Impact-related dike breccia lithologies in the ICDP drill core Yaxcopoil-1, Chicxulub impact structure, Mexico

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Abstract—Petrographic descriptions of three dike breccia lithologies from drill core Yaxcopoil-1 (Yax-1) are presented. They occur within allochthonous units of displaced sedimentary megablocks of the Chicxulub impact structure. The suevitic dike breccias are the uppermost dike lithology. They contain melt rock particles and melt injections into the dike groundmass. Shock features occur ubiquitously and indicate a strong thermal annealing. Flow textures suggest a highly energetic emplacement process, possibly during the excavation stage as a ground-surge related deposit. The impact melt rock dikes are present in a strongly brecciated megablock interval as flow textured, anastomozing veinlets of impact melt rock that were altered to clay minerals. The melt impregnated a dolomitic host rock, indicating a low viscosity and, thus, high initial temperatures. Brecciation of the impact melt rock dikes occurred while they were still below the glass transition temperature, suggesting that dynamic conditions prevailed shortly after the emplacement process. Major element data indicates that the impact melt rock dikes differ in composition from the homogenized impact melt rock of Chicxulub. This could point to an emplacement during the late compression or early excavation stages of cratering. The clastic polymict dike breccias are coeval with pervasive brittle fracturing of the host rocks. They bear clasts including some crystalline basement and possible melt rock particles in a fine-grained dolomite matrix with turbulent flow textures. Fabric and texture indicate a granular flow at ambient pressures. Such conditions could be envisaged for the excavation phase while the transient cavity grew and fractures opened.

INTRODUCTION

The Chicxulub impact structure, Yucatán Peninsula, Mexico, has a diameter of approximately 180 km (Hildebrand et al. 1995). It is one of the three largest known impact craters on Earth and was formed 65 million years ago (e.g., Hildebrandt et al. 1991; Dressler et al. 2003). Since it is the best preserved among these structures, it provides a unique opportunity for studying cratering processes.

The ICDP Yaxcopoil-1 (Yax-1) borehole was drilled about 60 km to the south-southwest of the center of the Chicxulub impact structure (Morgan et al. 1997, 2000), as determined by seismic exploration and the presence of a gravity anomaly (Pilkington and Hildebrand 1994; Ebbing et al. 2001). It is placed within the annular trough, between the peak ring and the crater rim; it reached a depth of 1511 m. Below 795 m of Tertiary sediments, about 100 m of suevite-type, impact melt rock-bearing breccia units were encountered (Dressler et al. 2003; Stöffler et al. 2004). These units are underlain by 616 m of “megablocks” (Kenkmann et al. 2004), most likely of Cretaceous age, in which Yax-1 terminated. The megablocks are predominantly composed of dolomite, some limestone, and about 27 vol% anhydrite (Fig. 1). Kenkmann et al. (2004) suggest various decoupling horizons and divide the sequence into three main blocks and nine sub-units that terminate at lithostratigraphic boundaries, zones of intense brecciation, and/or the occurrence of breccia dikes.

This study focuses on the dike lithologies in the megablock sequence of Yax-1 (Fig. 1). Being of ubiquitous presence in impact crater settings (e.g., Stöffler et al. 1988; French 1998; Dressler and Reimold 2001), impact-generated dikes were previously described in connection with the Chicxulub impact structure in the Yax-1 and Yucatán-6 drill cores (Dressler 2002; Stinnesbeck et al. 2003; Kenkmann et al. 2003; Wittmann et al. 2003; Dressler and Reimold Forthcoming). The dike lithologies are the prime indicators of an impact deformation of the sedimentary units in the “megablock sequence” of Yax-1 (Kenkmann et al. 2004). The carbonate and anhydrite lithologies only provided indirect
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This is due to their low potential for indicating shock metamorphic features (Reimold 1998; Deutsch et al. 2003) or preserving them in a setting where intense hydrothermal activity in an open geochemical system has to be considered (Hecht et al. 2004). Thorough petrographic descriptions, structural evaluations and geochemical data for these impact-related dike breccias are presented. The synthesis of these results is used to compare the Yax-1 impact dike lithologies with those of other impact structures to develop a genetic model for these dikes.

SAMPLES AND METHODS

Twenty samples were used for this study. Three half-core samples of 10–15 cm in length were available. The remaining 17 samples were quarter core sections of 2–3 cm in length. Standard preparation techniques were used to produce doubly polished thin sections. Due to hygroscopic reactions of clay minerals present in altered impact melt rock particles, the samples were treated with alcohol instead of water. The 360° scans of drill cores provided by ICDP/OSG-GFZ Potsdam (2002) and Soler-Arechalde et al. (Forthcoming) were evaluated to complement the macroscopic description. Optical microscopy on the thin sections was routinely performed for all samples to assess textural and compositional properties of the lithologies. Scanning electron microscopy (SEM-EDX) was performed with a JEOL-JSM 6300 instrument with a RÖNTEC X-ray energy-dispersive analytical system.

Additional petrographic information was gathered by cathodoluminescence microscopy, which was performed with a hot cathodoluminescence microscope LUMIC HC3-LM system operated at 14 kV and 0.08–0.15 mA on selected thin sections. A KAPPA Image Base DX 20 HC thermoelectronically cooled camera was used to capture and process the low-light CL images directly. The main activator for cathodoluminescence (CL) in carbonates is Mn$^{2+}$, and the main quenchers are Fe$^{2+}$ and Fe$^{3+}$ (Machel 2000). CL in calcite has been described as characteristically orange to yellow, while dolomite tends to show red CL (Adams and MacKenzie 1998). Shock-melted carbonates have been reported to show a strong luminescence-quenching effect due to the mixing of iron into carbonate melt (Jones et al. 2000). Schulte (2003) ascribed dull red-brown CL and a lack of CL to quenched carbonate melts associated with impact-generated spherules. Anhydrite, analcime, and iron sulfides generally showed no luminescence. The composition of the analyzed samples was checked by SEM-EDX to distinguish dolomite and calcite.

Quantitative chemical data was produced by electron microprobe analysis conducted with a JEOL JXA 8800 with four wavelength dispersive spectrometers. It was operated at 15 kV acceleration voltage and a 15 nA beam current. Measurement spots (beam radius of 10–3 µm) were checked for their compositional spectrum with an energy dispersive spectrometer (EDX) to assure that only calibrated major chemical components were present apart from volatiles. Calibrations were checked by regular analysis of the
international standard materials basalt glass USNM 11240/52VG-2 and tektite USNM 2213.

