High-resolution X-ray computed tomography of impactites

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[1] High-resolution X-ray computed tomography (HRXCT) is a nondestructive method used to study the interiors of opaque solid objects. Here we present the results of a first application of the HRXCT method to imaging the interior of impactites, in particular, suevites (glass-bearing impact breccias) from the Bosumtwi (Ghana) and Ries (Germany) craters and a Muong Nong–type tektite from Thailand. The aim of these studies was to determine the three-dimensional (3-D) distribution of clasts within the matrix of the suevites, to test this technique with respect to its suitability for the recognition of different clast types of different densities, and to determine textural characteristics of the tektite. The main part of the study concentrated on a large suevite sample (about 10 × 7 × 5 cm) from the Bosumtwi impact structure. Target rock fragments in the Bosumtwi sample consist of greywacke and sandstone/quartzitic rocks, shale and phyllite, and granites. Another large clast component is composed of impact melt and glass fragments. Macroscopic petrography and thin section petrography were used to identify the clast types in the specimen for correlation with its HRXCT signatures. The results show that HRXCT allows the easy discrimination of the relatively frothy inclusions of glassy melt in the suevites, as they are darker than the matrix in the raw X-ray scans and can be traced through the whole sample. Color or gray scale applications allow the distinction of at least four different clast types based on density differences. The size of the smallest discernable clasts (about 0.5 mm) is determined by the resolution of the measurements, which, in turn, is a function of scan slice thickness and field of view. In the case of the tektite sample, we were also able to image the 3-D distribution of vesicles, possibly indicating glass flow. The HRXCT method allows us to determine the three-dimensional distribution of clast populations in impact breccias by image processing techniques and to quantify their abundances in volume percent.

INDEX TERMS: 3672 Mineralogy and Petrology: Planetary mineralogy and petrology (5410); 3694 Mineralogy and Petrology: Instruments and techniques; 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 6240 Planetology: Solar System Objects: Meteorites and tektites; KEYWORDS: Impact breccia, Bosumtwi crater, X-ray computed tomography, suevite, tektite, Ries crater


1. Introduction

[2] High-resolution X-ray computed tomography (HRXCT) is a completely nondestructive means of examining the interiors of opaque solid objects. It produces two-dimensional images ("slices") that show the interior of an object as if it had been sliced open along the image plane for viewing. Contrast in an X-ray computed tomography (CT) image is generated by differences in X-ray attenuation that arise principally from density differences, but are also strongly influenced by atomic number [Markowicz, 1993]. To create tomographic images, a planar X-ray fan beam of known thickness is directed through a sample from multiple orientations and is intercepted by a linear array of detectors to measure the decrease in X-ray intensity caused by attenuation along each beam path. These data are used to compute an X-ray attenuation map of the specimen in the scan plane, giving the slice image. By stacking equidistant slices, it is possible to
obtain a continuous three-dimensional map of the density variations in the object. This technique was developed for medical diagnosis, but new CT instruments with significantly higher X-ray energy and spatial resolution allow imaging of the interiors of geological samples (see Ketchem and Carlson [2001] for details).

[1] The use of high-resolution X-ray CT to examine the three-dimensional distribution of phases in metamorphic rocks was pioneered by Carlson and co-workers [Carlson and Denison, 1992; Denison and Carlson, 1997; Denison et al., 1997]. Early medical instruments were used for the application of this method to meteoritics to examine and locate inclusions in meteorites for later analysis [Arnold et al., 1982], but the lack of resolution and penetration capability of these early generation instruments limited their usefulness. The advent of higher-resolution instruments has allowed much more detailed work, including the measurement of the size or shape of inclusions in meteorites to test hypotheses of their origin [Kuebler et al., 1999], the characterization of a metal melt segregation from a mixed silicate-metal matrix in a lodranite [Carlson and McCoy, 1998; McCoy and Carlson, 1998], or the internal structure of a Martian meteorite [Tsuchiyama et al., 1999]. Common applications of this technique deal with studies of fossils [e.g., Balanoff, 2001; Rowe et al., 2001].

