

Reconstruction of the Chicxulub ejecta plume from its deposits in drill core Yaxcopoil-1

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ABSTRACT

Formation conditions of suevite-like impactites from an ~100 m thick drill core sequence through the Cretaceous-Tertiary Chicxulub crater were reconstructed from empirical data obtained by petrologic and image analytical methods. The temporal evolution of the cratering process from the initial stage of excavation to the collapse of the ejecta plume is evidenced by the petrographic characteristics and modal composition of the suevitic rocks, including the size distribution and shape parameters of melt particles. Emplacement of the lowermost suevitic deposits likely started in the first minute after the impact by the passing ejecta curtain that interacted with the expanding ejecta plume. These ejecta deposits were capped by a tongue of coherent impact melt that was transported outward from the crater center during the collapse of the central uplift ~5 min after impact. On top of this brecciated impact melt rock, the collapsing ejecta plume deposited air-fall suevites. The basal air-fall unit, Middle Suevite, may have been deposited due to a density current-like clumping of hot debris. With progressive cooling, regions of the ejecta plume were entrained in its collapse that produced vapor condensates, accretionary rims, and different oxygen fugacities. After cooling progressed, atmospheric conditions began to reestablish over the crater and turbulence decreased, supposedly after the first 10 min of initial ejecta plume collapse. This led to a winnowing out of fine matrix material and distinct sorting. However, due to aquatic reworking, only material that was deposited until ~1 h after cessation of turbulent atmospheric conditions was retained.

Keywords: Chicxulub crater, suevite, impactite, meteorite crater, Yaxcopoil-1, ejecta, Cretaceous-Tertiary, Yucatan, impact.

INTRODUCTION

The ejecta plume of an impact crater consists of a highly dynamic mixture of vaporized and melted target rock and projectile material and solid rock debris. It forms from extreme starting conditions with pressures of several 100 GPa and temperatures of >10,000 °C in the first phase of the impact cratering process, when the penetrating hypervelocity projectile comes to rest in the target rocks (e.g., Melosh, 1989; Pierazzo et al., 1998; Shuvalov, 2003). The ejecta plume expands in its early phase with a velocity of >5 km/s (Melosh, 1991; Pierazzo et al., 1998), decelerates, and finally collapses. Products of this collapse are suevite rocks (Kieffer and Simonds, 1980), geologic recorders of this fundamental process on the terrestrial planets.

The 65 Ma, ~180-km-diameter Chicxulub impact crater is the largest known terrestrial impact crater of the Phanerozoic, the origin for global ejecta deposits and the most probable cause for the Cretaceous-Tertiary (K-T) mass extinction (e.g., Alvarez et al., 1980; Hildebrand et al., 1991; Swisher et al., 1992; Krogh et al., 1993; Claeys et al., 2002; Arenillas et al., 2006). Because the Chicxulub impact crater is buried and little drill core material had been available for scientific study until recently, most previous petrographic work was limited in focus to nonsystematic analyses (e.g., Kring and Boynton, 1992; Schuraytz et al., 1994; Ward et al., 1995; Sharpton et al., 1996; Kettrup et al., 2000; Claeys et al., 2003). This situation changed with International Continental Drilling Program's Yaxcopoil-1 (Yax-1) drilling, ~60 km south of the crater's center in the annular trough (Dressler et al., 2003; Urrutia-Fucugauchi et al., 2004). Beneath 795 m of post-impact Tertiary sediments, it intersected 100 m of continuous suevite-like impactites (Dressler et al., 2003) that were subdivided into 6 units (Stöffler et al., 2004): Upper Sorted Suevite (USS, 794–808 m),

Lower Sorted Suevite (LSS, 808–823 m), Upper Suevite (US, 823–846 m), Middle Suevite (MS, 846–861 m), Brecciated Impact Melt Rock (BMR, 861–885 m), and Lower Suevite (LS, 885–895 m). Two suevitic dikes, 8 and 80 cm thick, are present at 909 and 916 m.

Qualitative petrographic analyses were carried out on these units by Dressler et al. (2003, 2004), Hecht et al. (2004), Kring et al. (2004), Stöffler et al. (2004), and Tuchscherer et al. (2004a, 2004b, 2005). These authors distinguished various types of melt particles based on petrographic descriptions and chemistry. The preliminary interpretation of the suevitic section is a continuous deposit that underwent some reworking of the uppermost part, the extent of which is disputed (Dressler et al., 2004; Goto et al., 2004; Stöffler et al., 2004; Tuchscherer et al., 2004a). For its emplacement, Stöffler et al. (2004) invoked a model of subsequent phases of ground surging and plume collapse; they conducted two- and three-dimensional numerical modeling studies of the emplacement and the time frame for deposition of the suevitic units of Yax-1.

Dressler et al. (2004) presented an alternative ejecta deposition model: they regard only the upper two units, Upper Sorted Suevite and Lower Sorted Suevite, as ejecta plume deposits, and interpret the Upper Suevite and Middle Suevite as ground-surge related, and the Brecciated Impact Melt Rock and Lower Suevite as parts of the ejecta curtain.

Kring et al. (2004) remarked that the Yax-1 suevite-like units represent only ~20% of the amount of impactites that were intersected at the Yucatán-6 drilling, which is also located within the crater's annular moat. Moreover, Kring et al. (2004) pointed out that the Yax-1 impact breccias are by far richer in silicate melt fragments than suevitic deposits in other craters. An ejecta emplacement model combining previous petrographic evidence from Chicxulub was presented in Kring (2005).

In order to improve previous models and identify likely formation processes, this study presents systematic analyses of the continuous

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100-m-thick sequence of melt-rich impactites at Yax-1. The petrological characteristics of components and the quantification of their occurrence and distribution are combined with quantitative fabric and textural data in order to reconstruct conditions for their emplacement. This provides ground truth for present models of ejecta plume formation, atmospheric interactions, the temperature regime of the ejection event, and its temporal evolution. Ultimately, a reconstruction of these processes is fundamental in order to substantiate extinction

scenarios associated with the aftermath of the Chicxulub impact.

SAMPLES AND ANALYTICAL PROCEDURES

The 6.35-cm-wide half-core pieces from the depth of 795–920 m at Yax-1 were photographed. We used 60 single half-core piece photographs (Table 1) with a maximum size of 9.5×6.35 cm at constant three-fold magnification (Fig. 1A) to visually identify components. Outlines of

components with a minimum particle area of $\sim 1 \text{ mm}^2$ were drawn on templates (Fig. 1B) that could be processed by the image analysis software Leica Qwin (Leica Microsystems, 2004).

Particle parameters determined by the image analysis software are: (1) derived orientation, which is the direction of the longest recurring extent of a particle; (2) length as equivalent circle diameter, the diameter of a circle that has the same area as the particle, and length as the longest extent of a particle; (3) width, as the width of the particle that is perpendicular to the longest extent of that particle; (4) areas of particles and reference areas that are the total area of the sample; (5) perimeters of particles as the total length of the boundary of a particle; and (6) convex area, which is the area of the polygon circumscribing the feature, formed by tangents to its boundary. Shape parameters are calculated from these data: roundness is a shape factor that is calculated from the ratio of perimeter squared to area with an adjustment factor of 1.064 that corrects the perimeter for the effect of the corners produced by the digitization of the image (Leica Microsystems, 2004):

$$\text{perimeter}^2 / (4 \times \pi \times \text{area} \times 1.064). \quad (1)$$

Fullness ratio is a shape factor that is equal to the square root of the ratio of area to convex area (Leica Microsystems, 2004). Aspect ratio is length divided by width of a particle. For the processing of shape parameter data, particles that exhibit artificial boundaries from the sample limits were excluded from analysis.

Characterization of components is based on the petrographic study of 37 drill core samples (Table 1) by macroscopic observation, optical microscopy, and scanning electron microscopy with a JEOL-JSM 6300 instrument with a RÖNTEC X-ray energy-dispersive analytical system. Electron microprobe (EMP) analyses were performed with a JEOL JXA 8800 with four wavelength dispersive spectrometers to measure the bulk composition of devitrified impact melts with clay mineral and phenocryst sizes in the low micrometer (μm) range. Operation conditions for EMP measurements are given in GSA Data Repository Table C¹. Measurement traverses of 20 spots were produced from 90 melt particles on 13 thin sections (Table 1). To ensure representative measurements of bulk compositions of the impact melt particles, measurement spots that captured voids and inclusions were identified on the thin-section traverses and eliminated from the data processing procedure. Moreover, 17 thin sections (Table 1) with maximum sizes of 2.8×4.7 cm were used to verify particle identification. Therefore, fivefold magnifications from photographic prints were

TABLE 1. LIST OF SAMPLES USED IN THIS STUDY

Unit	Thin section depth (m)	Analytical methods	Core photographs (Depth [m]/area analyzed [cm^2])	
USS	797.84	(i-7.7) (E)	799/56.5	805.6/26.2
USS	800.25	(i-11.6) (E)	802.39/41.4	
USS	803.67	(i-5.3)	805.21/31.3	
LSS	808.87		809.07/30.8	816.9/50.1
LSS	813.53	(i-4.1) (E)	809.36/12.6	819.43/50.6
LSS	815.39	(i-21.6)	809.6/25.3	819.52/24.2
LSS	818.51	(i-8.1) (E)	815.88/24.8	822.04/55.1
LSS				823.05/56.5
US	823.86	(i-6.3) (E)	824.37/59.7	834.93/57.9
US	824.01	(i-11.4)	825.16/59.4	837.9/58.6
US	825.85		827.7/58.2	839.65/58.6
US	832.12	(i-6.9) (E)	827.92/59.9	842.02/58
US	838.29	(i-9.4)	829.92/58.1	843.15/57.4
US	842.06		831.7/58	844.71/56.2
US	842.51		833.13/58.8	
MS	848.38	(i-5.3) (E)	846.5/57.9	853.75/59.2
MS	852.05	(i-9.8) (E)	847.24/58.1	854.53/58.2
MS	852.8		848.43/56.8	857.5/59.9
MS	855.32		849.86/58.7	859/58.9
MS	860.25		852.29/59.3	860.27/59.1
MS				860.58/57.9
BMR	861.85		862.13/59.6	872.32/55.4
BMR	865.01		864.92/58.7	875.7/58.8
BMR	868.08	(i-6.4) (E)	867.15/58.5	878.23/58.1
BMR	875.25		867.3/58.6	879.92/59.3
BMR	879.58	(i-6.7) (E)	871.46/59.8	882.5/57.8
BMR				884.8/58.6
LS	884.92		887.5/52.9	893.7/58.9
LS	885.15	(i-12.3) (E)	887.95/55.6	893.96/58.8
LS	885.77		888.48/59.4	
LS	886.14		889.74/59.4	
LS	889.32		890.29/58.5	
LS	894.83	(i-8.2) (E)	891.76/59.8	
LS	895		892.11/59.1	
SD	909.01		916.14/56.8	
SD	909.11		916.27/59	
SD	909.19		916.37/49.2	
SD	916.23			
SD	916.34			
SD	916.65	(i-6.7) (E)		
SD	916.65			

Note: (i)—image analysis and area analyzed in cm^2 , (E)—electron microprobe measurements. Analytical methods refer to thin section samples. Image analysis was performed on the core photographs. USS—Upper Sorted Suevite; US—Upper Suevite; MS—Middle Suevite; BMR—Brecciated Impact Melt Rock; LS—Lower Suevite; SD—Suevitic Dike.

used for image analysis processing. Analyzed minimum particle areas were $\sim 0.5 \text{ mm}^2$ on the thin section scale.

