Upheaval Dome, Utah, USA: Impact origin confirmed

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ABSTRACT

Upheaval Dome is a unique circular structure on the Colorado Plateau in SE Utah, the origin of which has been controversially discussed for decades. It has been interpreted as a crypto volcanic feature, a salt diapir, a pinched-off salt diapir, and an eroded impact crater. While recent structural mapping, modeling, and analyses of deformation mechanisms strongly support an impact origin, ultimate proof, namely the documentation of unambiguous shock features, has yet to be successfully provided. In this study, we document, for the first time, shocked quartz grains from this crater in sandstones of the Jurassic Kayenta Formation. The investigated grains contain multiple sets of decorated planar deformation features. Transmission electron microscopy (TEM) reveals that the amorphous lamellae are annealed and exhibit dense tangles of dislocations as well as trails of fluid inclusions. The shocked quartz grains were found in the periphery of the central uplift in the northeastern sector of the crater, which most likely represents the cross range crater sector.

Keywords: impact craters, shock metamorphism, quartz, TEM data.

INTRODUCTION

Upheaval Dome (Fig. 1) is an unusual structural feature on the Colorado Plateau in Canyonlands National Park, southeastern Utah, USA. While the plateau is largely undeformed, the dome consists of strongly deformed and uplifted rocks that are surrounded by a structurally depressed ring syncline (Fig. 1). Although superbly exposed, the origin of Upheaval Dome has been a subject of controversy to date because of the lack of unequivocal evidence for shock metamorphism (e.g., Koeberl et al., 1999). Arguments in favor of an impact origin are based on Upheaval Dome's structure (e.g., Kriens et al., 1997; Kenkmann et al., 2005; Scherler et al., 2006), geophysical surveys (Kanbur et al., 2000), and the analysis of deformation mechanisms (Kenkmann, 2003; Okubo and Schultz, 2007). Despite these recent investigations, the interpretation of Upheaval Dome as the result of salt diapirism (e.g., Jackson et al., 1998) is still widespread. Here, we document a localized shock metamorphic overprint of quartz grains in sandstone samples from the Early Jurassic Kayenta Formation, making use of optical, scanning, and transmission electron microscopy (TEM).

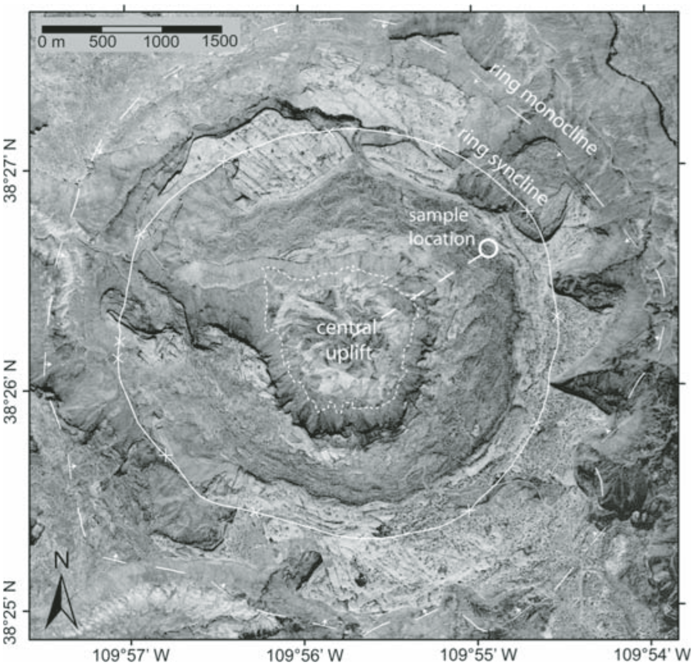

Figure 1. Top view of Upheaval Dome on Colorado Plateau in Canyonlands National Park, southeastern Utah, USA, and position of sample location.

THE SPHINX OF GEOLOGY: UPHEAVAL DOME

The very controversial debate about Upheaval Dome's origin has lasted nearly a century, over the course of which extremely different hypotheses (gradualism versus catastrophism) have been proposed. Bucher (1936) postulated a crypto volcanic origin. Mattox (1968) favored the hypothesis that the central uplift and surrounding structural depression were the result of salt flow in the underlying Paradox Formation. An impact origin for Upheaval Dome was then proposed on the basis of faulting and the inward and upward motion of rocks that is typical for central uplifts of complex impact craters (Shoemaker and Herkenhoff, 1983). Jackson et al. (1998), however, interpreted these faults to record motion of rocks into a cavity left behind by the upward passage of a salt diapir, now eroded away. The explanation of Upheaval Dome as a remnant of a pinched-off salt dome has been questioned (e.g., Huntoon, 2000) due to the fact that there is no evidence that salt moved through the core of the structure. Additionally, no relict fragments of the Paradox or hanging-wall formations have been documented (Huntoon, 2000; Kenkmann et al., 2005), although these should be found within the throat of a salt passage. Seismic reflection studies by Kanbur et al. (2000) have shown that the Paradox salt layer underneath Upheaval Dome has a relief of <100 m and shows no evidence for a pinched-off salt diapir. Detailed mapping and structural analysis have been conducted in the last decade (Kriens et al., 1997, 1999; Huntoon, 2000; Scherler et al., 2003; Kenkmann, 2003; Kenkmann et al., 2005). The deformation inventory has been shown to be compatible with the formation and collapse of an impact crater, and a good match between the structurally gained data and results from a numerical simulation of impact crater formation has also been achieved (Kenkmann et al., 2005).