[2] This is the first application of high-resolution X-ray CT to the study of impact breccias that the authors are aware of. Preliminary results of our study were presented in abstract form by Koeberl et al. [1998a]. The objective of the present study was to explore the use of the HRXCT method for impactites and to see if it is possible to not only determine the three-dimensional distribution of clasts in breccias, but also to quantify it.

2. Meaning of Computed Tomography (CT) Data

[3] The grayscales in X-ray CT images reflect the extent to which the various materials attenuate the X-ray signal along each beam path. For a monochromatic X-ray beam passing through a homogeneous material, this relationship is described by the equation

\[ I = I_0 e^{-\mu x} \]  

where \( I_0 \) and \( I \) are the initial and final X-ray intensities (photons \( s^{-1} \)), \( \mu \) (\( cm^{-1} \)) is the linear attenuation coefficient of the material at the X-ray energy used, and \( x \) (cm) is the distance traversed through the material. The attenuation behavior of any material is primarily a function of its density and its atomic constituents. For an inhomogeneous object consisting of multiple materials, this equation becomes

\[ I = I_0 e^{-\sum \mu_i x_i} \]  

An additional factor that complicates the direct interpretation of CT numbers is that the attenuation coefficient is also a strong function of X-ray energy. For any given material the linear attenuation coefficient diminishes over the energy range from roughly 10 to 5000 keV, with exceptions at the absorption edges of high-Z elements that are generally insignificant for CT work. Thus, lower-energy X-rays are attenuated more easily than higher-energy ones. Because the X-ray beam in most CT systems is polychromatic, for equation (2) to fully describe X-ray attenuation it must be integrated over the range of energies present in the beam. However, insofar as CT only produces a single grayscale value, this value is usually considered to represent the attenuation coefficient at some average energy.

3. Samples

[7] Suevite is defined as a breccia of impact origin that is composed of a mixture of clastic material (lithic and mineral fragments derived from the various target rocks occurring in the impacted region) and fragments of impact melt or glass, at various proportions. Generally, the distinction between suevitic and fragmental (also termed lithic) impact breccias is based on the lack or presence of melt/glass fragments, respectively. The term “suevite” is derived from the region in southern Germany (“Schwaben” = Suevia) where the type locality, the Ries meteorite impact structure, is located.

[8] The 11 km diameter, 1.07 Ma old, Bosumtwi impact structure is located in Ghana, West Africa. It is the youngest and best-preserved impact crater of this size. At Bosumtwi, suevite has been mapped as fallout impact breccia in the environs of the crater, mostly within 1 to 2 km outside of the crater rim, in the northern and south-southwest sectors [e.g., Koeberl et al., 1998b; Reimold et al., 1998, and references therein]. Outcrops are rare and small, but a shallow drilling program [Boamah and Koeberl, 1999, 2002] has in recent years established that remnants of the former coherent ejecta blanket are more extensive than surface mapping in this densely rain forested terrane has indicated. There is some indication of the extent of the fallout breccia from aerogeophysical data [cf. Boamah and Koeberl, 2002]. On the surface, suevite occurs as large blocks (Figure 1), but digging below the surficial soil reveals patches of suevite as well, which have been found [Boamah and Koeberl, 2002] to be up to 16 m thick in places.

[9] The sample used in the present study is part of a large collection of target rocks and breccias collected at the Bosumtwi impact structure during fieldwork by two of us (C.K., W.U.R.) in 1997. Some data on these samples have been published [e.g., Reimold et al., 1998], but more work is still in progress.