RESULTS

Petrography of Melt-Rich Impactites

Impact Melt Particle Types

Five types of melt particles could be distinguished, as in previous petrographic characterizations of Hecht et al. (2004) and Wittmann et al. (2004, 2006), mostly based on shapes, colors, and mode of quenching (Fig. 2).

Type 1 melt particles (Fig. 2A) exhibit dark greenish colors. Their shapes range from amoeboid to angular. Very rapid quenching is indicated by the scarcity of phenocrysts.

Type 2 melt particles (Fig. 2B) display light green colors and abundant vesicles. Shard-like morphologies and scarce aerodynamic shapes (Hörz, 1965) could indicate rapid quenching of airborne melts below the glass transition temperature and disruption of the particles due to expanding volatiles before deposition (Fisher and Schmincke, 1984; Avermann, 1999; Cas and Wright, 1995; Stöffler et al., 2004). Different rates of quenching are indicated by variable amounts of plagioclase phenocrysts that increase with depth. Phenocryst/groundmass ratios are $\sim 10\%$ – 20% at 800 m, 20% – 40% at 815 m, 40% – 60% at 824 m, 60% – 80% at 830 m, and $>80\%$ at 840–860 m. Such a quenching trend in Yax-1 was noted by Hecht et al. (2004), Tuchscherer et al. (2004a, 2006), and Wittmann et al. (2006).

Type 3 melt particles are thoroughly crystallized with plagioclase and clinopyroxene phenocrysts and minor matrix melt that was altered to clay minerals. Occasional blebs of Fe-oxide phases occur in schlieren or as coarse euhedral crystals. Two subtypes can be distinguished: type 3 BMR melt particles (Fig. 2C) exhibit gray-green colors and angular shapes, and type 3 schlieren melt particles (Fig. 2D) display reddish-white colors, schlieren textures and corroded, subangular margins.

Type 4 melt particles (Fig. 2E) are dark brown to black with subangular shapes. This melt particle type displays variable amounts of plagioclase phenocrysts next to abundant, finely dispersed Fe-(Ti)-oxide crystals that frequently exhibit skeletal shapes (Fig. 3). These particles may contain vesicles, schlieren, and variably shocked mineral clasts. Fe-oxide crystals were previously described as being of secondary origin (e.g., Pilkington et al., 2004; Tuchscherer et al., 2004a) or of a mixed secondary and primary nature (Kring et al., 2004). However, based on the close association of type 4 melt particles with other melt particle types that do not indicate such

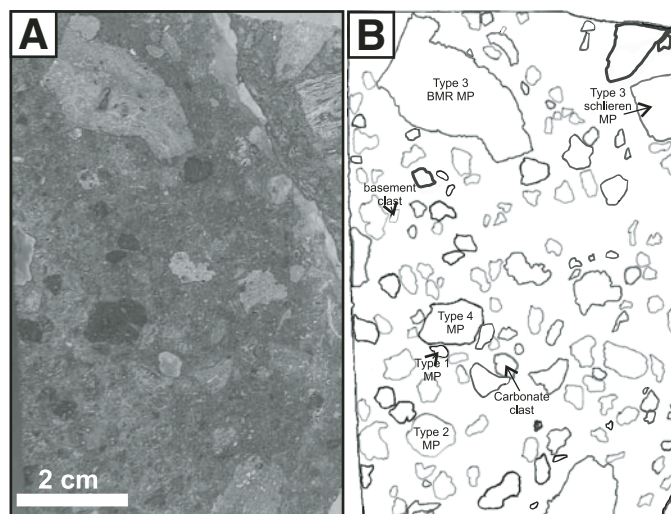


Figure 1. Image analysis procedure. (A) Enlarged half-core photograph at 834.93–835.03 m depth, Upper Suevite. (B) Template with identified lithic and melt particle (MP) components. BMR—Breciated Impact Melt Rock. Half-core diameter is 6.35 cm (width) and length of the core piece is 9.5 cm.

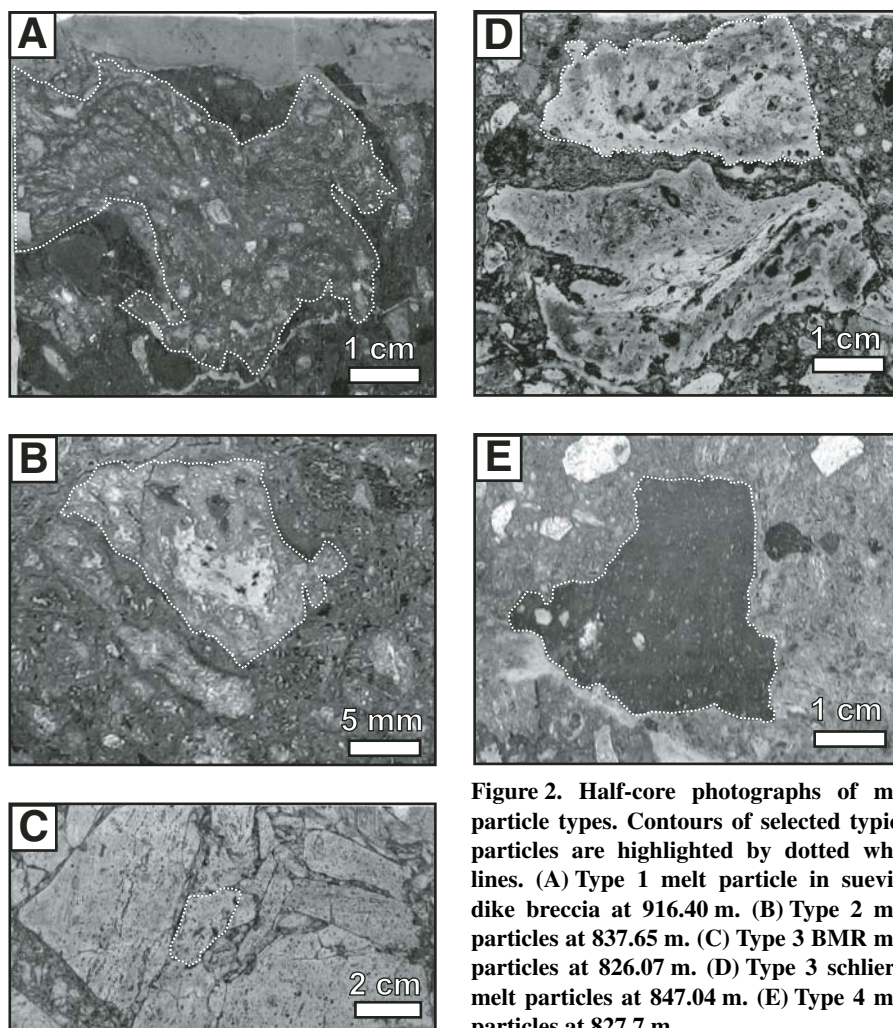


Figure 2. Half-core photographs of melt particle types. Contours of selected typical particles are highlighted by dotted white lines. (A) Type 1 melt particle in suevitic dike breccia at 916.40 m. (B) Type 2 melt particles at 837.65 m. (C) Type 3 BMR melt particles at 826.07 m. (D) Type 3 schlieren melt particles at 847.04 m. (E) Type 4 melt particles at 827.7 m.

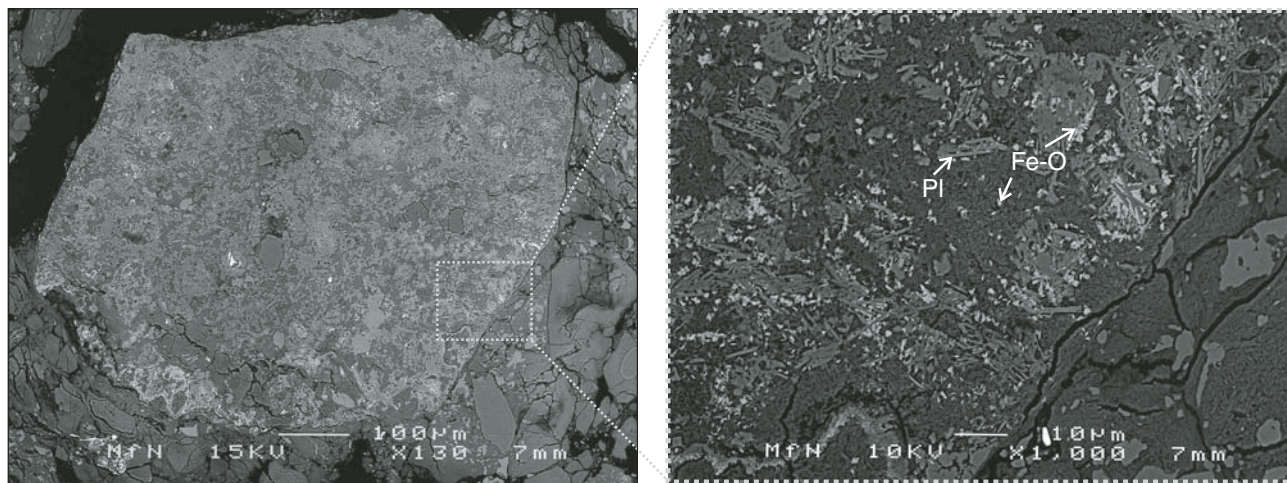


Figure 3. Scanning electron microscopy–backscattered electron images of type 4 melt particle in Upper Sorted Suevite sample at 800.25 m. Enlargement shows rim region of the melt particle with a smectite groundmass of low mass contrast. Laths of plagioclase (PI) 5–10 μm long form clusters. Skeletal crystals (μm size, arrows) of Fe-oxides (Fe-O) with a high mass contrast occur as solitary entities or together with plagioclase.

crystals (Figs. 1A, 1B), we suggest that Fe-O phenocrysts crystallized from a liquidus phase in the type 4 melt particles. Such phenocryst crystallization indicates elevated $f\text{O}_2$ in the melt with respect to the other melt particle types (Hörz, 1965; Frost, 1991; Giuli et al., 2005).

Lithic Clast Components and Matrix

Lithic clasts of crystalline rocks represent target lithologies derived from the pan-African basement rocks of the Yucatán Peninsula's Maya block (e.g., Krogh et al., 1993; Kring, 2005). They occur as submillimeter to 40-cm-sized clasts in the 100 m sequence. A comprehensive list of these clasts was given in Dressler et al. (2004) and Stöffler et al. (2004).

Lithic clasts of sedimentary rocks are mainly carbonates. They range from brownish micritic types with laminations to white, strongly crystallized types with diffuse boundaries toward the host material. Sedimentary clasts are frequently the main components in the Lower Suevite and the Suevitic Dikes, where they repeatedly reach block size. Only a few anhydrite clasts could be identified microscopically in the two uppermost units.

Fine material of the suevite-like deposits with a grain size <0.5 mm was regarded as particulate matrix. This matrix fills voids between the tightly packed clast- and melt-particle-supported Upper Sorted Suevite and Lower Sorted Suevite. In the Upper Suevite, clasts and melt particles are floating in matrixes that are variable in appearance but clearly particulate. The matrix in the Middle Suevite is coarsely crystallized and appears to having been melted toward the Brecciated Impact Melt Rock. Phenocrysts can

occasionally be recognized in the matrix of the Brecciated Impact Melt Rock, which suggests that the matrix was melted in parts. The Lower Suevite matrixes are very carbonate rich and crystallized. In the Suevitic Dikes, the matrix is particulate, carbonate rich, and only occasionally crystallized around melt injections.

