 2005). Nevertheless, because the impact melt can be distributed unevenly within the impact structure, it is then difficult to estimate the amount of melt for the full Chesapeake Bay structure only based on information obtained from drilling. An ~3-km-thick impact melt sheet is believed to occur inside of the peak ring at Chicxulub (Kring, 2005). In the Montagnais structure (45 km in diameter), the impact breccia on the central uplift contains two layers of recrystallized melt (71 and 35 m thick; Dypvik and Jansa, 2003). At the Locke structure (only 7 km in diameter), impact melt occurs as sand-sized particles in the arenites that formed in the final stages of the resurge deposits, but there is no information about the presence of melt bodies in the central part of the crater (Lindström...
et al., 2005). For the Chesapeake Bay impact structure, Shah et al. (2005) suggested—from investigation of the magnetic anomalies—that the volume of melt surrounding the central peak is 0.4–7 km³. Clearly, the total amount of impact melt at the Chesapeake Bay impact structure remains unresolved. The impact melt rock at the Chesapeake Bay impact structure contains microlites of feldspars and pyroxenes, probably formed by quenching of the impact melt; feldspar and pyroxene microlites have also been described in the impact melt from, e.g., Ries and Chicxulub (von Engelhardt, 1972; Osinski, 2003; Kring et al., 2004). Shard-like melt particles were observed in the upper part of impact breccia at the Chesapeake Bay impact structure. Similarly, angular shards of holohyaline glass have been described from surficial suevites from the Ries crater (e.g., Osinski et al., 2004). In the Ries crater, melt particles are preserved in a vitreous state in the chilled bottom and top layers of the suevite, whereas devitrified melt particles in the interior section of the suevite are altered (von Engelhardt, 1972). Melt particles of type 1 in the upper part of the impact breccia in the Eyreville B core could similarly have been preserved in the glassy state due to rapid cooling, compared to the slower cooling of melt in the deeper parts of the impact breccia section.

**SUMMARY AND CONCLUSIONS**

Forty-three samples from the impact breccia section at the Chesapeake Bay impact structure were subjected to detailed petrographic analysis. The suevite from the Eyreville B drill core is characterized by a grayish, fine-grained, clastic matrix that contains a variety of rock and mineral clasts, melt particles, and secondary minerals. The melt particles in the suevite are small (not larger than a few centimeters) and mostly elongated or amoeboid. The relative abundance of melt particles varies significantly through the suevite section; melt is most enriched near the top, where the suevite locally grades into impact melt rock. Five different types of melt particles have been distinguished, and the diversity of the melt particles suggests that they were formed from different precursors. The impactites from the Eyreville B drill core show evidence of hydrothermal alteration. Most of the melt particles (except for those at depths around 1415 m, where clear glass occurs) are altered to secondary minerals, such as smectite. Microcrystalline carbonates fill fractures and occur as irregular patches in suevite, but they occur more commonly in lithic clasts. Rarely, carbonates replace melt particles. The impactites contain a large variety of clasts with shock metamorphic indicators, such as PDFs in quartz, and melt particles, together with low-shocked material. This implies mixing of the different target rocks that were previously shocked at different pressures according to their original positions. The presence of impact melt rocks indicates that at least some target rocks experienced pressures of >60 GPa and temperatures >1500 °C.

Six different subunits of suevite have been recognized based mostly on the abundance and characteristics of lithic clasts and melt particles. The clast size generally increases with depth. Sedimentary clasts are dominant in most subunits (especially in U1, also in U3, U4, and in some parts of U6). There are melt-rich subunits (U1 and U3) and some melt-poor subunits with predominantly crystalline clasts (such as U2 and U5). The lower subunits (U5 and U6; below 1474 m) have larger clasts and large blocks of cataclastic gneiss, and mostly rare melt particles, that show no evidence of aerial transport, and they probably represent ground-surge material. Subunit U1, with shard-like melt particles and relatively small clasts originating from all different target lithologies, probably represents fallback material. Due to the origin of the core from the central crater moat, near the central uplift, deposition of the impact breccia sequence could have been disturbed by slumping of material from the central uplift and/or from the margin of the central crater. Consequently, we propose that the melt-poor subunit (U2) might represent “slump” breccia. The deposition of the impact breccia section was terminated by the ocean resurge that deposited the sedimentary sequence of the Exmore beds above the impactite sequence.