[10] Bosumtwi suevite contains a highly variable proportion of mainly glassy and vesicular, only partially weathered, impact melt fragments, the abundance of which ranges from about 30 to 60% by volume of the overall clast proportion. In addition, widely variable proportions of clasts derived from metasedimentary and granitoid target rocks occur. Their relative abundances may vary significantly, but every sample studied by our group contains a significant contribution of granite-derived clasts, as well as a component derived from quartz and quartz-feldspar pegmatites or veins. Every sample of Bosumtwi suevite studied by us contains at least some moderately (single to multiple sets of planar deformation features (PDFs)) or strongly shocked (presence of diaplectic glass, mineral and rock melts) granitoid-derived inclusions. In addition, greywacke and sandstone/quartzite, aplite, and shale/schist/phylite inclusions are important. Most metasedimentary lithic inclusions
are unshocked, but those clasts of this type that are shocked, display all stages of shock metamorphism.

[11] This investigation was mostly concerned with analysis of a large (10 × 7 × 5 cm) slice of a typical Bosumtwi suevite sample (sample number LB-39) (Figure 2). The sample was cut on top and bottom for experimental reasons. To determine the clast population of the Bosumtwi sample and to help calibrate the HRXCT images, two large (10 × 5 cm) thin sections were cut (after the HRXCT measurements) from near the top and the bottom of the sample (Figures 3a and 3b).

[12] For comparison with the detailed studies of the Bosumtwi suevite, two other samples were investigated as well: a large suevite sample from the Otting quarry in the Ries impact structure in southern Germany, and a Muong Nong–type tektite (ca. 6 × 5 × 5 cm) from Thailand (locality unknown). In contrast to the young Bosumtwi crater, the Ries is 15 million years old, whereas the Australasian tektite strewn field has an age of about 0.8 m.y.

Information on the petrography and shock metamorphism of suevite from the Ries is given by, for example, Stöffler [1966], von Engelhardt [1990, 1997], and von Engelhardt and Graup [1984], and references therein. The various characteristics and properties of Muong Nong–type tektites are described by Koeberl [1992].

4. Experimental Procedures

[13] The samples were all scanned at the University of Texas High-Resolution X-ray CT Facility, which consists of two linked tomography systems. The high-resolution system consists of a 420 kV dual-spot X-ray source (Pantak HF420) and two detectors. For the analyses described here, a 512-channel linear array detector (Bio-Imaging Research P250D) with discrete cadmium tungstate scintillators at 312-μm spacing was used. The ultra-high-resolution system consists of a 200 kV microfocal X-ray source (FeinFocus FXE-200.20) and 9-inch image intensifier. The image

Figure 1. Field occurrence of suevitic breccia at the Bosumtwi impact crater, Ghana. On the surface, suevite is found within the densely vegetated crater environs, mostly within 1–2 km outside the crater rim, in the form of large blocks of up to several meters in dimension. (a) View of a large, ridge-like outcrop of suevite, about 1.5 km north of the crater rim, which appears in the background (with one of the authors, C.K., on the left). (b) Boulder-like outcrop of suevite, same general location.

Figure 2. Photograph of cut surface of the Bosumtwi suevite sample used for this HRXCT study (bottom side). This side of the sample is characterized by numerous small (a few mm in size) clasts. The bright white clast in the lower third of the sample is aplite, the light gray clast on the right edge is greywacke, the frothy inclusion in the center is glass, and the dark area in the upper right is iron oxide staining. Scale is the same as in Figure 3.
created by the image intensifier is read by a CCD camera, and the video signal is divided into a 512-channel virtual detector using software. The system was designed and assembled to University of Texas specifications by Bio-Imaging Research of Lincolnshire, Illinois.

[14] In order to reduce scanning artifacts, all samples were placed in cylindrical containers and packed in glass sandblasting beads; this technique allows calibrations to be undertaken that help compensate for beam hardening and variable detector response that can lead to ring artifacts [Ketcham and Carlson, 2001]. Each sample was wrapped in cellophane before being packed in the container to protect it and provide a low-attenuation border between it and the glass, to facilitate later removal of the packing material from the scan images.