Rim Features on Suevite Components

Most melt particles and some lithic clasts exhibit submillimeter thick rims of clay minerals and accreted fine particles in the Upper Suevite between 824 m and ~842 m (Figs. 4A–4E). Rims in the same thin section are very diverse. They differ in thickness and are variably structured. Some appear to be alteration fronts (Fig. 4A), others formed around target rock fragments (Figs. 4B, 4C), and others show relics of particulate material (Fig. 4E). Zoned melt particles that are broken indicate that the rims were formed before deposition (Fig. 4D). In the Middle Suevite, Lower Sorted Suevite, and Upper Sorted Suevite, rims that indicate accretion of particulate matter are scarce and most particles do not indicate such features at all. In the Brecciated Impact Melt Rock, Lower Suevite, and Suevitic Dikes, no such rims were observed.

Macroscopic Description of Half Cores

Suevitic Dikes. Detailed petrography of the Suevitic Dikes was presented in Wittmann et al. (2004). They are mainly composed of lithic carbonate clasts, a fine, particulate matrix, and rapidly quenched melt particles that sometimes occur as melt injections. The silicate melt particles indicate reactions with incorporated anhydrite and contain blebs of iron sulfides.

Brecciated Upper Cretaceous (middle Campanian–Maastrichtian) limestone megablocks are the host material at 909 and 916 m (Arz et al., 2004; Kenkmann et al., 2004). At 895.8 m, a carbonate conglomerate that contains type 3 schlieren melt particles and crystalline basement clasts overlies the Cretaceous limestone megablocks. It is terminated at 895.1 m by a 10-cm-thick flow-textured melt zone that forms the transition to the Lower Suevite.

Lower Suevite. At 891.9 m, 891.2 m, and 889.2 m, ~5-cm-thick, flow-textured melt zones transect the drill core at 50° – 70° . These zones separate macroscopically distinct suevites, e.g., carbonate-rich suevites from melt particle-rich suevites. Above 895 m, type 3 schlieren melt particles and carbonate clasts float in a dark carbonate matrix until ~888 m. Within this sequence, an ~40-cm-thick granite clast occurs at 889.20, which is the largest lithic basement clast in Yax-1. The upper part of the Lower Suevite from 888 to 884.9 m is mainly composed of swirled, melt-textured carbonates and lithic carbonate clasts. This includes a dark brown, very dense carbonate component, and a pink carbonate component with vugs that include bead-like precipitates. Some BMR melt particles at the unit boundary near 884.9 m float in this carbonate mass and cm-size veins transect the carbonate groundmass that include abundant BMR-melt particles.

Brecciated Impact Melt Rock. This unit is mainly composed of intensely fractured green impact melt rock in a clastic matrix of fine debris that is mostly fused together. Sometimes, it exhibits liquidus phase plagioclase phenocrysts, which indicate that these portions of the matrix had been melted. At 868.3–867.3 m

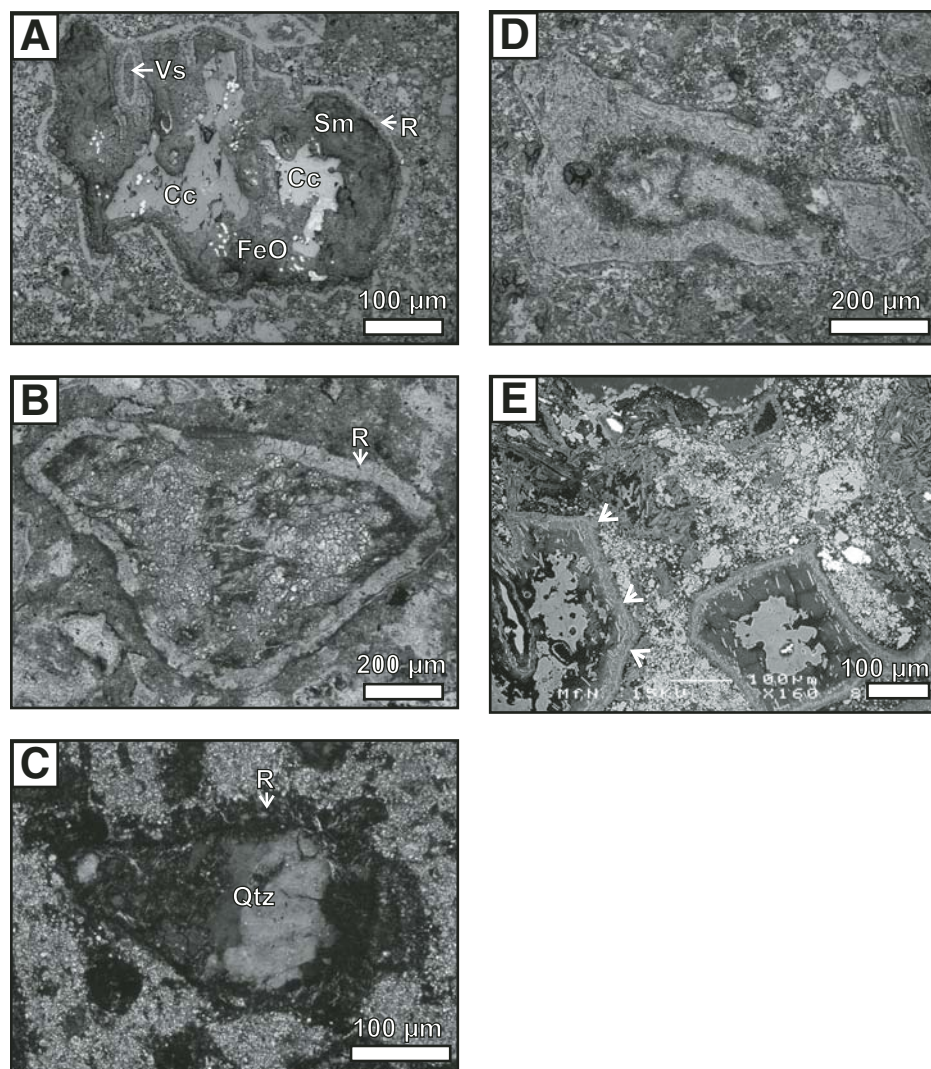


Figure 4. Thin section images of Upper Suevite sample at 824.01 m. (A) Shard-shaped melt particle with elongated vesicles (Vs) and thin rim of possible alteration front (R). Bright spots are Fe-oxide blebs (FeO); gray, smooth inclusions are sparitic calcite (Cc). Glassy melt was altered to brown smectites (Sm). Reflected light. (B) Carbonate-rich particle with prominent, discontinuous rim of altered silicate melt (R). Linear polarized light. (C) Quartz aggregate (Qtz) with relic planar deformation features and discontinuous rim of smectite (R). Cross-polarized light. (D) Fragmented, crystallized melt particle with distinct dark zonation around core. Reflected light image. (E) Scanning electron microscopy-backscattered electron image of shard-shaped melt particles with rims of accreted particles (arrows).

and 862–861.6 m, exceptional zones occur with reddish type 3 schlieren melt particles that float in a dark green melt matrix. Between 866.8 - 866.20 m, brecciated, coarse-grained marble clasts occur. The upper boundary of the Brecciated Impact Melt Rock is located at ~860.80 m. It is sharp, yet some schlieren and scaly fracturing off the top of the Brecciated Impact Melt Rock are observable.

Middle Suevite. Until 858.6 m, the matrix of the Middle Suevite appears melted to a

fluidal textured mass that cannot be resolved into particulate components. Schlieren and fluidal textured melt clasts float in this matrix and exhibit reaction coronas in the form of corroded embayments, possibly indicating resorption and thermal softening. Above 858.6 m, the suevitic matrix is recrystallized to a coarse, carbonate-rich, crystalline fabric until it appears particulate at 845–843.7 m. Furthermore, beginning around ~855 m, the Middle Suevite exhibits abundant breccia-in-breccia structures that sometimes

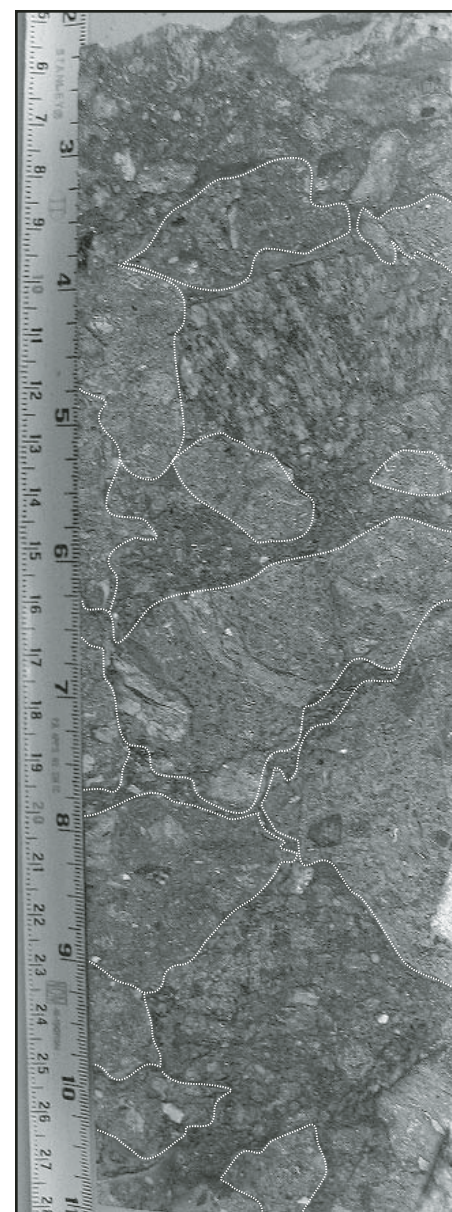


Figure 5. Breccia-in-breccia structures in half-core piece Yax-1, 842.7–842.9 m, Upper Suevite. Clasts of suevite are embedded in a suevite matrix. Scale on ruler is in cm on the left and in inches on the right.

occur together with networks of black shear-zones that contain comminuted clasts, e.g., at 846.60 m. Breccia-in-breccia structures indicate syn-depositional reworking of suevite in contrast to normal faults with slickensides that likely indicate post-cratering modification. Such faults with steep dips between ~50 - 80° only occur from the Brecciated Impact Melt Rock at ~867 m up to the top of the suevite section.

Upper Suevite. Breccia-in-breccia textures (Fig. 5) can be recognized throughout the Upper



Figure 6. Photographs of the basal Lower Sorted Suevite drill core box that contains core pieces from 819.99 m to 822.24 m. Two melt breccia intercalations occur at 820.9 m (A) and 821.4 m (B). Cc 1 indicates micritic limestone clasts and Cc 2 indicates recrystallized limestone clasts in core pieces from (A).

Suevite until ~823.2 m. The Upper Suevite bears diverse intercalations of dikes or pods of melt rock. They are dark with beige swirls at 841.4–841.7 m, red and flow-textured at 831–831.1 m, and grayish-green at 825.9–826.7 m. Up to ~827 m, greenish and whitish melt particles exhibit white contact aureoles toward the clearly particulate suevite matrix. Until ~840 m, all carbonate clasts are coarsely crystallized and exhibit diffuse boundaries to the suevitic matrix and no recognizable relic sedimentary texture. Such white carbonate clasts decrease in abundance toward the top and brownish micritic, laminated limestone clasts occur in increasing frequency.

Lower Sorted Suevite. The boundary to the Upper Suevite is marked by an ~15-cm-thick section of green brecciated melt rock at ~823 m. In contrast to the matrix-supported Upper Suevite, the Lower Sorted Suevite appears to be matrix deficient and clast supported. At 821.4 m, ~10 cm of brecciated melt rocks with igneous contacts to the surrounding suevite are present; ~30 cm are present at 820.9 m (Fig. 6). Sedimentary clasts entrained in these melt rocks are recrystallized due to thermal metamorphism.