**PETROGRAPHY OF DIKE LITHOLOGIES IN YAX-1**

*Suevitic Dike Breccias*

Suevitic dike breccias occur at 909 m and 916 m in Yax-1. They are moderately inclined with regard to the drill core axis and have thicknesses of 8 (Fig. 2a) and 80 cm (Figs. 2b–2c), respectively. The host rocks at 910.2 m are strongly brecciated, biomicritic limestones that are rich in foraminifers and bivalve shells. Clay minerals are present within these host rocks along steeply inclined fractures, and some anhydrite pebbles occur at ~911 m. At the lower contact of the thicker suevitic dike breccia, at ~916.8 m, the host rock is a white, dense limestone breccia cross-cut by potassium feldspar- and iron sulfide-bearing fractures (Fig. 3a). Contacts toward the host rocks are sharp and discordant, sometimes with groove marks. Drill core scans indicate a 3 cm-thick contact aureole in the host rock of the smaller suevitic dike breccia at 909 m and a 6 cm thick contact aureole for the thicker suevitic dike breccia at 916 m (Figs. 2a–2c).

*Matrix*

Suevitic dike breccias are polymict and composed of a variegated mixture of fragments with sedimentary clasts dominating over melt rock particles in a clastic suevite matrix (Figs. 3b–3c). Macroscopically, this matrix is of greenish-grey color but appears brown in thin section under linear polarized light. It is composed of micritic to microsparitic calcite grains. Sometimes, anhedral to euhedral limestone grains of ~50 µm in size occur in a groundmass of clay minerals with a flow texture (Figs. 4a–4c). This matrix type resembles the melt rock textures of the impact melt rock dikes and, therefore, indicates the presence of melt injections in the matrix of the suevitic dike breccias. Other matrix components are present in cracks within angular melt rock particles. An earlier generation of brown, fine-grained calcite veins with flow textures displays a reaction rim with the melt rock particles (mCc in Figs. 5a–5e). These veins are associated with analcime in 20 µm-diameter pores. Coarser-grained sparitic calcite veins of light color form a superimposed, cross-cutting network within the melt rock particles as fracture and vug fillings (sCc in Figs. 5b–5e). Some lepidoblastic anhydrite flakes without alignment are associated with this later fracture fill. The earlier generation of calcite veins show dull red cathodoluminescence that is notably quenched in comparison to the bright yellow cathodoluminescence of the cross-cutting calcite fracture fills (Fig. 5e). The earlier-stage calcite vein network could, therefore, represent a primary component that was subject to some alteration but retained original structural and compositional features.

*Fig. 2.* 360° core scans (ICDP/OSG-GFZ Potsdam [2002]; Soler-Arechalde et al. [Forthcoming]) with picture widths of 18.8 cm (a–c): a) drill core R0175/10—suevitic dike breccia at 909 m; b) drill core R0177/3—suevite dike breccia at 915.8 m; c) drill core R0177/4—same suevite dike breccia as (b), continued at 916.25 m.
Clasts sizes are in the cm range. No size sorting is evident. Sedimentary rock clasts are angular to sub-rounded, and some exhibit contortions (Fig. 2b). Dolomite clasts, fossil-bearing limestone clasts, and chalcedony-limestone intergrowths occur. Anhydrite clasts are scarce. A granite fragment (Fig. 5a) shows strong sericitization of biotite and plagioclase.

Melt Rock Particles
All melt rock matter found was pervasively altered to clay minerals. Two types of melt rock particles (SD 1 and SD 2) are distinguishable by their shape and color. SD 1 melt rock particles (Figs. 6a–6c) are macroscopically green and brown under linear polarized light. They are frequently associated with melt injections in the suevitic dike breccias. Frequently, this melt rock particle type is thinning out into veinlets that form anastomosing networks in the suevitic matrix (SD 3 in Figs. 3c, 4a–4c, and 6c). The SD 3-type melt rock resembles the siliceous matter of the impact melt rock dikes in appearance. Otherwise, SD 1 display ameboid shapes, suggesting a ductile deformation response. They exhibit alignment into a flow texture parallel to the strike of the dike breccias (SD 1 in Figs. 3b–3c and 6c). This melt rock particle type shows alteration structures that are reminiscent of palagonite (Stroncik and Schmincke 2002), since the clay minerals form rims of radially aligned platelets with lamellar structures. Some clay mineral domains exhibit an enrichment in magnesium, possibly due to stronger alteration or secondary growth in vugs, which would indicate some element flux within the melt rock particles (Hecht et al. 2004). Some rare phenocrysts of potassium feldspar and plagioclase composition can be observed in this melt rock particle type, but generally, they appear weakly crystallized before quenching. Potassium feldspar is also present within this melt rock particle type with polycrystalline checkerboard structures and reduced birefringence in ameboid or lenticular domains. The other type of melt rock particles (SD 2 in Figs. 5a–5e) is of a white-pinkish color and is similar to melt rock particles in the “lower suevite” unit of Yax-1 (Stöffler et al. 2004). These particles are angular shaped and bear inclusions of round sparitic carbonate clasts and subangular granite clasts. The melt is extensively crystallized, which is indicated by abundant flow texture-aligned phenocrysts. However, these phenocrysts are mostly corroded. Some plagioclase phenocrysts remain that appear accumulated around vesicles. Sometimes, this melt rock particle type is associated with greenish rims of melt rock. Polycrystalline feldspar aggregates associated with ameboid melt rock show dull gray or no cathodoluminescence, while relic feldspar grains show dull gray-blue-brown cathodoluminescence. Melt rock particles display no cathodoluminescence.