[15] The Bosumtwi sample was scanned on the high-resolution system operating in third-generation (rotate-only) mode, with X-rays generated at 410 kV and 4.8 mA with a 1.8-mm spot size. In rotate-only mode, the maximum sample diameter is about 300 mm, whereas in second-generation (rotate-translate) mode, it is about 500 mm. Slice thickness was set using tungsten collimators; a total of 200 250-μm-thick CT slices were collected at 200 μm intervals. Each CT slice was acquired by rotating the specimen through 1800 angular orientations (views), with a 64 ms acquisition time per view, resulting in a scanning time of roughly 2 minutes min per CT slice. Total acquisition time was on the order of 7 h. The images produced show a field of view of 130 mm.

[16] The Ries Crater sample was scanned using the high-resolution system using the same X-ray conditions as the Bosumtwi sample. A total of one hundred and forty 500-μm-thick CT slices were collected at 400 μm intervals, with 2400 views and an acquisition time of 32 ms per view for a total data acquisition time of approximately 80 seconds s per slice. The scans were acquired in a modified third-generation mode, in which the center of the sample was partially offset from the center of the X-ray fan beam, resulting in part of it being outside of the beam; during the course of a rotation all of the sample comes into the scan field. This modified scanning mode permitted the efficient acquisition of scans with a 175-mm field of view, despite the fact that the total detector width is only 160 mm.

Figure 3. (a) Photograph of cut surface of Bosumtwi suevite sample used for the HRXCT study (top side), with identification of major clasts. Abbreviations: Gr-Alt altered granite, S+C schist plus carbonate, GW greywacke, Qz quartzite, Qz-Peg quartz-pegmatite, Hem hematite. (b) Thin section (at same scale as Figure 3a) of the same surface of the Bosumtwi samples (a few mm above the surface shown in Figure 3a). Compare Figure 3a for clast types.
The tektite sample was scanned using the ultra-high-resolution system with X-rays generated at 180 kV and 0.133 mA, with a spot size of roughly 30 μm. Scanning conditions for this sample were slightly different compared to the suevite samples because of its smaller size. A total of two hundred and twenty-eight 150-μm-thick CT slices were collected at 140 μm intervals. Each slice consisted of 1800 views with two 1/30-second samples per view, for a per-slice data acquisition time of 2 minutes. Because the image intensifier collects volumetric data, the system is capable of acquiring three slices simultaneously, tripling scanning efficiency at a negligible cost in image distortion, which was minimized by scanning in two passes and interleaving the slices. The sample was scanned using an offset mode. The field of view for each image is 49 mm.

In the case of all three experiments, the resulting images were 12-bit grayscale (NB: earlier gray scale was spelled differently!), with values ranging from 0 to 4095, and with dimensions of 512x512 pixels. Grayscales were optimized to maximize contrast among the phases present in each sample, and were not calibrated to an external scale or each other. The images were then exported to 8-bit TIFF format for processing; the effect of the resulting loss of precision in the grayscale range is insignificant for the present study.

5. Processing of HRXCT Images: Results

The individual images of the Bosumtwi and Ries Crater samples were processed to remove the glass bead signatures in Adobe Photoshop, to facilitate measurements and three-dimensional visualization. The cellophane layer between the samples and the glass made selection and deletion of the glass beads fairly straightforward, although in many places the boundary had to be widened manually to increase the separation. The results of this step of the data processing are shown in Figures 4a–4d, which contains images of four different CT slices through the Bosumtwi suevite. The grayscales for the clasts show a wide variation, ranging from white to very dark gray. The images also show how significantly the clast population changes within spacings of about one centimeter. Only one large medium-gray clast is visible (lower left) in both Figures 4c and 4d, otherwise there is no overlap. Most small clasts persist only through 2–5 scan planes. The individual slices were then combined to give a three-dimensional image of the density distributions (i.e., clast population) in the sample, which shows up best in color-coded images, as shown in Figure 5. This figure gives three different views of the same sample, once with the groundmass rendered partly transparent (left), once emphasizing high density clasts (center), and once showing only low-density clasts (right).