Upper Sorted Suevite. The transition from the Lower Sorted Suevite to this poorly

consolidated, finer grained unit is near 807.75 m. Approximately 5 cm of graded and laminated suevitic sand at ~795 m mark the transition of the Upper Sorted Suevite to Tertiary carbonate sediments. This transition occurs over the depth of 794.9 to ~794.3 m and includes carbonates with redeposition features such as cross-bedding and intercalated microconglomerates of reworked suevite (Smit et al., 2004; Arz et al., 2004).

Quantitative Modal Composition

The bulk composition of Yax-1 was determined as the modal content of melt particles

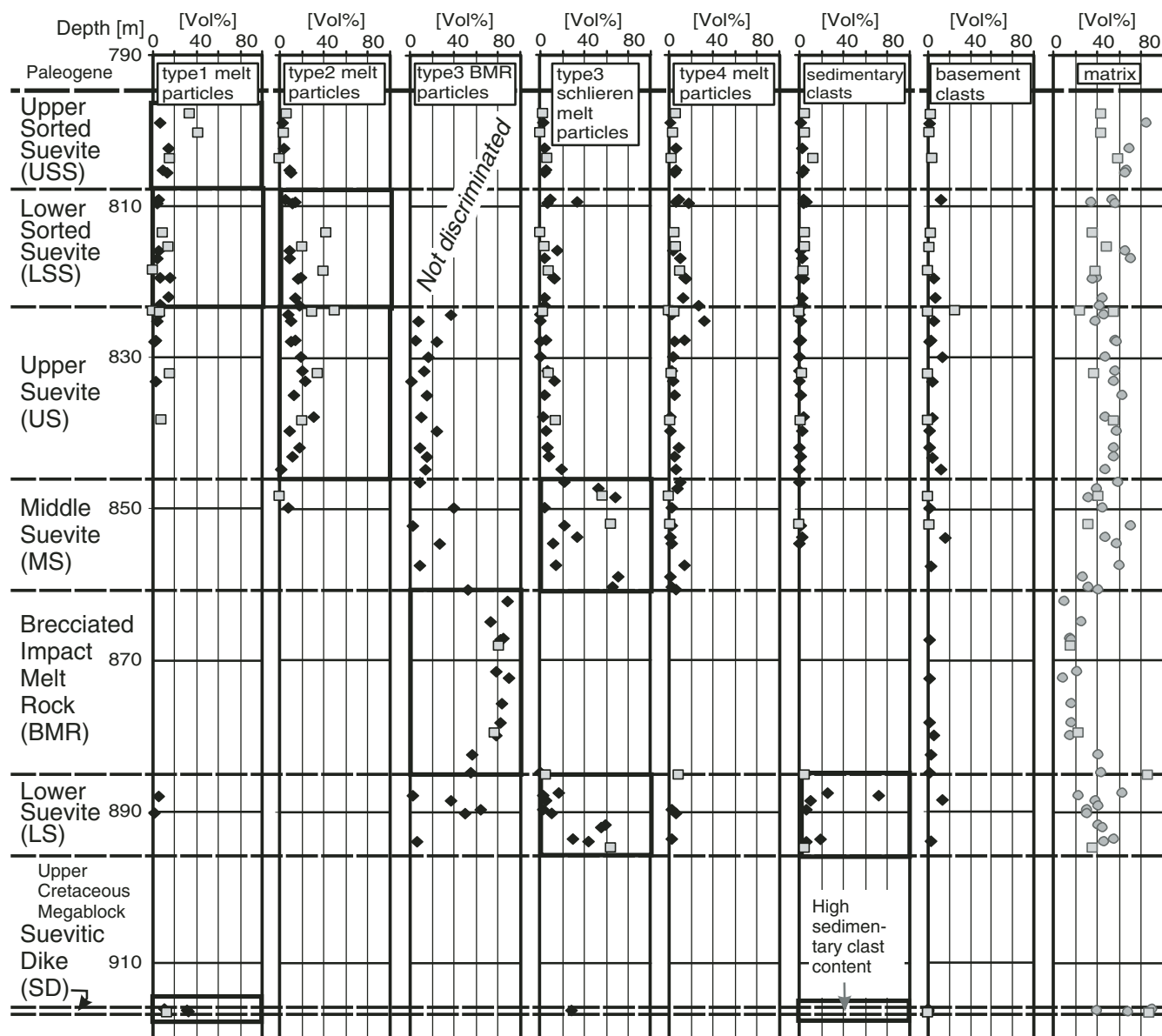


Figure 7. Modal composition of Yax-1 derived from image analysis data. Sample depths versus component contents and dominant unit components are highlighted. Black diamonds indicate half-core scale data, gray squares indicate thin section data, and gray circles indicate calculated matrix.

and lithic clasts. Component sizes >0.5 mm in diameter were recorded. Their distribution in Yax-1 is indicated in Figure 7. Sufficient precision of the identification process is indicated by the good agreement of macroscopic and microscopic data (Fig. 7; Tables DR-A and B [see footnote 1]). Anhydrite lithic clasts were only found in thin sections from the Upper Sorted Suevite; most other sedimentary

lithic clasts are carbonates. The Lower Suevite and Suevitic Dikes exhibit significantly higher contents in carbonate melts and sedimentary lithic clasts. Melt particle types exhibit a characteristic distribution throughout the drill core. Type 1 and type 2 melt particles are the dominant melt particle types in the Upper Sorted Suevite, Lower Sorted Suevite, and Upper Suevite. Type 1 melt particles are also the most abundant melt particle type in the Suevitic Dikes. The thoroughly crystallized type 3 melt particles are the characteristic melt particle component in the Brecciated Impact Melt Rock and neighboring units. The schlie-

ren subtype is abundant in the Middle Suevite and Lower Suevite. Type 4 melt particles occur with variable abundance next to the other melt particle types mostly in the Middle Suevite and Upper Sorted Suevite and show relative peak abundance in the basal Upper Sorted Suevite and the uppermost Upper Suevite.

Particle Size Distribution

Half-core particle size data (Figs. 8A, 8B) indicate the dominant component size classes that range from 0.5 to 64 mm. Histograms of the particle size distribution identify the dominant size population between 0 and -4ϕ (1–16 mm)

¹GSA Data Repository item 2007207, Tables DR A–D, is available at <http://www.geosociety.org/pubs/ft2007.htm>, or by requests from editing@geosociety.org.

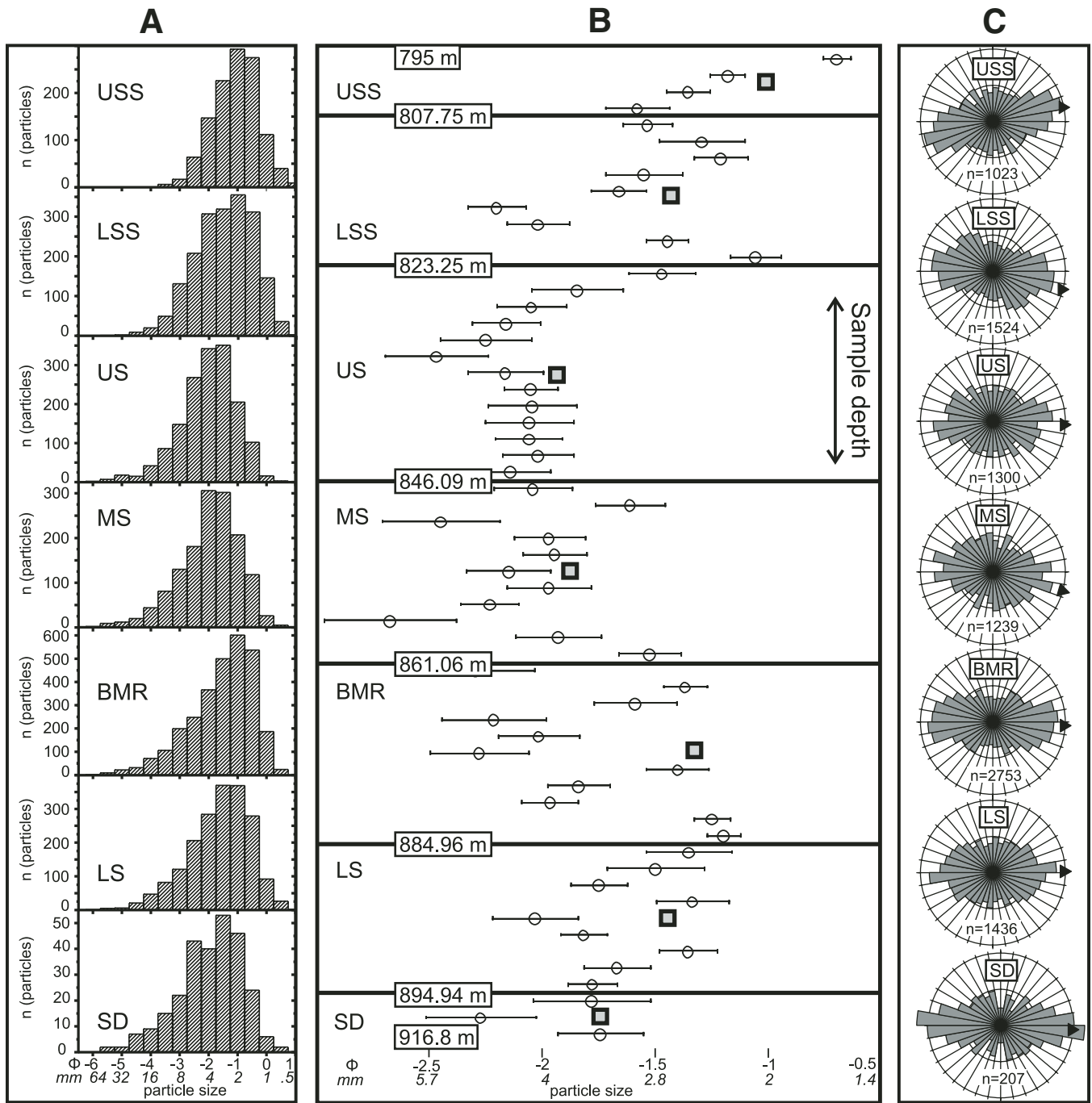


Figure 8. Size distribution and orientation of components in Yax-1 half-core samples. Unit abbreviations as in Figure 7. (A) Histograms of component size distribution. Φ values [$-\log_2(\text{particle length})$] indicated in the range of 0.5–64 mm (1 to –6 Φ) versus data count. (B) Particle lengths versus sample depth in Yax-1 suevite-like units. Median values of samples per unit as squares. 95% confidence intervals of means of component lengths per analyzed sample are circles and error bars. (C) Rose diagrams of derived orientations of melt particles derived from the dips of their length with respect to the drill core axis. Outer circle designates 10% of plotted data. Black triangles indicate statistical means of the plotted data. n gives number of plotted data.