Shock Metamorphic Features
In the shock stage IV melt rock particles, relic minerals of different shock stages occur (Stöffler 1971; Stöffler and Langenhorst 1994). Shock stage I phenomena like reduced birefringence and planar fractures are present in plagioclase and microcline. Quartz exhibits thermally annealed,
decorated PDFs in at least three directions (Figs. 7a and 7b). Such shock stage I features are also present in single mineral fragments floating in the groundmass. Polycrystalline checkerboard feldspar and ballen quartz (Fig. 7c) occur as inclusions in both types of melt rock particles. Some checkerboard feldspar bears inclusions of relic grains of tectosilicates that display decorated PDFs (Kenkmann et al. 2004). A grain of brown zircon with fine, cross-cutting sets of PDFs or parallel sets of planar fractures (Fig. 7d) was found as an inclusion in a bleb of iron sulfide. Electron microprobe (EMP) element concentration mapping and Raman spectroscopy revealed the presence of baddeleyite as tiny inclusions intergrown with this zircon (Wittmann et al. 2004). The shock-induced decomposition of zircon to baddeleyite \((\text{ZrO}_2)\) is a well-documented impact indicator (El Goresy 1968; Kleinmann 1969; Bohor et al. 1993). It is indicative of temperatures in excess of 1775 °C and was experimentally reproduced with shock pressures of 94 GPa (Kusaba et al. 1985). This is a feature indicative of shock stage IV.

**Structural Implications**

The suevitic dike breccias show sharp, discordant contacts with groove-marks in the brecciated host rocks. The groundmass has a flow texture, and components are generally...
aligned in the strike direction of the dikes. This indicates rapid, high energetic emplacement. Furthermore, angular shapes of melt rock particles indicate that this melt was already cooled beneath the glass transition temperature and, thus, responded in a brittle manner during emplacement. In contrast, the contorted shapes of melt rock particles (Fig. 6a) and the presence of some melt injections suggest that some melt was emplaced while it was below the glass transition temperature and, thus, was susceptible to plastic deformation.

**Impact Melt Rock Dikes**

Impact melt rock dikes occur in discrete zones at depths of 1347.2 m (thickness 2.5 cm), 1348 m (thickness 33 cm) (Figs. 8a and 8b), and 1350 m (1 cm and 3 cm thick), with shallow dip angles and sharp contacts to the “dolomite autoclastic breccia” (Dressler 2002) host rock. The 360° drill core scans (ICDP/OSG-GFZ; Potsdam 2002; Soler-Arechalde et al. Forthcoming) do not indicate contact...
Impact-related dike breccia lithologies

aureoles in the dolomite host rocks and do not resolve the contacts with the host rocks. Further occurrences were discovered as minor veinlets and particles in the dolomite breccia units between 1346–1375 m (Fig. 8c) and as reworked components of shear zones (Kenkmann et al. 2004).

Petrography

In the thickest impact melt rock dike vein at 1348 m (Figs. 8a and 8b), dark green melt rock constitutes an anastomozing network of 1–3 mm-wide veinlets throughout a fine-grained, greenish-white matrix. The groundmass is generally composed of ~10 μm large, euhedral dolomite crystals with interstitial melt rock. Domains of coarse, zoned dolomite rhombs >100 μm in size occur associated with thicker brown melt rock veinlets (Fig. 9a). The melt rock veinlets do not show cathodoluminescence, while the coarse dolomite rhombs show dull orange-red-brown luminescence and distinct concentric zonations. The presence of euhedral dolomite crystals in altered impact melt rock that show similar cathodoluminescence features was interpreted by Fouke et al. (2002) as secondary dolomite replacing clay minerals. Lüders and Rickers (2004) concluded from fluid inclusion measurements in dolomite at 1348.56 m that secondary dolomite grew at temperature conditions between 65 and 97 °C. This indicates that a thermal pulse was present that cannot be reconciled with thermal gradients alone. The thermal pulse may correspond to the close presence of the impact melt rock dike. Some of the coarse dolomite crystals also overgrow fine-grained, anhedral dolomite that shows bright orange-red luminescence. This luminescence color is similar to that of dolomite clasts (Figs. 7b–7d). The siliceous melt rock appears pervasively altered to clay minerals that display sweeping extinction and second-order interference colors under crossed polarizers. Bleb-like iron sulfides are common in the melt rock. Larger domains of sulfides display intergrowths of euhedral single crystals of ~1 mm in size. A few micritic dolomite clasts of several mm in size are present (Figs. 8b, 9b, and 9c). They do not show flow textures or alignment but display resorptive features like concave boundaries to the siliceous melt rock.

Shock Metamorphic Features

Thus far, no relic fragments of silicate minerals were found in the sample of the impact melt rock dike at 1348 m. In sample 1347.74 m, a minor impact melt rock particle is associated with checkerboard feldspar fragments in a black shear zone (Kenkmann et al. 2004). Some associated potassium feldspar grains show undulous extinction. The bleb-like appearance of iron sulfides within the impact melt rock veins (Fig. 9e) may indicate a formation from a melt due to liquid immiscibility of sulfide and silicate melts.

Structural Implications

Structural observations suggest that the injected
substance was a low viscosity melt, as melt rock veins frequently show a wavy, anastomosing development (Fig. 8b), and melt rock also occurs between dolomite breccia fragments (Figs. 9a–c and 9f). Some fine grained, subhedral dolomite is present within the siliceous melt rock veins as aggregates of lenticular shapes or trails of single crystals, indicating dispersion and alignment due to flow (Kenkmann et al. 2004). Siliceous melt rock is collected in pockets or lenses that are interconnected. A brittle deformation stage, characterized by sub-vertical and sub-horizontal faulting with displacements of up to a few cm, at most, took place while the siliceous melt was still partly viscous. The melt rock shows a ductile response and flow features induced by the dragging and displacement along the faults (Fig. 9f). Some cataclastic fracturing of the carbonate/siliceous melt rock also occurred. Some shear zones formed after melt emplacement. They crosscut earlier brittle faults and rework impact melt rock matter, leading to grain comminution of siliceous matter and dolomite.