The Bosumtwi images were then analyzed to determine the relative percentages of clasts of schist, pegmatite quartz, altered granite, aplite, and melt glass. To accomplish this, the sample was first sectioned along one of the scan planes, and the different clast types were directly identified on a large thin section as mentioned above. Then, the corresponding CT images were examined to determine how these clast types appeared and how they could be distinguished. Because of the variable composition within and among the clast types, separating them required taking into account both their grayscales, which correspond directly to the attenuation characteristics of their component materials, and their textural features. The grayscale ranges of various clast types had considerable overlap, so simple thresholding techniques for separating them were inadequate. Instead, each image was interpreted individually based on combined grayscale and texture information; each identified clast was marked. Only fairly large clasts (> 0.8...
mm long in-plane dimension) could be successfully identified; the smaller grains that constitute the groundmass could not be differentiated with confidence at the optical scale. In cases where differentiation between clast types was difficult, images from adjacent CT slices were used; all clast identifications were consistent from slice to slice. After reviewing this analysis, we determined that schist and altered granite could not be confidently distinguished from each other, so their results were combined. The three-dimensional distribution of the four clast types that could be discerned is shown in Figure 6, giving a striking impression of the thoroughly polymict nature of the suevite.

[21] Clast identification and marking was done on individual 2-D CT slices using Adobe Photoshop\textsuperscript{1}. Software is under development at the University of Texas that allows processing and analysis in three dimensions, greatly improving efficiency [Ketcham and Shashidhar, 2001].

[22] Results for the Bosumtwi sample are shown in Table 1. Clasts (>0.5 mm in size) make up one quarter of the sample, whereas the other three quarters comprise fine-grained groundmass or matrix. Impact glass, as well as schist and granite, make up the largest proportion of clasts (about 9 vol.% each). The sample was large enough to contain a statistically significant number of clasts on which this analysis is based.

[23] We have performed only a semi-quantitative evaluation of the results for the Ries suevite sample, but the proportions between clasts and matrix are similar to those of the Bosumtwi sample. A couple of images of CT slices through the Ries suevite are shown in Figure 7, and the three-dimensional reconstruction, as with the Bosumtwi sample showing clasts of high and low density, in Figure 8. A related image of the tektite sample is shown in Figure 9. In the case of the tektite, no clast inclusions larger than the limit of about 0.5 mm given by the scan thickness of 150 \( \mu \text{m} \) were seen. Secondary iron oxide-rich (lateritic?) material filling a few large fractures is fairly evident, as are a large number of bubbles throughout the solid glass. The
tekrite sample will be dealt with in more detail in a separate publication.

6. Discussion and Conclusions

[24] The present study is the first application of the HRXCT method to the investigation of impactites. Numerous CT slices through each sample were obtained and stacked with image processing techniques, allowing the construction of a three-dimensional density model of the rocks. The two-dimensional slices and the three-dimensional reconstructions can be used to identify a variety of clast types and their distribution, based on their relative density contrasts. In particular, the method allows the easy discrimination of the relatively frothy inclusions of glassy melt in the suevites. These melt clasts appear darker than the matrix in the raw X-ray scans and can be traced through the whole sample. Usage of color or grayscale values allows the distinction of at least four different clast types based on density differences. The size of the smallest discernable clasts (0.5–0.8 mm) is determined by the resolution of the measurements. The resolution is, to a first order, controlled by the data dimensions: the slice thickness and pixel size. While slice thickness is determined by either detector dimension or collimation, optimal pixel size is a function of detector coverage. As a general rule, the entire specimen cross-section must appear in the scan field (i.e., one can generally not scan only an interior subsection), and the number of detectors imaging this field of view determines the number of pixel dimension. For example, a 512-channel detector gathers enough information for a 512-pixel image, provided that most of the channels are used. If an offset mode is employed, effective detector coverage increases, justifying larger image sizes. In order to be resolvable, an individual object must span several pixels in an image, with precise requirements depending on its attenuation properties relative to surrounding materials. Thus, in the example of a 512-channel detector in the centered mode, an object must be at least a few 512th of the specimen dimension to be potentially resolvable. The chosen resolution also influences