**ACKNOWLEDGMENTS**

The drilling at Eyreville was supported by the International Continental Scientific Drilling Program (ICDP), U.S. Geological Survey (USGS), and National Aeronautics and Space Administration (NASA). The present work was supported by the Austrian Science Foundation FWF, project P18862-N10 (to Koeberl). We thank J.W. Horton Jr. and A. Wittmann for valuable discussions. We are very grateful to A. Schreiber and R. Wirth (GeoForschungsZentrum [GFZ], Potsdam, Germany) for the FIB preparation, A. Greshake (Museum of Natural History, Humboldt University, Berlin, Germany) for assistance with the transmission electron microscope (TEM), E. Libowitzky (University of Vienna) for assistance with the microRaman measurements, as well as F. Koller (University of Vienna) for help with optical microscopy. W. Fuzi and L. Slawek (both University of Vienna) are thanked for expert thin-section preparation. We thank Bevan French and Gordon Osinski for careful reviews that substantially improved this paper.
## APPENDIX. DETAILED PETROGRAPHIC DESCRIPTIONS OF SAMPLES FROM THE IMPACT BRECCIA SECTION

<table>
<thead>
<tr>
<th>Sample and rock type</th>
<th>Midpoint depth¹ (m)</th>
<th>Description based on macroscopic and microscopic observations</th>
<th>Shock metamorphism</th>
<th>Melt types present</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB6-093 S</td>
<td>1399.2</td>
<td>Suevite with clastic gray matrix; angular to subangular gray clasts &lt;1 cm (sandstone, siltstone, mudstone, graywacke); yellowish to beige melt particles up to 1.8 cm angular to amoeboid; olive green elongated melt particles with flow structures, altered and crumbly</td>
<td>Qtz, feldspar, Ms, Bt, opaque minerals</td>
<td>2, interm.², ³</td>
</tr>
<tr>
<td>CB6-094 S</td>
<td>1399.7</td>
<td>Suevite with gray fine-grained matrix; subangular to rounded clasts of siltstone &lt;2 cm, large amoeboid melt particles up to 4 cm, dark olive green, crumbly, with white rim; subangular clasts of sandstone and polycrystalline quartz &lt;0.5 cm; clasts of crystalline basement rocks, beige clasts with gray bands &lt;2 cm; small clasts of shale</td>
<td>Qtz, Kfs, Ms, Bt, Chl, opaque minerals</td>
<td>3</td>
</tr>
<tr>
<td>CB6-095 S</td>
<td>1401.3</td>
<td>Suevite with greenish gray clastic matrix, angular to subangular clasts of siltstone &lt;1 cm; rounded clasts of crystalline basement &lt;1 cm, minor dark purple melt particles &lt;0.8 cm, yellowish weathered clasts or melt particles &lt;2 cm, large clast (3 cm) of arkose (rounded gray and white grains)</td>
<td>Qtz, Kfs, Ms, Bt, Pl, opaque minerals, Ap</td>
<td>2 (5 ?)</td>
</tr>
<tr>
<td>CB6-096 S</td>
<td>1409.3</td>
<td>Suevite with gray matrix, some parts of matrix melted, very rich in clasts; subangular clasts of mudstone &lt;2 cm; subrounded clasts of schist 2 cm; subangular clasts of siltstone 1 cm; yellowish subrounded clasts of sandstone 1.5 cm; white subangular to rounded clasts 0.6 cm; amoeboid purple brown melt particles with flow structures; beige melt particle with rounded shape; yellowish melt particle with irregular shape</td>
<td>Qtz, feldspar, Bt, opaque minerals</td>
<td>PDFs in some clasts and single Qtz grains, toasted Qtz</td>
</tr>
<tr>
<td>CB6-097 S</td>
<td>1412.8</td>