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A critical step in proving or disproving an impact origin for the Upheaval Dome structure is the characterization of shock metamorphic indicators. Kriens et al. (1997) described some shatter cone–like features in the center of the structure, but they did not fulfill the strict diagnostic criteria of shock-produced shatter cones (Kenkmann, 2003). Likewise, vesicle-rich nodules, interpreted as ballistic, once molten ejecta (Kriens et al., 1999), have been proven to be unrelated to the impact (Koeberl et al., 1999). Kriens et al. (1999) and Kenkmann and Scherler (2002) presented planar microstructures in quartz of the White Rim Sandstone. However, subsequent analysis on these rocks using transmission electron microscopy (Kenkmann, 2003) showed that they represent thin deformation bands (Boehm lamellae). Kenkmann (2003) and Okubo and Schultz (2007) inferred deformation mechanisms from microstructures in sandstones of Upheaval Dome and estimated stresses that are incompatible with lithostatic pressures for the region and that could have resulted from salt diapirism but that might also be consistent with attenuated shock waves caused by an impact. Thus, these studies may provide circumstantial evidence for an impact, but for ultimate proof, proper documentation of generally accepted shock features should be presented (e.g., Stöffler and Langenhorst, 1994).

GEOLOGICAL OUTLINE

Upheaval Dome consists of a deeply eroded sequence of faulted and uplifted rocks surrounded by a structurally depressed ring syncline (Fig. 1), which also shows intricate faulting. Rocks exposed at Upheaval Dome are mainly sandstones and siltstones. The exposed strata consist of rocks of uppermost Permian age in the very center (White Rim Sandstone) to strata of Triassic (Moenkopi, Chinle Formation) and Jurassic age (Wingate Sandstone, Kayenta Formation, Navajo Sandstone) located at progressively increasing distances from the center (Kriens et al., 1999; Huntoon, 2000). Structurally, the feature exhibits an outer annular, inward-dipping monocline with a diameter of 5.2 km that defines the extent of the structure. Inside this monocline, there is a 3.6-km-diameter circular syncline (Fig. 1) surrounding a central uplifted area with a stratigraphic rise of ~250 m (Kenkmann et al., 2005). The inner part of the central uplift forms a morphological depression that is ~1.4 km wide and 300 m deep. The central depression plays a key role for the understanding of the structure of Upheaval Dome; it exposes radial folds and a complex sequence of folded and faulted strata. A characteristic imbrication of thrust slices, roughly toward the southeast, is preserved in the internal structure of the central uplifted area and has been interpreted as the result of an oblique impact from the northwest (Scherler et al., 2006).

SAMPLE LOCATION

This microstructural study focuses on rock samples collected from bedrocks of the Early Jurassic Kayenta Formation during a field campaign in September 2005. The samples were taken from bedrocks in the “Intermittent Creek,” ~1.3 km northeast of the proposed crater center and 450 m southwest of the ring syncline axis (Fig. 1). The concentrically striking, outward-dipping rocks are situated at the inner limb of the ring syncline and at the outer margin of the central uplift. The deposits of the Kayenta Formation are layered fluvial sediments and consist of middle- to coarse-grained silica-cemented sandstones, composed of 85% quartz and 15% feldspar grains. Several clastic dikes occur in the Kayenta Formation (Kriens et al., 1999; Kenkmann et al., 2005) but were not explicitly found at the sample location. The investigated rocks are partly brecciated and display narrow-spaced networks of meso- to microscale faults. The regular and subparallel arrangement of these faults, with shear displacements in the order of centimeters and partly opposite shear sense, may have accommodated the macroscopic uplift of strata in a seismically excited state.

METHODS

About 120 standard polished thin sections were prepared to investigate possible shock features and the petrography from all stratigraphic levels of Upheaval Dome using an optical microscope and a scanning electron microscope (JEOL JSM 6300). Here, we focus on samples of the Kayenta Formation that display shock overprinting. We used a five-circle LEITZ universal stage to determine the orientation of parallel lamellae within quartz grains. Micro-Raman spectrometry of these quartz grains was performed with a notch filter–based LabRam spectrometer (Jobin Yvon-Dilor), using a He-Ne laser of 632.8 nm wavelength, to prove possible shock metamorphic overprint. A microrefractometer spindle stage was used to measure the refractive indices of the investigated quartz grains. Specimens with possible planar deformation features were selected for transmission electron microscopy (TEM). They were carefully removed from the thin section, glued on copper nets, and thinned with a GATAN 600 DIF ion-beam thinner. Samples were investigated with a Philips CM 20 STEM microscope operated at 200 kV voltage at the Museum of Natural History of the Humboldt-University Berlin.