TABLE 2. STATISTICAL DATA FOR COMPONENT SIZE DISTRIBUTION (LENGTHS OF COMPONENTS) IN Yax-1 SUEVITE-LIKE UNITS AT THE HALF-CORE SCALE

		Mean	95% CI for means		Median	s	Maximum	Minimum	Skewness	Kurtosis
			Lower bound	Upper bound						
USS (n = 1189)	ϕ values	-1.064	-1.109	-1.019	-1.018	0.793	-3.718	0.982	-0.262	-0.062
	mm	2.1	2.2	2.0	2.0	0.6	13.2	0.500		
LSS (n = 1896)	ϕ values	-1.478	-1.522	-1.433	-1.414	0.988	-5.279	0.804	-0.399	-0.122
	mm	2.8	2.9	2.7	2.7	0.5	38.8	0.600		
US (n = 1605)	ϕ values	-2.023	-2.071	-1.975	-1.929	0.977	-6.180	0.518	-0.689	0.933
	mm	4.1	4.2	3.9	3.8	0.5	72.5	0.700		
MS (n = 1443)	ϕ values	-1.965	-2.018	-1.912	-1.829	1.035	-5.985	0.394	-0.715	0.706
	mm	3.9	4.1	3.8	3.6	0.5	63.3	0.800		
BMR (n = 2905)	ϕ values	-1.562	-1.602	-1.522	-1.346	1.108	-6.329	0.520	-0.881	0.633
	mm	3.0	3.0	2.9	2.5	0.5	80.4	0.700		
LS (n = 1912)	ϕ values	-1.635	-1.683	-1.587	-1.482	1.072	-6.391	0.810	-0.699	0.558
	mm	3.1	3.2	3.0	2.8	0.5	83.9	0.600		
SD (n = 271)	ϕ values	-1.949	-2.083	-1.815	-1.760	1.120	-5.547	0.514	-0.596	0.205
	mm	3.9	4.2	3.5	3.4	0.5	46.8	0.700		

Note: CI is confidence interval. USS—Upper Sorted Suevite; LSS—Lower Sorted Suevite; US—Upper Suevite; MS—Middle Suevite; BMR—Brecciated Impact Melt Rock; LS—Lower Suevite; SD—Suevitic Dike Breccia; *n*—number. See text Figure 8.

on the half-core scale (Fig. 8A). Particle size distribution in the Upper Sorted Suevite shows a relatively narrow range: this indicates good sorting. However, in the other units, relative broad ranges prevail and, with the possible exception of the Lower Sorted Suevite, kurtosis values tend to be peaked and skewness values show heavy tails (Table 2). This may partly be due to the particle size resolution given by the limits of observational scale. It has been suggested (Goto et al., 2004; Stöffler et al., 2004) that the Lower Sorted Suevite exhibits distinct sorting. Sorting may be indicated by the lack of coarsest grain size fractions in the Lower Sorted Suevite (particles >40 mm; Fig. 8A; Table 2). This size class is prominent in the units from the Upper Suevite to the Suevitic Dikes. Moreover, the Lower Sorted Suevite appears to be matrix deficient compared to the Upper Suevite.

Spatial Orientation of Particles

Derived orientations are the dip of melt particles' long axes relative to the axis of the drill core and designate a shape-preferred alignment. On the half-core scale, type 1 melt particles show the clearest shape-preferred alignment and are thus the source for the distinct subhorizontal orientation of particles in the Upper Sorted Suevite and Suevitic Dikes (Fig. 8C), where this melt particle type is the dominant component. Type 4 melt particles display shape-preferred alignment in the Upper Sorted Suevite and the Lower Suevite. Melt particle types 2 and 3 generally do not exhibit a strong tendency for alignment. The alignment trend in a subhorizontal direction is more diffuse in the melt particle data from the Upper Suevite, Middle Suevite, and Lower Suevite, where type 3 melt particle types are

more prominent components than in the Upper Sorted Suevite, Lower Sorted Suevite, and Suevitic Dikes. A subhorizontal clustering of orientation data is displayed by the melt particle data from the Brecciated Impact Melt Rock.

Shape Parameters of Particles

Roundness values >1 are characteristic for particles that deviate from simple geometric forms (Fig. 9A). The trend of melt particle roundness values in Yax-1 is toward more complex shapes with depth. The Lower Suevite and Suevitic Dikes indicate the most extreme deviation from simple shapes with that respect.

Fullness ratios of particles that exhibit shapes with embayments or concave boundaries are <1 (Fig. 9B). The trend of melt particles in Yax-1 somewhat mirrors the trend of roundness values in that increasingly more complex sculptured shapes are indicated with depth, possibly suggesting intense reactions of the particle boundaries with the matrix in the Middle Suevite to the Suevitic Dikes.

Aspect ratios (Fig. 9C) are expected to show flattening trends of melt particles due to plastic deformation in response to thermal softening, e.g., as in welded tuffs (Fisher and Schmincke, 1984; Cas and Wright, 1995). From the Upper Sorted Suevite to the Upper Suevite, melt particles exhibit no distinct flattening. Such a trend is indicated from the Upper Suevite toward the Brecciated Impact Melt Rock and Lower Suevite, but reaches extreme values in the Suevitic Dikes. This likely is an expression of stronger plastic deformation of melt particles due to thermal softening toward the Brecciated Impact Melt Rock and the emplacement of viscous melts with the Suevitic Dikes.

Chemical Composition of Impact Melt Particles

EMP data of Yax-1 melt particles (Table C; see footnote 1) is displayed as box plots in Figure 10 to show the compositional variations of melt particle types. The compositions are grossly similar. Almost identical concentration ranges are indicated in all melt particle types for SiO_2 , Al_2O_3 , and TiO_2 . CaO and Na_2O exhibit enrichment trends toward the more densely crystallized melt particle types 3 and 4. Melt particle types 1 and 2 exhibit relative depletion in CaO and Na_2O and relative enrichment in FeO and MgO compared to other melt particle types.

In order to display characteristics of melt particle types on the unit scale, the EMP data was recalculated to 100 wt%, assuming that this correction is necessary to account for hydration and porosity effects. The recalculated data means were normalized to Chicxulub-1 impact melt rock after data that Schuraytz et al. (1994) regard as a pristine Chicxulub impact melt composition that underwent little secondary alteration. The normalized element concentrations (Fig. 11) indicate similar trends for most melt particle types in the Upper Sorted Suevite–Upper Suevite with pronounced enrichments of MgO, moderate enrichments of FeO, and depletions of CaO and Na_2O . In the Middle Suevite, divergence of melt particle composition patterns is pronounced. Except for the scarce type 1 melt particles, FeO, MgO, and CaO are strongly depleted, while K_2O and Al_2O_3 appear strongly and moderately enriched, respectively. In the Brecciated Impact Melt Rock, the type 3 schlieren and BMR melt particles show a remarkably similar concentration pattern with slight variation in CaO, K_2O ,

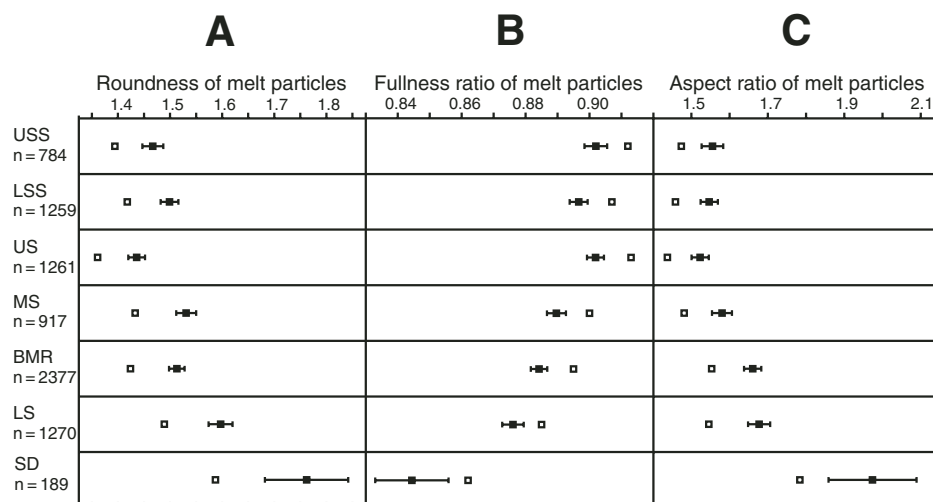


Figure 9. Shape parameter data for melt particles of the Yax-1 suevite-like units. Unit abbreviations as in Figure 7. Data contains half-core scale particles >1 mm in equivalent circle diameter that are not bounded by the drill core limits; means (filled symbols) with 95% confidence intervals and median values (empty symbols) are plotted. n is number of data used. (A) Roundness is ratio of perimeter squared to area of a particle. (B) Fullness ratio is the square root of the ratio of the particle's area to the area of a polygon that circumscribes the particle by the tangents to its boundary. (C) Aspect ratio is the length by perpendicular width of a particle.

and Na₂O. The strong enrichment of MgO is the only pronounced deviation from values of the Chicxulub-1 impact melt. Melt particles in the Lower Suevite indicate a nearly identical compositional pattern of type 3 and type 4 melt particles. Type 3 BMR melt particles mostly follow the enrichment and/or depletion trends, but exhibit more extreme depletion in FeO, MgO, and CaO and stronger enrichment in K₂O. The SiO₂, Al₂O₃, and TiO₂ values are remarkably similar. Melt particle types in the Suevitic Dikes are distinctly different in trend and magnitude of deviation from element concentrations in Chicxulub-1 impact melt. They clearly indicate a mixture of type 1 melt particles that show the affinity of this particle type in the upper air-fall suevites, and type 3 schlieren melt particles that reflect the compositional trends, except for K₂O, of this melt particle type in the Middle Suevite and Lower Suevite.

DISCUSSION

Chemical Composition of Yax-1 Impact Melt

Previous interpretations of the Yax-1 impact melt compositions ranged from distinct, poorly homogenized, and variably altered (Tuchscherer et al., 2004a, 2004b; Hecht et al., 2004) to grossly similar (Dressler et al., 2004; Kring et al., 2004; Kring, 2005). Our chemical data suggest that the petrographically distinct melt par-

ticles are grossly similar in their concentration ranges of SiO₂, Al₂O₃, and TiO₂ (Fig. 10), which mostly corresponds within error to previously published data (Hecht et al., 2004; Table D [see footnote 1]). TiO₂ is typically regarded as potentially least mobile under conditions of hydrothermal alteration of silicate glasses (e.g., Staudigel and Hart, 1983; Hecht et al., 2004), while Al₂O₃ is potentially retained depending on pH conditions (Fisher and Schmincke, 1984; Naumov, 2002). Thus, in contrast to other studies, e.g., at the Ries (Osinski, 2003), and Sudbury (Muir and Peredery, 1984) sites, no significant primary heterogeneities of impact melts are apparent from our data of melt particle compositions (Fig. 10). The described variation in chemical composition of melt particles is most likely due to alteration effects. Depletion in alkalis can occur during alteration of melt particles that had much higher original glass contents. Apart from alkali depletion, the relative enrichments of FeO and MgO in such melt particles probably also reflects hydrothermal alteration involving interaction with seawater (Hecht et al., 2004). This could account for the type 1 and type 2 melt particle characteristics that contrast with the degree of phenocryst crystallization in type 3 and type 4 melt particles. Crystallization of plagioclase or pyroxene phenocrysts from a melted synthetic Ries suevite glass was shown to be mainly controlled by the degree of quenching and oxygen fugacity in the melt (von Engelhardt

et al., 1995). A significant difference between bulk melt particle compositions of Yax-1 on the unit scale is indicated from the comparison with Chicxulub-1 impact melt (Fig. 11). Generally, melt particle concentrations are most similar to the Chicxulub-1 impact melt composition in the Brecciated Impact Melt Rock. The largest scatter is indicated in the Lower Suevite and Middle Suevite, likely reflecting intense reaction of melt particles with the matrix.

It can be concluded that grossly uniform element concentration patterns of the potentially least mobile elements of the melt particle types likely indicates derivation from a homogenized bulk impact melt that underwent transformation to the characteristic melt particle types during the ejection process and subsequent alteration. This is indicated by the relative variance between melt particles in the respective units (Fig. 11) in contrast to the relatively similar concentrations of melt particle types (Fig. 10).