<td>Suevite with light-gray matrix, very rich in clasts, dark-gray subangular clasts &lt;2.5 cm, some with beige bands; angular beige clasts &lt;1 cm; rounded clasts of granite 1.5 cm, fractured; white clasts of polycrystalline quartz; yellowish subangular soft clay clasts 1.5 cm; small clasts of graywacke; recrystallized greenish to yellowish melt particles 2.5 cm with schlieren</td>
<td>Qtz, Pl, Kfs, Ms, Bt, opaque minerals</td>
<td>PDFs especially in polycrystalline Qtz, at least two sets, some toasted Qtz grains</td>
</tr>
<tr>
<td>CB6-098 S</td>
<td>1418.8</td>
<td>Suevite with gray matrix, very rich in clasts, angular to subrounded gray clasts of siltstone &lt;2 cm; yellowish amoeboid altered clasts; reddish subangular clast of granite 0.5 cm; large (5 cm) yellowish clast of sandstone, partly melted and altered; white elongated melt clasts 1 cm long; melt particle 2 cm long with olive green altered core</td>
<td>Qtz, Bt, Ms, feldspar, opaque minerals, carbonate</td>
<td>Abundant PDFs especially in polycrystalline Qtz clasts</td>
</tr>
<tr>
<td>CB6-099 S</td>
<td>1421.7</td>
<td>Altered suevite with gray matrix; rich in clasts; subangular clasts of mudstone &lt;1 cm, part of one mudstone clast melted; clasts of siltstone 2 cm; large yellowish fractured subangular clast of sandstone (4 cm) plus a few smaller clasts; beige crumby clasts of altered melt 2 cm; olive melt particles, rounded or elongated with white crystals in the middle, amoeboid shape, &lt;4 cm long, mostly altered to clay minerals</td>
<td>Qtz, Ms, Bt, Kfs, Pl, opaque minerals, Chl, Tur, Ep</td>
<td>1, interm.</td>
</tr>
<tr>
<td>CB6-100 S</td>
<td>1427.0</td>
<td>Suevite with gray matrix, crystalline clasts very abundant, subangular fractured white to gray crystalline clasts &lt;2.5 cm, one pinkish subangular clast of granite; minor angular to subangular dark-gray clasts of siltstone 0.5 cm; a few shale clasts &lt;3 mm</td>
<td>Qtz, Pl, Kfs, Ms, Bt, Chl, opaque minerals, carbonate, garnet, amphibole, Ep</td>
<td>Abundant well-developed PDFs in Qtz, some with 2 sets, toasted Qtz grains, kink banding in Ms</td>
</tr>
<tr>
<td>CB6-101 S</td>
<td>1431.1</td>
<td>Suevite with gray matrix rich in clasts; angular to subangular clasts of siltstone 0.7 cm; white to gray subangular clasts of schist 2 cm; large yellowish melt particle with partly melted crystalline clast, some dark olive crystals and green pigment, amoeboid, 4.5 cm; abundant small vesicles; altered melt on the bottom edge of the sample</td>
<td>Qtz, Kfs, Pl, Ms, Bt, Chl, opaque minerals, Ttn, Ep</td>
<td>Most Qtz grains show PDFs, some at least two sets, decorated, some Qtz grains toasted</td>
</tr>
</tbody>
</table>

(Continued)
### APPENDIX. DETAILED PETROGRAPHIC DESCRIPTIONS OF SAMPLES FROM THE IMPACT BRECCIA SECTION (Continued)

<table>
<thead>
<tr>
<th>Sample and rock type*</th>
<th>Midpoint depth† (m)</th>
<th>Description based on macroscopic and microscopic observations</th>
<th>Mineral composition§</th>
<th>Shock metamorphism</th>
<th>Melt types present</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB6-102 S</td>
<td>1436.6</td>
<td>Suevite with light-gray matrix, small angular clasts of mudstone &lt;0.5 cm, clasts of siltstone &lt;0.5 cm; large clasts of chert up to 5 cm; large clast through all core diameter with light-gray grains, coarse-grained, very fractured, meta-arkose or crystalline rock?; sulfide minerals with ochre pigment rim; dark olive green melt particles ~1 cm; abundant vesicles</td>