**Clastic Polymict Dike Breccias**

Clastic polymict dike breccias occur in the Yax-1 drill core between depths of 1314.7 m and 1374 m. This encompasses the lowermost part of the “dolomite and anhydrite interlayered” lithological unit and transgresses into the “dolomite autoclastic breccia” unit (Dressler 2002) (Fig. 1). Characteristically, the dip of the clastic polymict dike breccias changes from steeply inclined/nearly vertical between 1314.7 and 1316.2 m (Figs. 10a and 10b) to about 60° at 1341.6 m (Fig. 10c) and horizontal at 1373.9 m. Clastic polymict dike breccias range in thickness from <1 cm to 36 cm, and several occurrences show branching. Contacts to host rocks are sharp and discordant with regard to the sedimentary bedding.
Fig. 8. a) 360° core scan (ICDP/OSG-GFZ Potsdam [2002]; Soler-Arechalde et al. [Forthcoming]) with picture widths of 15.7 cm. Drill core R0319/2—impact melt rock dike at 1347.8 m; b) thin section photograph sample 1347.96 m. Impact melt rock veins (IM) are associated with iron sulfide (IS) and rare dolomite clasts in a dolomite/interstitial melt rock matrix. This impact melt rock dike is cut by numerous fractures (dashed lines); c) thin section photograph of sample 1368.63 m. A thin impact melt rock vein with abundant iron sulfide intruded a strongly brecciated dolomite host rock.
Fig. 9. Microphotographs of impact melt rock dike sample 1347.96 m. (IM) is siliceous impact melt rock, (Dol) is dolomite, (Dol-1) is primary dolomite, (Z-Dol) is zoned, later dolomite, (Dol/IM) is dolomite with interstitial impact melt rock. (IS) is iron sulfide: a) backscattered electron image of compositionally zoned dolomite and interstitial impact melt rock; b) linear polarized light image showing an impact melt rock vein next to a dolomite clast with a resorption embayment; c) cathodoluminescence image of the same region as in (b). Several compositionally distinct dolomite phases are indicated; d) enlarged region of (c): a cathodoluminescence image of zoned dolomite overgrowing primary dolomite and replacing altered impact melt rock; e) backscattered electron image of impact melt rock vein with anhedral dolomite and blebs of iron sulfide; f) linear polarized light image of an impact melt rock vein lacing a fault, suggesting that the faulting took place while the impact melt was still viscous.
Matrix

The groundmass of the “regular” clastic polymict dike breccias is composed of gray dolomite with grain sizes of 5–20 µm and displays a flow texture (Fig. 11a). It is poorly consolidated (Fig. 11b) and bears a variety of angular to sub-rounded clasts. The dolomite groundmass shows cathodoluminescence of medium intensity red to pink, similar to the dolomite component of the dolomite-anhydrite host rocks (Figs. 11c and 11d). However, some minor deviations, such as streaks and patchy domains within the groundmass, have different, orange luminescence of higher intensity. This could indicate that the groundmass recrystallized together with the host rock dolomite to the present composition, possibly during equilibration with hydrothermal fluids, or that it was mainly derived from host rock material. The anhedral shape of matrix grains and poor consolidation (Fig. 11b) supports the latter interpretation.

Clasts

Clast types present are angular to sub-rounded and are dominantly dolomite, some anhydrite, anhydrite-dolomite, iron sulfides, and rare limestone and organic matter-bearing clasts (Figs. 12a–12c). They appear to be mostly derived from host rock lithologies. “Exotic” clasts are present as angular to sub-rounded siliceous types, occasionally with aphanitic textures. They contain clay minerals intergrown with anhedral, 10 µm-sized potassium feldspar (SC in Fig. 12c). Some fluorite was found as overgrowths in these
siliceous clasts, indicating a hydrothermal overprint. A portion of the “exotic” clasts are predominantly composed of a fine-grained mass of fluorite with a flow texture and some tiny inclusions of quartz, potassium feldspar, and disseminated iron sulfide grains (FC in Fig. 12c). Iron sulfides are frequently associated with silicate clasts as finely disseminated grains or coarse, mm-sized, subhedral grains but also form separate, angular clasts in the dolomite groundmass. Scarce angular granite clasts of 0.5–2 cm in size were reported by Dressler (2002) in the largest clastic polymict dike breccia at 1341 m. Clast sizes are below 1 cm in the thinner dikes. No sorting is observed. The matrix-clast ratio of the clastic polymict dike breccias is high, especially in the thinner dikes, which show a less-dense packing of clasts than the thicker dike at 1341.6 m (Fig. 12b).

Shock Metamorphic Features

Shock indicators in the clastic polymict dike breccias are scarce and somewhat ambiguous in the samples available. A few grains of polycrystalline potassium feldspar with a checkerboard texture and a halo of brown clay minerals were found in the large clastic polymict dike breccia at 1341 m (Fig. 13). It is speculated that these clasts could represent relics of altered impact melt rock.

Structural Implications

Several stages of deformation can be inferred from the structure and composition of the clastic polymict dike breccias. The jagged and sharp contact to the host lithologies and brecciation of host rocks indicates a brittle response to the emplacement of the dikes. Indicators for turbulent flow within the dike matrix are present as convoluted thin bands of anhydrite (Fig. 14a) and fine, dark streaks in the dolomite groundmass. These emplacement conditions could have been responsible for the rounding of some clasts within the dikes and the sub-rounded to angular shapes of matrix grains. It is likely that the matrix grains moved with respect to each other during the formation of these dikes. When ductile deformation in the dikes had ceased, the dike groundmass must have rapidly gained coherence by some sort of cementation process that was possibly thermally enhanced because both matrix and clasts were subsequently affected by localized brittle deformation (Fig. 12a). This deformation stage produced networks of anastomosing microfaults parallel to the strike directions of the dikes (Fig. 14b).

The clastic polymict dike breccias also cut across organic matter-bearing sediment layers (Kenkmann et al. 2004). This indicates that the emplacement of the clastic dolomite dike breccias post-dated the formation of organic matter-bearing layers. However, some organic matter migrated after the emplacement of the dikes, using brittle shear zones and faults in the clastic polymict dike breccias as pathways and hosts (Fig. 14b).

If siliceous particles present in the clastic polymict dike...
breccias represent reworked impact melt rock particles, then a later stage formation of the clastic polymict dike breccias than the impact melt rock dikes would be indicated. However, since no cross-cutting relationships between these two lithologies can be resolved in Yax-1, this assumption is highly speculative.