Origin and Emplacement of the Suevitic Subunits

Suevitic Dikes and Lower Suevite

The Suevitic Dikes and Lower Suevite contain abundant clastic debris derived from the Mesozoic surficial target rocks. The Suevitic Dikes in Yax-1 were interpreted as drag- and spallation-induced injections into displaced megablocks of platform sediments during the passing of the ejecta curtain (Kenkmann et al., 2004; Wittmann et al., 2004). Such a process was also inferred for the Ries crater (Kenkmann and Schöni, 2006). Particle shape data (Figs. 8C and 9A–9C) suggest that some of the injected type 1 melt in the Suevitic Dikes and Lower Suevite was still viscous and thus produced extremely aberrant aspect ratios, fullness ratios, and roundness values compared to melt particles in the other suevite-like units.

A numerical model of a stream-tube deposition of impact melt predicts ballistic sedimentation of the Lower Suevite at Yax-1 (Stöffler et al., 2004; Ivanov, 2005). Moreover, Stöffler et al. (2004) discussed a ground-surge process on the floor of the transient cavity for the formation of the Lower Suevite. However, this seems to be difficult to reconcile with the assumed size of the transient cavity at Chicxulub of 90–120 km diameter, according to Ivanov (2005), with a probable dimension of ~100 km (Kring, 1995, 2005; Morgan et al., 1997).

Other genetic interpretations of the Lower Suevite (Dressler et al., 2004; Kring et al., 2004) suggest that the Lower Suevite and Brecciated Impact Melt Rock constitute a melt breccia with some clastic material. However, the basal con-

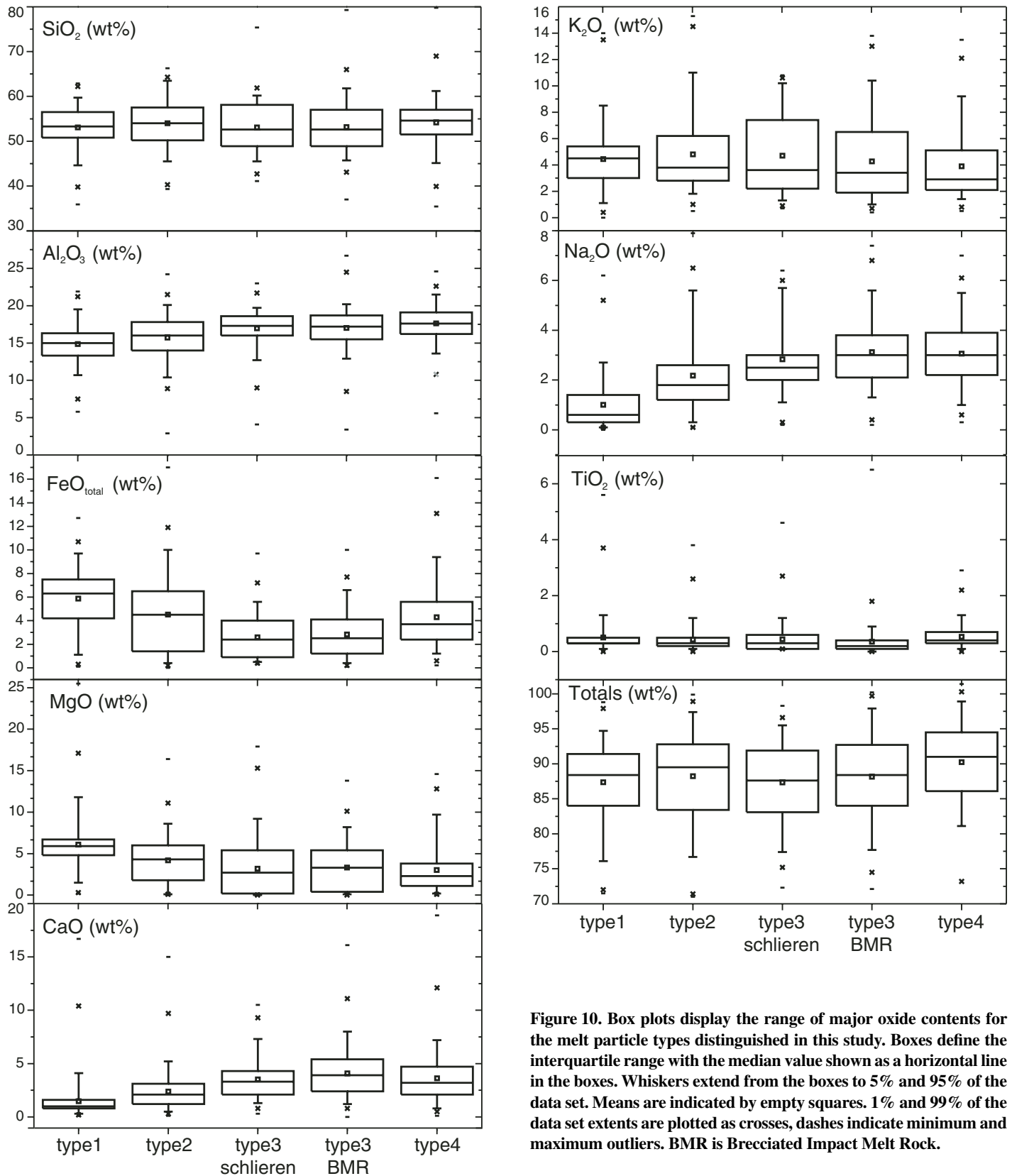


Figure 10. Box plots display the range of major oxide contents for the melt particle types distinguished in this study. Boxes define the interquartile range with the median value shown as a horizontal line in the boxes. Whiskers extend from the boxes to 5% and 95% of the data set. Means are indicated by empty squares. 1% and 99% of the data set extents are plotted as crosses, dashes indicate minimum and maximum outliers. BMR is Brecciated Impact Melt Rock.

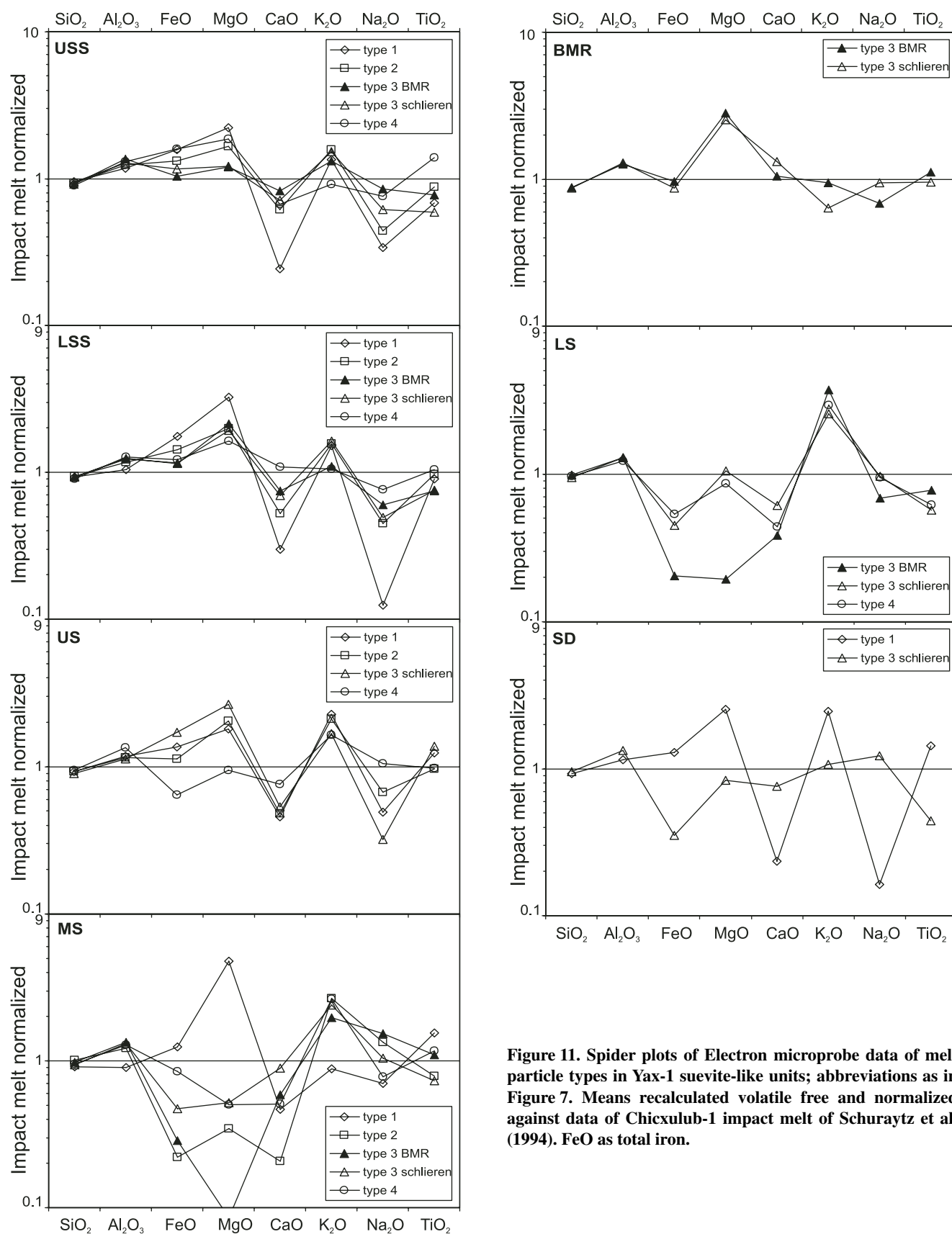


Figure 11. Spider plots of Electron microprobe data of melt particle types in Yax-1 suevite-like units; abbreviations as in Figure 7. Means recalculated volatile free and normalized against data of Chicxulub-1 impact melt of Schuraytz et al. (1994). FeO as total iron.

tact of the Lower Suevite with the underlying limestone megablock shows no signs of thermal metamorphism. Instead, this contact region exhibits a clastic matrix that is not crystallized. Furthermore, abundant clastic carbonate debris in the Lower Suevite that ranges from melted to unmetamorphosed with preserved fossils (Tuchscherer et al., 2004a) argues against conditions of residence in an impact melt rock unit.

No type 2 melt particles that may indicate airborne transport occur in the Lower Suevite (Fig. 7). However, a trend of elongation of melt particles (Figs. 9A, 9C) and their rather chaotic alignment (Fig. 8C) are in agreement with Shuvalov's (2003) model of excavation-flow material interacting with the ejecta plume. This scenario appears to yield similar effects with regard to the deposit being composed of a mixture of material derived in approximate equal parts from the sedimentary cover and the crystalline basement as in the stream-tube deposition model of Stöffler et al. (2004) and Ivanov (2005). Thus, it is likely that the Lower Suevite represents an early deposit of the excavation flow that contains some ground-surge-related components.

Brecciated Impact Melt Rock

A possible scenario for the formation of the Brecciated Impact Melt Rock is as a film of melt on the central uplift that was moved outward during the collapse of the central uplift. According to numerical models by Collins et al. (2002) and Ivanov (2005), the largest portion of impact melt would have been trapped in the central depression of the crater and a tongue of melt overran the peak ring and may have spilled into the annular moat. Comparison with the scarce petrographic data from the Yucatán-6 drilling, which is ~10 km closer to the crater center, suggests that the ~24-m-thick impact melt rock unit (Brecciated Impact Melt Rock) at Yax-I is stratigraphically similar to a coherent impact melt that measures 360–380 m in thickness at Yucatán-6 (Kring and Boynton, 1992; Sharpton et al., 1996; Stöffler et al., 2004).

Some fracturing of the Brecciated Impact Melt Rock was probably attained during the lateral outward transport from the crater center and later crater modification. Some intercalations of type 3 schlieren melt particles near the top of the unit may represent assimilated surfaces (chilled margins) of the melt flow that were reincorporated into the turbulent flowing melt. However, this explanation cannot account for the pervasive small-scale fracturing that affected the Brecciated Impact Melt Rock. A comparison with volcanoclastic deposits reveals that hyaloclastites macroscopically exhibit a very similar style of fracturing (e.g., Cas and Wright, 1995).