<td>Qtz, Kfs, Ms, Bt, Pl, opaque minerals, Gr</td>
<td>PDFs in Qtz, some decorated especially in polycrystalline Qtz, some at least 3 sets, some Qtz grains melted</td>
<td>2</td>
</tr>
<tr>
<td>CB6-103 S</td>
<td>1440.0</td>
<td>Suevite, very light gray, large clasts with light pinkish and greenish crystals form majority of the sample, one class of granite along all sample (12 cm), angular to subangular clasts of siltstone &lt;0.1 cm; cavities after altered melt, dark beige, elongated &lt;3.5 cm; angular beige clast of sandstone 2.5 cm; pyrite grains occur</td>
<td>Qtz, Kfs, Pl, Ms, Chl, Ep, carbonate, opaque minerals</td>
<td>PFs and PDFs (up to 4 sets) in Qtz</td>
<td>2</td>
</tr>
<tr>
<td>CB6-104 S</td>
<td>1443.75</td>
<td>Suevite with light-gray matrix, angular to subangular clasts of siltstone and mudstone to 1 cm, one large clast through all diameter of the core plus a few smaller clasts &lt;1 cm of schist; clasts of polycrystalline quartz with light-gray crystals &lt;2.5 cm; cavities &lt;1 cm; olive green crumbly weathered melt particles &lt;2 cm</td>
<td>Qtz, Kfs, Pl, Ms, Chl, graphite, opaque minerals</td>
<td>Abundant PDFs, up to 3 sets, especially in polycrystalline Qtz, PDFs also in schist, some Qtz grains very toasted and fractured</td>
<td>2, 5</td>
</tr>
<tr>
<td>CB6-105 S</td>
<td>1445.8</td>
<td>Suevite with light-gray matrix, angular dark-gray clasts of siltstone to 0.5 cm; large olive green amoeboid melt particle 3.5 cm; light-gray clasts of sandstone &lt;0.7 cm; sample is fractured on the bottom edge</td>
<td>Qtz, feldspar, Ms, Chl, opaque minerals</td>
<td>Decorated PDFs in Qtz, toasted Qtz in single grains or clasts</td>
<td>2</td>
</tr>
<tr>
<td>CB6-106 S</td>
<td>1447.0</td>
<td>Suevite with light-gray matrix, subangular clasts of siltstone &lt;2 cm, somewhere with filled parallel cracks, light-gray subangular crystalline clasts &lt;3 cm; subrounded to subangular greenish-gray metasedimentary clasts &lt;1.5 cm; vesicles &lt;1 cm</td>
<td>Qtz, Kfs, Pl, Ms, Chl, graphite, opaque minerals, Ep</td>
<td>PDFs in Qtz, at least 2 sets, toasted Qtz grains</td>
<td>2, 5</td>
</tr>
<tr>
<td>CB6-107 S</td>
<td>1449.8</td>
<td>Suevite with gray matrix, rich in clasts; angular to, subangular, often irregularly shaped clasts of mudstone &lt;2 cm; angular brown clasts, amoeboid &lt;3 cm, sometimes with bands; subrounded clasts of polycrystalline quartz &lt;2 cm; rounded silica-melt clast with clear core and light rim, 2 cm in size</td>
<td>Qtz, feldspar, Ms, Chl, graphite, opaque minerals</td>
<td>Toasted Qtz grains, PDFs, ballen Qtz</td>
<td>2, 3, 5</td>
</tr>
<tr>
<td>CB6-108 S/I</td>
<td>1451.0</td>
<td>Suevite; very fractured; altered; minor matrix, most clasts deformed; clasts of mudstone &lt;3 cm; dark beige to gray clast (5 cm) with lighter and darker bands; olive green crystals; light-gray to yellowish amoeboid melt particles to 1.5 cm; deformed purple-colored melt particles with residual quartz grains inside; matrix also melted</td>
<td>Qtz, Pl, Bt, opaque minerals</td>
<td>Some very toasted Qtz clasts, ballen Qtz, some decorated PDFs, abundant ballen Qtz</td>
<td>3, 4, all partly melted</td>
</tr>
<tr>
<td>CB6-109 S</td>
<td>1452.3</td>