**Unusual Clastic Dike Breccia Types**

An unusual, “black” clastic polymict dike breccia lithology occurs at depths of 1397.5 m to 1399.5 m. Here, steeply inclined (usually >70°), coarse-grained dolomite breccia dikes (Figs. 15a and 15b) with thicknesses of a few cm cut the calcarenite and “carbonaceous siltstone with minor dolomite” host rock lithologies (Dressler 2002) discordantly. They are characterized by the ubiquitous presence of disseminated iron sulfides and a thick lacing with black organic matter in interstices (Fig. 15c), consisting of bitumen and oil (Lüders and Rickers 2004). Their groundmass is composed of angular dolomite grains that are coarser-grained and more densely packed than those of the dolomite groundmass of the other clastic polymict dike breccias. Their matrix-clast ratio is distinctly smaller than the generally high ratio of other clastic polymict dike breccias. Clast types found in the single sample available were all derived from sedimentary host rocks and generally exhibit angular shapes. They include predominant dolomite clasts, rare anhydrite clasts, and rare limestone clasts. The latter show patches of dolomite (Fig. 15d) with concave boundaries toward limestone, indicating incumbent replacement by calcite. Siliceous clasts were not found. The unusual “black” clastic polymict dike breccias intruded megablock units in a distinctly separate section of the drill core where organic matter was present. Their position and different development may indicate different, less energetic formation conditions and shorter transport distances, which are indicated
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GEOCHEMISTRY

Whole Rock Data

X-ray fluorescence analyses of selected dike samples of Yax-1 are presented in Schmitt et al. (2004). The chemical composition of the suevite dike breccia at 916 m does not show significant differences to that of the Yax-1 suevite-type units. A clastic polymict breccia dike at 1316 m is dominated by locally derived material from the host rock and contains 12–14 wt% of a siliceous matter that is similar to that of the Yax-1 suevite units. In contrast, the black clastic dike breccia at 1399 m has only a minor siliceous component (<3 wt%) and displays only slight enrichments of the titanium and potassium content in comparison to the host rock. The impact melt rock dike at 1348 m has a quite different chemical composition (enrichments of the TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, Rb, and Zr contents and depletions of the SiO$_2$ and CaO contents) in comparison to the suevite dike breccia, the Yax-1 suevite, or the Yucatán-6 impact melt rock (Schmitt et al. 2004). The Cr/ TiO$_2$ and Zr/V ratios (Fig. 16) indicate that the chemical compositions of the dike lithologies are distinctly different from the dolomitic breccia host lithologies, with the exception of the black clastic breccia dike. Instead, they lie within the range of the suevite units of Yax-1. The impact melt rock (Fig. 16) shows a clearly different trace element composition than the dolomite breccias and an average shale (Turekian and Wedepohl 1961), respectively. This should most likely rule out a sedimentary origin, e.g., as a residuum from dissolution of dolomite or as a hydrothermally altered shale layer (Schmitt et al. 2004). With the exception of the unusual black clastic polymict dike breccia, all other analyzed dike lithologies are distinctly enriched in the potassium content in comparison to their host rocks. This is probably due to a strong hydrothermal overprint (Hecht et al. 2004; Schmitt et al. 2004).

Compositions of Melt Rock Particles and Siliceous Matter

Melt rock particles and siliceous matter were analyzed by electron microprobe (EMP). For analysis, the following components were distinguished: SD 1: two SD 1-type melt rock particles (Fig. 17a) of the suevite dike breccias were analyzed in sample 916.65 m; SD 2: five SD 2-type melt rock particles (Fig. 17b) of the suevite dike breccias of samples 916.23 m, 916.65 m, and 916.34 m were analyzed; SD 3: SD 3-type melt rock matter (Fig. 4c) of the suevite dike breccias was analyzed in samples 909.01 m, 909.11 m, and 909.19 m; SD 4: SD 4-type siliceous matter of the suevite dike breccias is fracture and vug fill within SD 1-type melt rock particles (Fig. 17a) and was analyzed in samples 916.23 m, 916.34 m, and 916.65 m; IMD: green, siliceous melt rock veins (Fig. 17c) were analyzed in the impact melt rock dikes. Associated iron sulfides and dolomite were avoided. The measurements represent samples 1347.96 m (spot...
Fig. 15. Unusual “black” clastic polymict dike breccias: a) 360° core scan with picture width of 15.7 cm. Drill core R0335/6; the depth at top is 1398.7 m; b) photograph of sample 1398.35 m showing crushed limestone fragments in the “black” clastic polymict dike breccia. This sample was not available for analysis; c) linear polarized light image of sample 1399.06 m. Micritic limestone clast (Cc) in the dolomitic dike breccia matrix is laced with organic matter (black) and filled with angular dolomite (Dol) clasts; d) backscattered electron image of sample 1399.06 m, showing a limestone clast (Cc) with relic dolomite (indicated by black arrows). The calcite clast is surrounded by dolomitic dike groundmass (Dol). (IS) is iron sulfide.
measurement and defocused beam) and 1368.63 m (spot measurement); CPD: the siliceous matter analyzed in the elastic polymict dike breccias represents intergrowths of potassium feldspar with interstitial clay minerals (CPD in Fig. 17d). The data contains measurements with defocused beams and spot measurements on sample 1314.77 m. Spot analyses of the interstitial clay mineral matrix matter are indicated by the white arrow in Fig. 17d.

Reference Materials

For comparison, EMP data for melt rock particles of the suevite/impact melt rock units of Yax-1 from 796-894 m are plotted in Figs. 18 and 19. The shaded areas MP 1–2 and MP 3–4 represent melt rock particles that are similar in appearance to SD 1 and SD 2, respectively. MP 1–2 encompasses the data for 20 particles of “type 1 and 2 melt rock particles” of Hecht et al. (2004). They represent altered melt rock particles of samples from the upper three sub-units of the “impact breccias and melt rocks” (Fig. 1) of Yax-1. These melt rock particles are sub-rounded melt rock particles and melt rock shards of green to brownish colors. They are poorly crystallized in that they show only minor to moderate phenocryst development (Hecht et al. 2004). MP 3–4 represents 30 more or less well-crystallized melt rock particles from samples of “impact breccias and melt rocks” (Fig. 1) of Yax-1. They are equivalent to “type 3 and 4 melt rock particles” according to Hecht et al. (2004). “Type 3” and “type 4” melt rock particles show variable shapes from sub-angular to elongated and lumpy. They range in colors from greenish to pale beige and dark brown. Generally, these particles are extensively crystallized and, therefore, exhibit abundant plagioclase and pyroxene phenocrysts (Hecht et al. 2004). These authors present a more detailed discussion of the MP 1–4 melt rock particles. The C-1 and Y-6 data sets represent whole rock EMP-data of Chicxulub impact melt rock from drill cores Chicxulub-1 (C-1) (Schuraytz et al. 1994) and Yucatán-6 (Y-6) (Kettrup et al. 2000; Schuraytz et al. 1994). C-1 impact melt rock is considered less affected by alteration than Y-6 impact melt rock (Schuraytz et al. 1994). All data for selected silicate components presented herein are listed in Table 1. All data presented in Fig. 19 were calculated to 100% totals.