Table 1. Percentages of Clasts in Bosumtwi Crater Sample Identified in CT Images

<table>
<thead>
<tr>
<th>Clast Type</th>
<th>Vol.%</th>
<th>Pegmatite</th>
<th>Schist + Altered Granite</th>
<th>Melt (Glass)</th>
<th>Aplite</th>
<th>Total Clasts</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Pegmatite</td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schist + Altered Granite</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melt (Glass)</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aplite</td>
<td>24.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Clasts</td>
<td></td>
<td>75.8</td>
<td></td>
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the duration (and, thus, cost) of the experiment. Slice thickness for the Bosumtwi suevite sample was 250 \( \mu m \), which resulted in a scanning time of about 7 h. If 500-\( \mu m \) slices had been acquired, per-slice acquisition time could have been halved to achieve similar noise levels, resulting in a reduction of scanning time by a factor of 4. However, in that case the smallest discernable clast would have been on the order of 1.0–1.5 mm.

[25] The method allows quantification of the abundance of the various clast populations by image processing techniques. In the present case we were able to quantify the clast population and the clast to matrix (groundmass) ratio of the Bosumtwi suevite sample. We found that about 25% by volume of the sample are composed of clasts, whereas matrix comprises 75% (by volume) of the suevite. Averaged point-counting analysis on the two large thin sections resulted in very similar values. Semi-quantitative image processing indicates similar results for the Ries suevite sample as well. These data agree very well with classical petrographic data obtained by von Engelhardt [1997] on fallout suevite at the Ries. Based on a petrographic study of 806 clasts from 10 outcrops: he found that Ries fallout suevite contains, on average, 79 vol.% groundmass and 21 vol.% clasts (including 16 vol.% glass, 4 vol.% crystalline basement clasts, and 0.4 vol.% sedimentary rocks). Von Engelhardt [1997] obtained his data by petrographic study of each clast in thin section.

[26] In the present study we were able to obtain statistically significant results within just one sample, based on a similarly large number of clasts, without having to cut the rock and prepare and study a large number of thin sections. As the images in Figures 4a–4d show, each CT slice contains at least 50 identifiable clasts larger than about 0.8 mm. A few of them are up to several cm in size, but most of them are just up to a few mm in size. Given the slice thickness of 250 \( \mu m \) and a spacing of 200 \( \mu m \) (i.e., minimal overlap), most clasts extend over 4–10 slices, but the smaller ones will be recognizable in only about half to two thirds of that number. With 200 slices through the Bosumtwi sample, this results in close to 1000 clasts being counted in the image processing procedure. The size of the smallest discernable clasts was about 0.5 mm; this is determined by the resolution of the measurements, which depends on scan slice thickness and field of view. Compared to standard thin section analysis, each CT slice of the Bosumtwi suevite covers an area about ten times larger. The results of our statistical analysis of the clast population indicate that a significant fraction of the clasts in the Bosumtwi sample are derived from the basement, and that they (and the glass fragments) are more or less homogeneously distributed throughout the suevite sample.

[27] In conclusion, HRXCT allows the nondestructive determination of the three-dimensional distribution and relative abundance of clast types within fist-sized or larger samples of suevitic impact breccia. The results are statistically significant and agree well with previous studies based on the classical petrographic study of dozens to hundreds of thin sections. Despite the long scanning times and the

Figure 9. Three-dimensional reconstruction of the Muong Nong–type tektite sample. The images on the left and bottom right show the whole sample from two different angles with the matrix rendered transparent; in this mode of display the vesicles that occur throughout the whole sample show up very well. The white areas represent lateritic fracture fills, and the lighter gray areas indicate the sample edges. The image on the upper right side represents a cube cut out of the tektite, with opaque matrix, indicating the layered texture that is typical of Muong Nong–type tektites. In this view the light and dark gray zones represent differences in density due to the presence of small vesicles. A fracture filling is obvious on the left side of the top face of the cube.
extensive image processing, the method is less involved and
time-consuming than classical petrographic analysis of a
sufficient number of thin sections to obtain a similar statisti-
cal result, and it also provides potentially useful 3-D
textural data.

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