<td>Minor matrix, dark-gray subangular clasts of mudstone to 2 cm, large beige to gray amoeboid clast 4 cm; amoeboid melt particles, elongated to 4 cm with spherules, yellowish with ochre rim; gray subangular clasts of siltstone up to 0.5 cm in size</td>
<td>Qtz, Kfs, Pl, carbonate, Ms, Bt, opaque minerals, Zrn</td>
<td>Up to 3 sets of PDFs in Qtz, toasted Qtz grains, rare ballen Qtz</td>
<td>2, 3, 5, (1)</td>
</tr>
<tr>
<td>CB6-110 S</td>
<td>1455.2</td>
<td>Suevite; minor dark-gray matrix, abundant angular dark-gray clasts of mudstone &lt;2.5 cm, some partly melted; angular beige clasts &lt;1.7 cm; small white clasts &lt;4 mm, white clasts with gray bands &lt;1.5 cm; large clast of graywacke ~6 cm with white, greenish, and gray crystals</td>
<td>Qtz, Kfs, Pl, carbonate, opaque minerals</td>
<td>Qtz with PDFs in graywacke, granite, sandstone clasts, at least 2 sets; toasted Qtz grains</td>
<td>5, 4, 2, interm.</td>
</tr>
<tr>
<td>CB6-111 S</td>
<td>1458.2</td>
<td>Minor matrix, angular to subangular dark-gray clasts of siltstone &lt;3.5 cm; greenish beige clasts of mudstone &lt;1.5 cm, crumbly; light-gray subangular to rounded clasts of granite &lt;3 cm; light-gray clasts of sandstone, subrounded, &lt;1.2 cm; small white subangular clasts of polycrystalline quartz up to 0.4 cm in size</td>
<td>Qtz, Kfs, Pl, carbonate, mica, opaque minerals, Ap, Tur</td>
<td>Abundant PDFs in polycrystalline Qtz, some toasted Qtz grains</td>
<td>2</td>
</tr>
</tbody>
</table>

(Continued)
### APPENDIX. DETAILED PETROGRAPHIC DESCRIPTIONS OF SAMPLES FROM THE IMPACT BRECCIA SECTION (Continued)

<table>
<thead>
<tr>
<th>Sample and rock type*</th>
<th>Midpoint depth† (m)</th>
<th>Description based on macroscopic and microscopic observations</th>
<th>Mineral composition§</th>
<th>Shock metamorphism</th>
<th>Melt types present</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB6-112 M</td>
<td>1459.2</td>
<td>Clast of conglomerate, 40 cm; white subangular grains &lt;0.5 cm; light-gray subrounded clasts of siltstone &lt;2 cm; dark-gray subrounded clasts of mudstone &lt;1 cm; gray rounded clasts of sandstone; subrounded clast of polycrystalline quartz ~2.5 cm plus similar smaller finer-grained clasts</td>
<td>Qtz, Kfs, Pl, Ms, opaque minerals, carbonate, Ap</td>
<td>Strongly toasted Qtz grains, abundant PDFs, often 2 sets</td>
<td></td>
</tr>
<tr>
<td>CB6-113 S</td>
<td>1464.0</td>
<td>Suevite with gray matrix; dark-gray subangular clasts of mudstone and siltstone &lt;3.5 cm; white to gray subangular clasts of sandstone &lt;1 cm; clasts of graywacke, crystalline clasts; yellowish amoeboid melt particles &lt;1.5 cm; parts of core are fractured</td>
<td>Qtz, Kfs, Ms, Ms, Bt, Chl, carbonate, opaque minerals, Tur</td>
<td>PDFs and PF in Qtz, kink banding in mica</td>
<td>2</td>
</tr>
<tr>
<td>CB6-114 S</td>
<td>1467.4</td>
<td>Suevite with gray matrix; angular dark-gray clasts of siltstone &lt;3.5 cm with bands; light-gray clasts of graywacke with white sub-mm crystals 6 cm; weathered clayish clasts of various colors (light yellowish, dark gray, dark beige) &lt;0.5 cm; minor subrounded white clasts &lt;3 mm; minor subrounded light-gray clasts &lt;0.5 cm; crystalline clasts occur</td>
<td>Qtz, Kfs, Bt, Ms, carbonate, opaque minerals</td>
<td>PDFs, not decorated</td>
<td>2</td>
</tr>
<tr>
<td>CB6-115 S</td>
<td>1473.5</td>