Major Element Concentrations

The results of the EMP analyses are listed in Table 1. The relative compositions of sample types are plotted along with average clay mineral compositions after Newsom et al (2004) in Fig. 18. Since, at this stage, no crystal structural control by XRD data is available, it can only be tentatively concluded that the dike lithology samples are composed of mixed-layer minerals, with the IMD and CPD spot compositions plotting closely to an illite average composition. This also agrees well with example compositions of illites from Newman and Brown (1987).

Harker diagrams (Fig. 19) indicate a strong enrichment of magnesium in the melt injections associated with the suevitic dike breccias (SD 3) and the strongly altered melt rock/newly grown clay minerals (SD 4) when compared to the other sample matters plotted. There is a trend of enrichment in the weakly crystallized suevite melt rock particles of the “suevite-type units” (~796—894 m) of -1 (MP 1–2) and those of the suevite dike breccias (SD 1). The siliceous component of the impact melt rock dike (IMD), the siliceous clasts in the elastic polymict dike breccias (CPD), and the strongly crystallized melt rock particles in the suevitic dike breccias (SD 2) reflect the concentration level of the homogenized impact melt rock of Chicxulub as plotted for Y-6 and C-1. Calcium and sodium are strongly depleted in almost all dike sample populations, possibly due to intense alteration. Potassium shows a reverse trend: most samples are enriched with respect to the average concentrations in Y-6 and C-1. A similar trend of enrichment is reflected in the aluminum concentrations of the dike sample populations. Iron essentially exhibits equal concentration ranges within the dike sample populations, but petrographical observations suggest that iron occurs concentrated in the masses of sulfides in the dike lithologies, which are not accounted for in the microprobe analyses. Therefore, the compositional range of iron is problematic. Titanium is exhibiting average concentrations that are around 0.5 wt% for the bulk melt rock composition, MP 1–2, and MP 3–4, SD 1, and CPD. The scatter may be explained by the local occurrence of titanium oxide minerals. However, the data set indicates a composition with a statistically sound standard deviation (Table 1) and, thus, confirms an enrichment in titanium of about 1 wt% in...
the IMD when compared to the other melt rock compositions from the Chicxulub impact melt rocks. The same trend is present in the whole rock data of Schmitt et al. (2004). It should, therefore, represent a distinct characteristic of the impact melt rock dikes. Some depletion in titanium compared to this average concentration is indicated in most melt rock sample populations of the suevitic dike breccias (SD 2, SD 3, and SD 4), which are nonetheless still within the concentration range of reference materials from the suevite-type units of Yax-1 (MP 1–2 and MP 3–4). Interestingly, there is no correlation between titanium and silicon concentrations. This suggests that a relative enrichment in titanium with a coinciding decrease in silicon is unlikely.

**DISCUSSION**

**Comparison with Dike Breccias of Other Impact Structures**

Impact generated dike lithologies are a ubiquitous feature in terrestrial impact craters (e.g., French 1998; Reimold 1998; Dressler and Reimold 2001). However, most studies on impact-induced dike lithologies describe settings where crystalline target rocks were intruded. The dike lithologies in Yax-1 are special as they occur in predominantly carbonaceous/evaporitic host rocks. Bjørnerud (1998) described “fault breccias,” “breccia lenses,” and “breccia dikes” in the 13 km-diameter Kentland impact structure, which occur in carbonate host rocks of the central uplift. From cross-cutting relationships and particle-size analysis of the breccias, Bjørnerud (1998) concluded that the breccia lithologies formed during the crater modification phase as the central uplift developed.

Lambert (1981) discriminated two main types of dike breccias from observations in the Sudbury, Charlevoix, and Rochechouart impact structures. The first type has a fine-grained to cryptocrystalline matrix and a flow texture, which was ascribed to the compression stage of crater formation. The second type exhibits mineral fragments in a matrix of fine-grained debris and was ascribed to the decompressional
Table 1. Electron microprobe (EMP) data for siliceous dike breccia components in Yax-1. The sample types are explained in the text; “Ø” refers to the electron beam diameters for the respective measurements; FeO is total iron.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Ø</th>
<th>Oxides in weight percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean (n = 21)</td>
<td>Na(_2)O</td>
</tr>
<tr>
<td>SD 1</td>
<td>20 µm</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.08</td>
</tr>
<tr>
<td>SD 1</td>
<td>6 µm</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.25</td>
</tr>
<tr>
<td>SD 2</td>
<td>20 µm</td>
<td>4.10</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>1.05</td>
</tr>
<tr>
<td>SD 3</td>
<td>6 µm</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.50</td>
</tr>
<tr>
<td>SD 4</td>
<td>20 µm</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.22</td>
</tr>
<tr>
<td>CPD</td>
<td>20 µm</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.10</td>
</tr>
<tr>
<td>CPD</td>
<td>6 µm</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.06</td>
</tr>
<tr>
<td>IMD</td>
<td>20 µm</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.03</td>
</tr>
<tr>
<td>IMD</td>
<td>6 µm</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Fig. 18. Ternary diagram with average mineral compositions after Newsom et al. (2004).

rebound of the sub-crater floor following the progression of the shock wave. Bischoff and Oskierski (1987) refined these observations at the Rochechouart crater where they linked pseudotachylites to the compression stage and impact melt breccia injection to the end of the compression stage and the beginning of the excavation stage. Dikes with a clastic matrix and fragmental breccias in the crater floor of the Rochechouart structure reworked the pseudotachylites and melt rock dikes and, therefore, indicated a later formation. These authors believe that suevitic dike breccias formed during the crater modification phase due to gravitational deposition of fall-back breccias into subcrater fractures. However, according to these authors, these suevitic dike breccias display no preferred particle orientation. Elongated melt rock particles and flow textures within the suevitic dike breccias in Yax-1 indicate that a different emplacement mechanism and cratering stage have to be inferred.