Furthermore, the pronounced potassium metasomatism that affected the Lower Suevite and Suevitic Dikes was previously linked to hydrothermal fluids and the interaction with seawater (Hecht et al., 2004; Schmitt et al., 2004; Wittmann et al., 2004). Because the deposition of the Lower Suevite included a sizeable amount of surficial target rocks that were water saturated and possibly also affected portions of the shallow ocean, the sudden capping with superheated impact melt rock must have led to the instantaneous generation of steam. The explosive release of this steam could have caused fragmentation of the Brecciated Impact Melt Rock. However, the intense crystallization of phenocrysts and the occasional melt character of the intra-clast matrix of the Brecciated Impact Melt Rock suggest prolonged annealing.

Middle Suevite–Upper Suevite

The contact region of the Middle Suevite with the Brecciated Impact Melt Rock is characterized by erosive reworking of material from the Brecciated Impact Melt Rock. Furthermore, abundant breccia-in-breccia structures (Fig. 5) attest to an erosive surge during the collapse of a hot ejecta plume with high turbulence that resulted in the unsorted and poorly oriented arrangement of melt particles in the Middle Suevite (Figs. 8A–8C). The melted matrix and peripheral corrosion of fluidal textured type 3 melt particles in the Middle Suevite (Fig. 2D) suggest rheomorphic reactions. Similar fluidal textured melt particles and microbreccias of the Grey Member suevite deposits of the Sudbury impact crater Onaping Formation (Muir and Peredery, 1984) were interpreted to indicate a ground-surge deposit that grades into a fallback sequence (Stöffler et al., 1994; Avermann, 1999).

In the Upper Suevite, ejecta plume collapse continued with lower contents of type 3 melt particles (Fig. 7) and decreasing reaction textures of melt particles. The deposition of matrix-supported impact breccias ended during progressive cooling of the debris cloud at the top of the Upper Suevite. At this stage of ejecta plume collapse, the returning atmosphere may have winnowed out fine particles (Stöffler et al., 2004). The occurrence of type 2 and type 4 melt particles indicates mixing of different plume regions during the deposition of the air-fall suevites (Middle Suevite to Upper Sorted Suevite) (Fig. 7). Oxygen fugacities likely varied due to turbulence, inflowing air, and/or contact with vapor produced from the cover rocks and shallow ocean.

Melosh (2004) proposed ejecta deposition due to clumping of debris to produce density currents. This scenario is in reasonable accordance

with the petrographic characteristics of the Middle Suevite and Upper Suevite at Yax-I and the nuée ardente model of Dressler et al. (2004) for these units. In order to produce breccia-in-breccia structures (Fig. 5), fine debris (matrix) must have rapidly fused with melt particles, including types that indicate airborne transport, and lithic clasts. This process may also be recorded as rims around ejecta components (Figs. 4A–4F). While some of these coatings may represent alteration fronts of glassy melt particles (Fisher and Schmincke, 1984; Stronick and Schmincke, 2002; Greshake et al., 2005) (Fig. 4A), irregular thicknesses (Figs. 4C–4E), particulate textures (Fig. 4F), and the occurrence on lithic clasts (Figs. 4B, 4C) could indicate that such rims represent accreted particles or condensed silicate vapor from the ejecta plume. The presence of broken rimmed clasts (Fig. 4E) rules out postdepositional formation of these rims. Accretionary rims were reported from lunar impact breccias (Grieve et al., 1975) and interpreted as indicative for the base surge of an impact ejecta plume.

According to current models of the formation of the ejecta plume at Chicxulub, the superheated, vapor-rich plume portion that is generated at the initial stages of the impact is the portion that receives highest ejection velocities, and thus is the quickest to leave the crater to form distal ejecta deposits (Melosh, 1991; Alvarez et al., 1995; Pierazzo et al., 1998). Numerical modeling of homogeneous nucleation from a Chicxulub-size impact vapor cloud (de Niem, 2002) predicts an initial stage starting with the production of spherical melt particles (spherules) of millimeter size at temperatures of ~3900 K. Such spherules with sizes between 0.5 and 1 mm are known from K-T boundary sections (e.g., Schulte et al., 2003). A second nucleation stage is predicted to start at temperatures of ~1700 K to produce spherules three orders of magnitude smaller. Some 40–60 µm spherule-like melt particles that were altered to smectites occur in the Upper Suevite (Dressler et al., 2004; S. Mayr, 2006, personal commun.). The size of these spherule-like particles in the Upper Suevite is in the range (1–100 µm) predicted for vapor condensates from the central part of an expanding ejecta plume (de Niem, 2002; Shuvalov, 2003). These spherule-like particles may represent material that condensed from the early, vapor-rich part of the ejecta plume that likely contained most of the vaporized projectile. Apparently, portions of it got entrained in the later stage collapse over the crater. The scarcity of these particles is reflected by the lack of significant concentrations of platinum group elements in the Yax-I suevite-like units (Tagle et al., 2004; Gelinas et al., 2004; Tuchscherer et al., 2004b).

Lower Sorted Suevite–Upper Sorted Suevite: Continuous or Variably Redeposited?

Some preliminary petrographic descriptions concluded that there was excessive reworking of the Upper Sorted Suevite and Lower Sorted Suevite (Arz et al., 2004; Tuchscherer et al., 2004a). This was mainly based on particle characteristics, the presence of well-preserved fossils of foraminifers, and the friable, matrix-deficient nature of the Upper Sorted Suevite and Lower Sorted Suevite. Furthermore, Goto et al. (2004) suggested that both units are composites of gravity flows due to the invasion of ocean water or an impact seismic wave that produced eight cycles of graded depositional sequences in the Upper Sorted Suevite–Lower Sorted Suevite.

Kring et al. (2004), Stöffler et al. (2004), and Dressler et al. (2004) pointed out that the Lower Sorted Suevite does not indicate any sedimentary evidence for redeposition, and argued for only minor aqueous reworking of the uppermost 1–2 m of the Upper Sorted Suevite. Furthermore, Zürcher and Kring (2004) and Kring et al. (2004) concluded from geochemical evidence of alteration products in the Upper Sorted Suevite and Lower Sorted Suevite that the top of the impactite sequence was subject to subaerial or very shallow subaqueous weathering before being covered by marine Tertiary sediments.

Preserved foraminifer fossils in the uppermost Upper Suevite span the same age range (late Campanian–early Maastrichtian) as the fossils recovered from the Upper Sorted Suevite and the Lower Sorted Suevite (Goto et al., 2004), which suggests a continuity of the sequence from the Lower Sorted Suevite to the Upper Suevite. No preserved foraminifers were described in the Upper Suevite below 823.56 m (Goto et al., 2004; Tuchscherer et al., 2004a). The change in preservation of foraminifer fossils more likely reflects cooler conditions in the ejecta plume during the late stages of plume collapse at the top of the Upper Suevite.

No reworked clasts of suevite occur in the Upper Sorted Suevite–Lower Sorted Suevite that would have to be expected if material from the Upper Suevite had been eroded by tsunami waves (Dressler et al., 2004; Goto et al., 2004; Stöffler et al., 2004). Instead of such breccias-in-conglomerates, the components of the Upper Sorted Suevite and Lower Sorted Suevite barely exhibit accreted rims and mostly constitute clast types of single lithic clasts or melt particles. Impact melt rocks with igneous contacts toward the matrix at the base of the Lower Sorted Suevite (Fig. 6) are another strong argument against the tsunami-induced mass flow theory of Goto et al. (2004) for these deposits.

A reduced thickness of magnetostratigraphic R29 in the “Tertiary”² section overlying the Upper

Sorted Suevite (Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004) and missing early Paleocene foraminiferal biozones (Arz et al., 2004; Keller et al., 2004; Smit et al., 2004) indicate a gap in sedimentation. Moreover, the reconstruction of the infilling history of the crater from geophysical data (Bell et al., 2004) suggests a gradual filling of the crater basin that would not be expected if the basin had been filled by tsunami-like backflowing seawater immediately after the impact (Goto et al., 2004; Tuchscherer et al., 2004a). Moreover, it is in accordance with calculations and results from numerical models that predict that the final crater rim of the Chicxulub crater reached 600–1000 m above the pre-impact sea level (Kring, 1995, 2005; Stöffler et al., 2004).

At the Yucatán-6 drilling, petrographic data confirms preserved microfossils in at least the upper 100 m of suevite deposits (Sharpton et al., 1996; Kettrup et al., 2000; Claeys et al., 2003) that, judging on petrographic similarities, probably correspond to the 28-m-thick Upper Sorted Suevite and Lower Sorted Suevite section in Yax-1. This could confirm radial oscillations of ejecta thicknesses due to atmospheric interactions (Shuvalov, 2003). The interpretation of the Upper Sorted Suevite and Lower Sorted Suevite as a fallback unit that underwent sorting due to atmospheric interactions with only minor aquatic reworking (Stöffler et al., 2004; Dressler et al., 2004) was likewise concluded for a petrographically similar sequence at the Ries crater (Jankowski, 1977). Jankowski (1977) based his interpretation on grain-size distribution analyses and petrographic evidence of a graded suevitic sequence. Shuvalov (2003), however, predicted gradation of ejecta due to momentum exchange of different-sized particles with the gas flow. The winnowing out of fines and the poor sorting of the Lower Sorted Suevite (Figs. 8A, 8B) suggest somewhat turbulent conditions during settling. Therefore, it can be tentatively concluded that the Upper Sorted Suevite and Lower Sorted Suevite were likely deposited under the influence of a reestablishing atmosphere before the topmost 1–2 m of the Upper Sorted Suevite were reworked during the infilling of the crater.

Temperature History of Yax-1 Suevitic Deposits

It is generally assumed that ~100 s after its formation, an impact melt sheet establishes initial temperature equilibrium above ~1200 °C (Onorato et al., 1978). Subsequently, the melt crystallizes

²Tertiary” is used to acknowledge the still-contested fact that the Chicxulub crater’s impactites are Tertiary deposits, as the Chicxulub impact marks the end of the Cretaceous

and assimilates clastic debris. An impact melt deposit can be described to cool by conductive heat transfer according to the formula

$$t^* = h^2/\kappa, \quad (2)$$

where t^* is cooling time, h is thickness of deposit, and κ is the thermal diffusivity coefficient, experimentally determined to be 0.64 mm²s⁻¹ for suevite glass (von Engelhardt et al., 1995). The resulting cooling time for the 25-m-thick Brecciated Impact Melt Rock would thus be ~30 yr and ~500 yr for a 100 m section. However, this model of conductive cooling likely is too conservative for the section, given that hydrothermal heat transfer most likely accelerated cooling of the 100 m section of suevite-like impactites at Yax-1 (e.g., Hecht et al., 2004; Zürcher and Kring, 2004; Abramov and Kring, 2007). Moreover, pervasive brecciation suggests rapid cooling below the glass transition temperature of 680 °C (von Engelhardt et al., 1995).

A body of melt-textured carbonate at the top of the Lower Suevite (Schmitt et al., 2004) that marks the contact to the Brecciated Impact Melt Rock could be explained by heating from the overlying Brecciated Impact Melt Rock and inhibited degassing (Ivanov et al., 2004). Temperatures of 1240 °C are required for the melting and/or decomposition of CaCO₃ at ambient pressures (Ivanov and Deutsch, 2002). Anhydrite decomposes to CaO, SO₂, and O₂ above 1200 °C (Riedel, 1994); depending on confining pressures, it may melt instead (Ivanov et al., 2004). However, such high postdepositional temperatures below the Brecciated Impact Melt Rock are difficult to reconcile with the pervasive small-scale fracturing of the Brecciated Impact Melt Rock that suggests rapid cooling below the glass transition temperature of 680 °C (von Engelhardt et al., 1995).