<td>Suevite with greenish gray matrix, upper part fractured beige to gray siltstone; dark-gray subangular clasts of mudstone &lt;2 cm; light-beige clayish clasts &lt;1.5 cm; light-gray clast of graywacke 3 cm</td>
<td>Qtz, Kfs, Ms, Bt, opaque minerals</td>
<td>Kink banding in mica, PDFs not decorated, up to 3 sets</td>
<td>2, melted matrix?</td>
</tr>
<tr>
<td>CB6-116 S</td>
<td>1480.8</td>
<td>Suevite with gray matrix; one part consists of gray clasts of schist subangular &lt;2 cm in lighter gray matrix; black angular clast of mudstone 1.2 cm; part weathered, porous, with ochre-colored pigment in abundant vesicles, boundaries of different parts are inclined from horizontal level (about 80 degrees)</td>
<td>Qtz, Kfs, Ms, Chl, Bt, opaque minerals</td>
<td>Rare PDFs mostly in larger grains of polycrystalline Qtz</td>
<td>2?</td>
</tr>
<tr>
<td>CB6-117 S</td>
<td>1481.7</td>
<td>Suevite with light-gray matrix, fractured and altered; small subangular clasts of mudstone &lt;4 mm; dark-beige to angular clasts &lt;1.2 cm; gray subrounded clasts of schist &lt;0.5 cm; amoeboid polycrystalline quartz &lt;2 cm; porous and weathered parts, parts with ochre pigment</td>
<td>Qtz, Kfs, Ms, Chl, Bt, carbonate, opaque minerals, Ep, Tur</td>
<td>Abundant PDFs especially in polycrystalline Qtz, at least 2 sets, toasted Qtz grains</td>
<td>2?</td>
</tr>
<tr>
<td>CB6-118 S</td>
<td>1484.1</td>
<td>Suevite; angular clasts of sandstone, white with minor gray minerals &lt;2 cm; large light-gray yellowish clasts with tiny fractures filled with darker material &lt;1 cm; darker beige subangular clasts of mudstone &lt;1 cm; large clast of graywacke 5 cm; white greenish crumbly clast 2 cm; weathered cavities, parts with ochre pigment</td>
<td>Qtz, Kfs, mica, carbonate, opaque minerals</td>
<td>Some PDFs (not decorated) in arkose and sandstone clasts</td>
<td>2?</td>
</tr>
<tr>
<td>CB6-119 C</td>
<td>1494.0</td>
<td>Cataclasite of gneiss; matrix poor; light-gray matrix, subangular gray clasts &lt;3 cm, fractured; minor white clasts; cavities; minor subangular dark gray clasts, minor ochre spots; white veinlets of carbonate</td>
<td>Qtz, Ms, Chl, opaque minerals, Bt</td>
<td>Toasted large single grains of Qtz (with tiny PDFs), some PDFs in large Qtz crystals</td>
<td></td>
</tr>
<tr>
<td>CB6-120 S</td>
<td>1504.3</td>
<td>Suevite with gray matrix; white to gray angular clasts &lt;1 cm; large light-beige clast 4 cm with light rim, weathered; minor angular clasts of mudstone &lt;0.5 cm; clast with white and greenish crystals 1.5 cm; subangular to subrounded clasts of siltstone &lt;2 cm; two dark reddish and beige clasts of mudstone 0.6 and 2.5 cm</td>
<td>Qtz, Ms, Pl, Kfs, Chl, carbonate, opaque minerals, Bt</td>
<td>Toasted Qtz grains with tiny PDFs, PDFs and PFs in Qtz</td>
<td>2</td>
</tr>
<tr>
<td>CB6-121 S</td>
<td>1508.5</td>
<td>Suevite, matrix with white and greenish crystals; large beige to yellowish to gray clasts of supposedly siltstone &lt;3.5 cm; gray subangular clasts of siltstone &lt;1.2 cm; clasts of graywacke; crumbly, abundant vesicles</td>
<td>Qtz, Ms, Kfs, Chl, opaque minerals, Tur, Zrn</td>
<td>PDFs in Qtz, toasted Qtz grains</td>
<td>2</td>
</tr>
<tr>
<td>CB6-122 C</td>
<td>1511.9</td>
<td>Cataclasite of gneiss, light-gray with darker-gray to greenish fractured clasts; parts with polycrystalline quartz; small fractures filled with carbonate; tiny sulfides in a cavity</td>