A relationship between the relative thickness of dike breccias and their formation time was presented by Stöffler et al. (1988). Relatively thin breccia dikes with a melt matrix and thin breccia dikes with a clastic matrix formed in earlier cratering stages than thicker ones. In addition to that, Thompson and Spray (1994), and Dressler and Reimold (Forthcoming) suggested that thinner pseudotachylites are formed during the compression stage, and larger pseudotachylite bodies may be formed during the crater modification phase.

Similar conclusions were drawn for the ~25 km-diameter, Ries crater (Stöffler et al. 1988). Melt breccias (pseudotachylites and impact melt breccia dikes), monomict breccias, and polymict clastic dike breccias that penetrated the crystalline basement floor were described by Rehfeldt (1983) and Stöffler et al. (1977, 1988). Melt breccia formation was attributed to the late compression and early excavation phase of cratering as dynamic injections or frictional melts. Polymict...
Fig. 19. Harker diagrams of the electron microprobe (EMP) data listed in Table 1. Major elements versus SiO₂. Additional data are from Schuryatz et al. (1994), Kettrup et al. (2000), and Hecht et al. (2004).
dike breccias of the Ries crater (Fig. 20) resemble the clastic polymict dike breccias in Yax-1 macroscopically: they also bear fine-grained, mosaic-like recrystallizations of feldspar (Stöffler et al. 1977). These components could be an analogue to the potassium feldspar clasts associated with the clastic polymict dike breccias (Fig. 17d) and the suevitic dike breccias in the Yax-1 drill core (Figs. 3b, 3c, 6b, and 6c).

Wiest (1987) described polymict dikes, fragmental breccias, suevitic breccias, and impact melt breccias in the ~39 km-diameter Carswell structure. He ascribed these dike lithologies to injections from the transient crater cavity into blocks of the crater wall, the crater floor, and the central uplift during the excavation phase. This author also suggested that injections into the crater floor may continue during the crater modification phase along with the collapse of the transient crater cavity. However, as the impact melt rock dikes and elastic polymict dike breccias in Yax-1 are truncated by some faults, their formation might have occurred earlier.

Impact melt rock dikes in the ~100 km-diameter Popigai structure were described as apophysis-like injections into suevite units and into brecciated gneisses of the ring uplift (Masaitis 1994, 2002; Vishnevsky and Montanari 1999). The injection of impact melt into the crater floor was ascribed by Masaitis (1994) to a short time interval before the excavation stage.

Kenkmann (2003) showed that dike formation in sandstones of the 7–8 km-diameter Upheaval Dome structure starts during shock loading. This leads to “distributed cataclastic flow” at high confining pressures, which is initiated by grain crushing, collapse of pore space, and subsequent intergranular shear. The flow of the perversively crushed material continues during transient cavity growth and crater modification by a granular flow mechanism at fluctuating lower pressures that allow dilatancy.

Structural Synthesis for the Origin of Dike Breccias at Chicxulub

Suevitic dike breccias observed in Yax-1 appear to be structurally and compositionally most closely related to a highly energetic and, thus, early suevitic deposit, as they are associated with melt injections. Such formation conditions are only found in the lowermost units of the suevite-type and brecciated impact melt rock section of Yax-1. For the lowermost unit (“lower suevite”), ground-surging is suggested as a deposition process (Stöffler et al. 2004). According to Kenkmann et al. (2004), this took place near the rim of the transient cavity when it had reached its maximum extent, and the ejecta curtain moved beyond the cavity rim. Drag and spallation-induced fissures in the surface lithologies, which were filled with ground-surged suevite material, was proposed by Kenkmann et al. (2004) as a formation mechanism for the suevitic dike breccias.

The impact melt rock dikes of Yax-1 should most probably represent dynamic injections of low viscosity and, thus, hot impact melt into carbonate host rock. Their composition is not derived from the host rock lithology (Schmitt et al. 2004), which is a characteristic feature of local, in situ frictional and/or shock melts (pseudotachylites) (e.g., Reimold and Colliston 1994; Thompson and Spray 1994; Reimold 1998; Dressler and Reimold Forthcoming). Impact melt rock breccia dikes have been explained as melt injections during the compression and/or early excavation phase and the growth of the transient cavity (e.g. Lambert 1981; Masaitis 1994; Dressler and Reimold 2001). Von Engelhardt et al. (1992) suggested that such dike breccias represent intrusions of melt into fractures produced in an extensional stress regime during the crater modification phase. Dressler and Reimold (Forthcoming) also suggest a relatively late stage for the formation of impact melt dike breccias at Vredefort and Sudbury. However, these authors cite the “granophyre” and the “offset dikes” of the Vredefort and Sudbury impact basins, respectively, as possible examples of homogenized, undifferentiated impact melt related to the main coherent impact melt sheet of these basins. Clearly, this is not the case for the impact melt rock dikes present in Yax-1 since they reflect a chemical composition that is distinctly different from the homogenized coherent impact melt rock of Chicxulub (Schmitt et al. 2004). Bischoff and Oskierski (1987) attributed
the injection of their “type 1-A” melt breccia dikes into the crater floor of the Rochechouart crater to the cratering stage characterized by high-energy conditions. They reasoned that the lack of lithic fragments, the lower content of clasts, smaller clast sizes, and the presence of flow textures support this conclusion. The impact melt rock dikes of Yax-1 may indicate a similar formation stage, as they generally lack lithic silicate fragments and show flow textures. Their frequent faulting and cataclastic reworking may serve as additional evidence for an early formation. However, most importantly, because they are low viscosity/high temperature melt injections, a very short temporal hiatus between their emplacement and the passage of the shock wave must be inferred.

The clastic polymict dike breccias of Yax-1 include some reworked impact melt rock and, therefore, post-date the earliest formation of impact melt injections, presumably during the compression stage. Flow textures suggest turbulent flow conditions during emplacement. Later, brittle deformation stages that may be linked to displacements of megablocks during crater modification affected the clastic polymict dike breccias. The presence of clastic polymict dike breccias near lithological boundaries could also indicate a formation during the crater modification stage. Their spatial relation to dislocation horizons in the megablocks (Kenkmann et al. 2004) would be consistent with models of strongly localized granular flow as invoked by Melosh (1983, 1989) for the crater modification stage to accommodate mass movements. Therefore, granular flow within the dikes could have been the responsible deformation mechanism that led to the intrusions of the clastic polymict dike breccias. This can account for the fine-grained groundmass consisting of crushed and rounded mineral grains, flow textures, and the predominance of host rock-derived clasts.