Incipient welding in the Lower Suevite is indicated by the aspect ratio data (Fig. 9C) and roundness data (Fig. 9A) of melt particles. However, compared to welded tuffs (Fisher and Schmincke, 1984; Cas and Wright, 1995), the melt particles in the Lower Suevite indicate little postdepositional welding due to thermal softening. According to von Engelhardt et al. (1995), temperatures above 750 °C are required for plastic deformation of chemically similar suevite glass from the Ries crater in Germany. Such deformation would also be indicated by the alignment of melt particles. Instead, the orientation data for melt particles in the Lower Suevite (Fig. 8 C) indicate little alignment. Therefore, most melt particles in the Lower Suevite must have been quenched below the glass-transition temperature of 680 °C (von Engelhardt et al., 1995) rapidly after deposition. Consequently,

welding and crystallization of liquidus phase phenocrysts must have occurred during formation and residence in the excavation flow.

Wittmann et al. (2006) identified a temperature gradient in the Yax-1 suevitic deposits based on the distribution of preserved shock metamorphic features in zircons. This temperature gradient is also evident from the distribution of rapidly quenched type 1 melt particles. They are concentrated in the Upper Sorted Suevite and the Lower Sorted Suevite and quickly decline in abundance toward the Brecciated Impact Melt Rock (Fig. 7), indicating prolonged annealing. Cooling of the ejecta plume is also indicated by the progressively less intense crystallization of plagioclase phenocrysts in type 2 melt particles toward the Upper Sorted Suevite (Stöffler et al., 2004; Tuchscherer et al., 2004a; Wittmann et al., 2006). Furthermore, sedimentary lamination and foraminifers are preserved in some carbonate clasts at the top of the Upper Suevite (Goto et al., 2004). However, toward the Brecciated Impact Melt Rock, carbonate clasts are recrystallized and indicate reactions with the matrix. According to Todor (1976), the onset temperature of CO_2 loss from calcite is at 675 °C. Considering the sluggish decomposition reaction of carbonate (e.g., Ivanov and Deutsch, 2002) or back reaction of decomposition products to carbonate (Agrinier et al., 2001), such carbonate clasts were possibly preserved or recrystallized, while anhydrite likely decomposed under hot ejecta plume conditions. For the melt particles, a weak trend of increasing roundness and aspect ratios and decreasing fullness ratios from the Upper Suevite toward the Brecciated Impact Melt Rock (Figs. 9A, 9C) suggests that most of them were deposited as solid particles at temperatures below 680 °C (von Engelhardt et al., 1995).

Constraints on Oxygen Fugacities in Yax-1 Impact Melt Particles

The abundant crystallization of μm -size Fe(Ti)-O phenocrysts in the type 4 melt particles likely indicates oxidizing conditions above the fayalite-magnetite-quartz buffer, possibly reaching into the magnetite-hematite oxygen fugacity space (Fig. 12) during the formation of these melt particles (e.g., Frost, 1991; Giuli et al., 2005).

Other melt particles were likely formed from impact melts within the oxygen fugacity space of the fayalite-magnetite-quartz oxygen fugacity space. The close spatial occurrence of type 4 melt particles together with other melt particle types that do not indicate the presence of Fe-oxide phenocrysts rules out a simple secondary alteration process for the formation of this style of Fe-oxide crystallization. Such secondary alteration that led to the transformation of type 3

melt particles to type 4 melt particles may have occurred locally in the Lower Suevite, where abundant water-saturated lithic clasts were present next to melt particles. As a source for oxygen, the dissociation of H_2O from the shallow sea, CO_2 from the carbonates, and SO_2 from the evaporites of the target sequence can be invoked (Frost, 1991; Chen et al., 1994; Alvarez et al., 1995; Pierazzo et al., 1998). Ebel and Grossman (2005) suggested that strongly oxidizing conditions prevailed in a portion of the Chicxulub ejecta plume from which Ni-rich spinels could condense. The general lack of anhydrite as a component in the Yax-1 suevites (Schmitt et al., 2004) further substantiates this assumption. It is therefore suggested that the type 4 melt particles sampled portions of the ejecta plume that contained increased abundances of volatiles from decomposed surficial target rocks or came under the influence of inflowing air.

Temporal Evolution of the Ejecta Plume at Yax-1

The enrichment of surficial target clast components in the Lower Suevite suggests ballistic emplacement during the passage of the ejecta curtain (Hörz, 1965; Oberbeck, 1975). Melosh (1991) estimated a maximum velocity for the ejecta curtain (v_c) of at most 0.1 the impactor velocity (v_i). A commonly used value v_i for the Chicxulub projectile is 20 km/s (Pierazzo et al., 1998; Collins et al., 2002). Given the present distance of Yax-1 from the crater center of $D \sim 60$ km, which may have undergone some inward and downward transport during crater modification (Kenkmann and von Dalgwigk, 2000; Kenkmann et al., 2004), the early excavation flow that deposited the Lower Suevite at the time t_{LS} likely began in the first minute after the projectile's contact with the Yucatán surface if $t_{LS} = D / v_c$. This is even the case if substantial inward slumping of the section during crater modification of 10–20 km occurred and the contact and compression phase of the projectile are regarded. However, the Lower Suevite also contains abundant silicate impact melt particles that were derived from the crystalline basement as part of the expanding ejecta plume. Expansion of the ejecta plume's early stage vapor-rich portion is estimated to occur at velocities v_p of $\sim 1/2 v_i$ (Melosh and Vickery, 1991). This likely indicates a recording of interfingering of the ballistic excavation flow with the ejecta plume in the Lower Suevite, which is consistent with the ejecta plume–ejecta curtain interaction model of Shuvalov (2003).

The compositional similarity of the Brecciated Impact Melt Rock with the continuous impact melt sheet known from the Chicxulub-

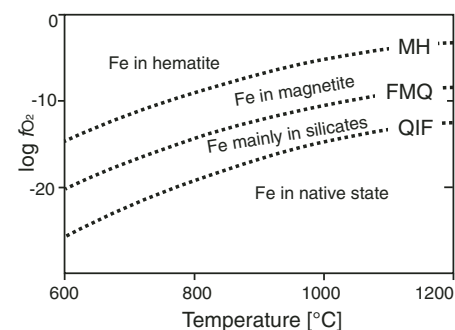


Figure 12. Log oxygen fugacity–temperature diagram showing the relative stabilities of the various oxidation states of iron in the system Fe-Si-O. Redrawn and modified after Frost (1991) to indicate the temperature range of phenocryst crystallization from suevitic melts after von Engelhardt et al. (1995); oxygen buffers: MH—magnetite-hematite, FMQ—fayalite-magnetite-quartz, QIF—quartz-iron-fayalite.

1 drilling (Fig. 11) suggests that the Brecciated Impact Melt Rock could be a portion of the continuous melt sheet. Moreover, its position at Yax-1 is in excellent agreement with predictions from numerical models of Collins et al. (2002), who modeled the formation of the peak ring due to the overriding of (melted) central peak material over the collapsing transient cavity rim. For this process, ~ 5 min after initial impact likely marks the beginning emplacement of the Brecciated Impact Melt Rock on top of the Lower Suevite.

Because no type 2 melt particles were found in the Lower Suevite, it can be assumed that the ejecta plume only started to collapse after the Brecciated Impact Melt Rock was deposited. Breccia-in-breccia textures, the mixing of various plume regions, and grain-size distribution data clearly indicate high turbulence conditions during the deposition of the Middle Suevite–Lower Sorted Suevite (Figs. 5, 7, 8A, and 8B). According to Shuvalov (2003), most ejecta components larger than 10 cm are deposited from the ejecta plume within 10 min after the impact. The restricted grain-size spectrum of the Lower Sorted Suevite indicates that this unit was likely emplaced after most of the larger ejecta components had been deposited.

Furthermore, it is predicted that a Chicxulub-size impact should produce an ejecta plume that expands beyond the atmosphere (Melosh, 1989, 1991; Pierazzo et al., 1998). However, the finest portion of ejecta on top of the Upper Sorted Suevite that probably contained the most highly shocked portions of target and projectile material was removed by aquatic reworking (Arz et al., 2004; Smit et al., 2004; Goto et al., 2004).

The Upper Sorted Suevite contains particles with sizes as large as ~1 cm; therefore deposition may have been through an undisturbed atmosphere that was reestablished by that time. The largest fragments contained in the Upper Sorted Suevite are ~1 cm in diameter (Table 2), suggesting deposition through a reestablished atmosphere. By a first-order calculation of particle settling through an undisturbed atmosphere, thus after cessation of turbulent atmospheric conditions, this results in a settling time for the preserved section of the Upper Sorted Suevite of ~1 hour (Stöffler et al., 2004).

CONCLUSIONS

The petrographical image analysis of drill core Yaxcopoil-1 revealed a systematic record of the depositional history and changes in physical boundary conditions of the Chicxulub ejecta plume. The International Continental Drilling Program provided an excellent test for current models of the formation of large meteorite impact craters. The drilling sampled a unique, continuous sequence of melt-rich impactites that overlie and intruded megablocks of sedimentary rocks in the annular moat of a terrestrial multiring impact crater. Geochemical evidence suggests that impact melt particles from this sequence exhibit grossly uniform element concentration patterns of the potentially least mobile elements. This likely indicates derivation from a homogenized bulk impact melt that underwent transformation to the characteristic melt particle types during ejection and subsequent alteration. The following interpretation of this sequence at Yaxcopoil-1 can be concluded.

The two lowermost suevite units Suevitic Dikes and Lower Suevite represent material that was produced in an early stage of the excavation flow, which interacted with the expanding ejecta plume. During crater modification, this material was transported inward and downward along with slumping megablocks.

A portion of the continuous impact melt sheet is deposited on top of these suevitic deposits as brecciated impact melt rock. This material most likely originated as a film on top of the radially outward- and downward-collapsing central uplift. While the interference of the collapsing central uplift material with the inward-slumping transient cavity wall produced the peak ring, the film of impact melt had retained sufficiently low viscosity and inertia to overrun the central peak ring and spill into the developing annular trough. This interpretation is in very good agreement with numerical models (e.g., Collins et al., 2002; Ivanov, 2005) that predict that the edge of the transient crater cavity comes to a rest near the overturned outer limb of a peak ring.

Impact melt particles that likely indicate airborne transport start to occur in the Middle Suevite, which marks the onset of the record of ejecta plume collapse in Yaxcopoil-1. Deposition temperatures of ~700 °C and erosive surging suggest the collapse of a hot portion of the ejecta plume under very turbulent conditions. This is supported by particle shape data, lack of sorting, and more random shape-preferred orientations of melt particles. Emplacement at this stage was possibly as a flow of fused debris. The fallback suevite indicates a cooling gradient toward the top. Ejecta components likely sampled variable plume regions: this is manifested as rims of accreted fine particles around melt particles and lithic clasts, the mixing-in of melt particles that were formed under elevated oxygen fugacity conditions, and spherule-like components. Furthermore, these particles confirm interactions with the atmosphere and provide evidence for models of condensation from the Chicxulub ejecta plume.

In the uppermost two suevitic deposits, a reestablishing atmosphere winnowed out fines that used to constitute the matrix during late fallback from the collapsing ejecta plume. Distinct sorting as indicated by grain-size distribution data is only indicated in the uppermost unit that contains the most rapidly quenched melt particles. Sorting most likely took place due to interaction with a reestablished atmosphere under minor turbulence. Definite evidence for aquatic reworking is only present in the top meter of the Upper Sorted Suevite.

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