<td>Qtz, Chl, carbonate, Ms, Kfs, opaque minerals</td>
<td>Many Qtz grains with PDFs, some PFs</td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Sample and rock type*</th>
<th>Midpoint depth† (m)</th>
<th>Description based on macroscopic and microscopic observations</th>
<th>Mineral composition‡</th>
<th>Shock metamorphism</th>
<th>Melt types present</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB6-123 C</td>
<td>1514.3</td>
<td>Cataclasite of mafic rock; greenish gray clasts &lt;5 cm, very fractured; fractures filled with dark greenish minerals; carbonate in form of small white crystals or filling of fractures</td>
<td>Qtz, Kfs, Pl, amphibole (Tr), Chl, Ms, opaque minerals, carbonate</td>
<td>Rare PDFs, Qtz too fine-grained and rare</td>
<td></td>
</tr>
<tr>
<td>CB6-124 C</td>
<td>1516.2</td>
<td>Cataclasite of gneiss; gray clasts up to 3 cm, very fractured; fractures filled with light-gray to greenish minerals</td>
<td>Qtz, Chl, Ms, carbonate, Kfs, opaque minerals</td>
<td>Many Qtz grains with PDFs, some PFs</td>
<td></td>
</tr>
<tr>
<td>CB6-125 M</td>
<td>1522.7</td>
<td>Clast of conglomerate (about 40 cm long in the core); subrounded to rounded clasts of siltstone &lt;4 cm; subrounded white clasts of sandstone &lt;0.5 cm; inclined white vein (about 70 degrees); minor clasts of mudstone to 3 mm</td>
<td>Qtz, Pl, Kfs, Ms, calcite, opaque minerals, Zrn</td>
<td>Most of the Qtz grains shocked, toasted, abundant PDFs, at least 2 sets, some PFs</td>
<td></td>
</tr>
<tr>
<td>CB6-126 S</td>
<td>1529.3</td>
<td>Suevite with gray matrix; large angular clast of sandstone 10 cm, light-gray with white minerals in tiny fractures plus smaller sandstone clasts; angular clasts of mudstone &lt;1.5 cm; subangular white clasts &lt;4 mm; greenish gray crumbly weathered clasts, altered melt particles</td>
<td>Qtz, Ms, Bt, carbonates, opaque minerals, Pl, ompaque minerals</td>
<td>Tiny PDFs in sandstone and in single Qtz grains</td>
<td></td>
</tr>
<tr>
<td>CB6-127 S</td>
<td>1535.4</td>
<td>Suevite; gray matrix; subangular darker-gray clasts of siltstone &lt;3 cm; angular to subangular light-gray to white clasts &lt;1.5 cm; large clasts of arkose &lt;5 cm with white and light-gray grains &lt;3 mm; clasts of graywacke</td>
<td>Qtz, Kfs, Ms, Bt, carbonates, opaque minerals, Pl, ompaque minerals</td>
<td>Many grains slightly tosted, especially in conglomerate clast, some PDFs PDFs in Qtz</td>
<td></td>
</tr>
<tr>
<td>CB6-128 L</td>
<td>1536.5</td>
<td>Polymict lithic impact breccia; upper part—massive white and gray quartz, fractured and altered along fractures; middle part—beige clayish material; bottom part—gray matrix, angular gray clasts &lt;1.5 cm, deformed white clasts &lt;0.5 cm</td>
<td>Qtz, Kfs, Pl, Ms, Bt, Chl, carbonates, opaque minerals, Tur</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB6-129 C</td>
<td>1542.7</td>
<td>Cataclastic schist/gneiss, gray clasts &lt;0.8 cm, deformed, mylonitic structure, narrow white bands, inclined layering (about 45 degrees), graphitic</td>
<td>Qtz, Chl, Ms, Bt, opaque minerals, garnet</td>
<td>No shock effects, Qtz too fine-grained and not abundant</td>
<td></td>
</tr>
<tr>
<td>CB6-130 C</td>
<td>1547.4</td>