The unusual “black” clastic polymict dike breccias could reflect a lower energetic emplacement process with shorter transport distances during the end of the excavation phase. This would explain their low matrix to clast ratio and the lack of reworked silicate melt rock. A similar explanation was presented by Bischoff and Oskierski (1987) for the monomict “type 3-A” breccia dikes in the Rochechouart impact structure.

**Geochemical Implications for the Genesis of Dike Breccias**

The behavior of major elements during the alteration of silicate glasses, in particular during the transformation of basaltic glass to palagonite, is dependent on many physicochemical parameters apart from structural and compositional properties of the pristine glassy material (e.g., Jercinovic et al. 1990; Utzmann et al. 2002; Stroncik and Schmincke 2002). Comparing electron microprobe (EMP) analyses with whole rock chemical data, Staudigel and Hart (1983) found that titanium was a rather immobile component that is least affected by the hydrothermal alteration of basaltic glass. Utzmann et al. (2002) suggested that high field strength elements are preferentially retained/enriched in the alteration products of basaltic glass by sorption through clay minerals.

Titanium concentrations in samples of the suevitic dike breccias are similar to the average composition of Chicxulub melt rocks (Fig. 19), thus indicating a close geochemical relationship. In contrast, impact melt rock dikes indicate a different composition if the relative enrichment in titanium is considered a primary feature. This is most obvious when the impact melt injections accompanying the suevitic dike breccias (SD 3) are compared to the impact melt rock dikes. Although similar in appearance, they are chemically distinct, especially considering their titanium concentrations. Relative enrichment in aluminum and potassium in the impact melt rock dikes of Yax-1 in comparison to the average concentrations of the coherent Chicxulub impact melt rock (Y-6 and C-1) could be taken as additional evidence for a distinct melt composition of the melt rock dikes. However, the relative enrichment in potassium could be due to intense hydrothermal alteration, as observed in the suevite units of Yax-1 (Hecht et al. 2004) and in impacters of many other impact structures (e.g., Reimold et al. 1994; French et al. 1997; Gurov et al. 1998). Nevertheless, the presence of a mafic to intermediate component in the Chicxulub impact melt, which could account for elevated titanium concentrations, was already suggested by Kettrup et al. (2000) from trace element isotopic data and clast contents in the impact breccias. Schulte et al. (2003) suggested mafic melt components in the Chicxulub impact melt from EMP data of Chicxulub impact melt spherules. Further implications for heterogeneous melt compositions at Chicxulub are indicated by the variable compositions of Haitian tektite-like glasses that are attributed to the Chicxulub impact melt (Koeberl and Sigurdsson 1992). In impact breccia dikes of the Rochechouart crater, titanium and other major chemical elements are enriched in comparison to the coherent Rochechouart impact melt rock. This was attributed to the contribution of a mafic component to the melt source rock mixture (Oskierski and Bischoff 1983; Reimold et al. 1983). To account for inhomogeneities in impact melt compositions, Masaitis (1994) suggested primary differences in target rock compositions, radial variations in shock level, and ejecta velocity. The preservation of the distinct signature of the impact melt rock dikes in Yax-1 may be explained by their emplacement process. If the impact melt rock dikes represent a very early product of impact melt injection at the compression to early excavation stage, they could have originated from a relatively distinct target lithology that did not get homogenized with the main melt mass. At this early stage, the homogenization process induced by the rebound of the crater floor and the growth of the central peak, which should thoroughly mix the impact melt (Grieve et al. 1977), could still be incomplete. Intense homogenization should have occurred in the main mass of the coherent impact melt sheet as present in Y-6 and C-1, while the melt rock particles in the ejecta plume contained now in the suevite-type units probably reflect an incomplete homogenization that prevailed until the
end of the excavation stage. The chemical composition of siliceous clasts from the clastic polymict dike breccias is ambiguous (CPD in Table 1). In Fig. 19, this sample matter plots within the range of compositions of the reference melt particle compositions from Yax-1 except for a strong enrichment in potassium. Therefore, it is most likely that the clastic polymict dike breccias contain reworked impact melt rock particles, which are present as siliceous particles (Figs. 12c and 17e). The close spatial relationship of clastic polymict dike breccias and impact melt rock dikes in Yax-1 supports this interpretation. The different titanium concentrations in the CPD could mean that the clastic polymict dike breccias sampled impact melt rock from diverse target lithologies, as long transport distances are indicated within the clastic polymict dike breccias by the presence of granite fragments derived from the crystalline basement.

CONCLUSIONS

The “megablock” sequence of the Chicxulub drill core Yax-1 contains impact breccia dike lithologies that intruded displaced sedimentary megablocks. Intense hydrothermal alteration and some auto-metamorphic effects complicate the unraveling of their origin. However, titanium concentrations indicate that impact melt rock dikes show a melt composition that is distinctly different from the average melt compositions of the coherent impact melt rock sheet of the Chicxulub structure and of the other melt rock particles contained in the suevite of Yax-1. Petrologic evidence, structural implications, and some geochemical characteristics suggest formation of the dike lithologies in the following cratering stages:

1. Injection of impact melt rock dikes could have occurred in close spatial relationship to the highly energetic material flow induced by the propagating shock wave during the growth of the transient cavity. The required conditions for dynamic injection were only prevailing during the compression and the excavation phases. This limits the formation of impact melt rock dikes to these stages.

2. Emplacement of clastic polymict dike breccias could span the excavation and crater modification phases. Granular flow could have been the dominant deformation mechanism within these dikes. This could be related to mass movements during the collapse of the transient cavity as megablocks slumped inward and downward. However, formation of the clastic polymict dike breccias could have occurred even earlier on while the growing transient cavity produced a pattern of deep fractures that were subsequently filled with crushed, cohesionless material. Lower energetic emplacement conditions prevailing at a later stage could have been responsible for the formation of the unusual types of clastic polymict dike breccias that lack siliceous particles.

3. Drag- and spallation-induced delamination have probably accommodated the injection of suevitic dike breccias during ground surging at the base of the ejecta curtain. This could have happened as the ejecta curtain moved beyond the rim of the transient cavity when it had reached its maximum extent. At this stage, the upper megablock unit of Yax-1 must have been at its present position on top of the “megablock sequence” already.

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