<td>Cataclastic schist/gneiss, light greenish gray schist, highly deformed, with white quartz veins; minor sulfides (ochre rim) in veins, in upper part inclined layering (45 degrees); small bottom part—gray matrix with angular white and gray clasts to 0.5 cm</td>
<td>Qtz, Ms, Chl, carbonate, Ep, opaque minerals</td>
<td>Some PFs and PDFs in veins, decorated, some toasted Qtz grains</td>
<td></td>
</tr>
<tr>
<td>KB-2 I</td>
<td>1402.9</td>
<td>Impact melt rock, clast-rich with dark-gray melt matrix; some larger clasts of sandstone; small quartz clasts; other small partly melted clasts; abundant flow textures</td>
<td>Qtz, feldspar, opaque minerals, laths of pyroxene</td>
<td>PDFs in Qtz, at least 2 sets, but generally not much shocked and only slightly toasted</td>
<td></td>
</tr>
<tr>
<td>KB-3 I</td>
<td>1404.4</td>
<td>Impact melt rock, dark-gray melt matrix, some larger clasts—schist, sandstone, quartz; small clasts of fine-grained sediments; most clasts partly melted; some small (mm-sized) altered olive-green melt particles; abundant flow textures</td>
<td>Qtz, Bt, feldspar, clay minerals, opaque minerals</td>
<td>PDFs in Qtz, at least 2 sets, Qtz slightly toasted, similar to KB2, but more shocked</td>
<td></td>
</tr>
<tr>
<td>Sample and rock type*</td>
<td>Midpoint depth† (m)</td>
<td>Description based on macroscopic and microscopic observations</td>
<td>Mineral composition§</td>
<td>Shock metamorphism</td>
<td>Melt types present</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------------------</td>
<td>---------------------------------------------------------------</td>
<td>----------------------</td>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>KB-4</td>
<td>1405.7</td>
<td>Impact melt rock, dark-gray melt matrix, clasts are only small and all are partly melted, some clasts of dark-gray fine sediments; sandstone clasts; abundant flow textures in melt matrix</td>
<td>Qtz, feldspar, Bt, opaque minerals, laths of pyroxene</td>
<td>PDFs in Qtz, slightly toasted, ballen Qtz</td>
<td>4, 3, 5?</td>
</tr>
<tr>
<td>KB-5</td>
<td>1412.9</td>
<td>Suevite with light-gray particulate matrix, clasts are small (&lt;2 cm), abundant dark-gray sedimentary clasts—siltstone, mudstone; clasts of schist, clast of granite, very abundant small (~0.5 cm) yellowish melt particles, similar to sample CB6-097</td>
<td>Qtz, Ms, Bt, Kfs, Pl, Chl, opaque minerals</td>
<td>PDFs in Qtz, some slightly toasted, abundant in polycrystalline Qtz</td>
<td>1, 2</td>
</tr>
<tr>
<td>KB-6</td>
<td>1468.7</td>
<td>Conglomerate clast (40 cm), large clasts (5 cm) of mostly sandstone, some crosscutting quartz veins, opaque minerals (rutile, ilmenite) in veins and fractures, clasts of granite, all fractured (possibly pre-impact fracturing)</td>
<td>Qtz, Pl, Kfs, opaque minerals (rutile, ilmenite), Chl</td>
<td>Qtz grains very toasted, abundant PDFs in Qtz</td>
<td></td>
</tr>
</tbody>
</table>

*S—suevite, I—impact melt rock, L—polymict lithic impact breccia, C—cataclasite, M—conglomerate.
†Depths are corrected values (L. Edwards, U.S. Geological Survey, 2007, personal commun.).
§Qtz—quartz, Kfs—K-feldspar, Pl—plagioclase, Ms—muscovite, Bt—biotite, Chl—chlorite, Tur—tourmaline, Tr—tremolite, Zrn—zircon, Ep—epidote (Kretz, 1983). Minerals are listed in order of abundance, which is only estimated from the microscopic observations.
#interm.—melt type intermediate between type 1 and 2.
REFERENCES CITED