RESULTS

The vast majority of the quartz grains in the sandstone and siltstone layers of the investigated rocks of the Kayenta Formation do not exhibit shock features. Undulose extinction and subgrain structures are occasionally observed and indicate plastic work at elevated temperatures. These deformation microstructures indicate rate-dependent plastic deformation and most likely stem from the source region of the deposits. Many of the quartz grains show slightly curved, thin deformation lamellae (Boehm lamellae), in particular at grain-to-grain contacts. They occur in parallel sets but never cross each other. Previous TEM studies have revealed that they were formed by a bending of the crystal lattice and concentrations of lattice defects (Kenkmann, 2003). Transgranular and intragranular fractures, as well as shear and compaction bands, are also present. Here, we focus on the rare shock indicators:

Quartz grain 1 (Figs. 2A and 2B) is hypidiomorphic and not fractured; quartz grain 2 (Figs. 2C and 2D) appears to be xenomorphic and intact. Quartz grain 1 displays two dominant sets of thin straight lamellae. Measurements on the universal stage showed that the *c*-axis is parallel to the angle bisector of these lamellae, corresponds to the long grain axis, and plunges at 10° to the section surface. The angle between (0001) and the poles of the straight lamellae is ~22°, corresponding to $\{10\bar{1}3\}$. At the optical microscope scale, the spacing between the individual planar features of the dominant sets ranges between ~2 and 7 μm. The lamellae are decorated with trails of fluid inclusions that are lined up every 1–2 μm. At higher resolution, subordinate sets of planar lamellae, namely $\{10\bar{1}2\}$ and probably $\{10\bar{1}1\}$, can be seen (Fig. 2B). In some domains of the quartz grains, sets of lamellae with different orientation are dominant, but interpenetration is also frequent. At the optical microscopic scale, the lamellae fulfill the characteristics of planar deformation features (Stöffler and Langenhorst, 1994). The refraction indices of quartz grain 1 in the thin section plane are not reduced and range between n_o and n_e (n_o, n_e: refractive indices for the ordinary and extraordinary rays, respectively). Raman analysis of grain 1 disproves the occurrence of coesite and stishovite along the lamellae and shows the standard quartz bands that coincide with Raman spectra of neighboring quartz grains. Quartz grain 2 (Figs. 2C and 2D) exhibits $\{10\bar{1}3\}$ lamellae at all three rhombohedral planes and closer spacing and more intricate interpenetration. This grain also shows a brownish staining of its rim (“toasted quartz”; see Fig. 2C), which is often observed in shocked quartz (e.g., Whitehead et al., 2002). Figure 2A shows that quartz grain 1 is surrounded by fractured feldspar, while the quartz grain itself shows no signs of brittle deformation. TEM inspection (Fig. 3) also documents that the lamellae are straight and parallel. At a higher resolution, more lamellae and closer spacing are visible (0.6–1.0 μm). The lamellae themselves have extremely high

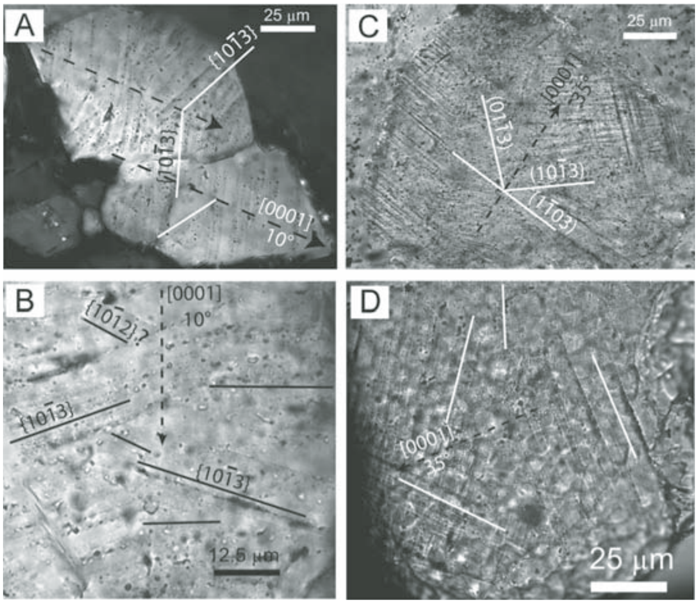

Figure 2. Shocked quartz grains investigated in thin sections. A–B: Quartz grain 1 showing two dominant sets of decorated planar deformation features parallel to $\{10\bar{1}3\}$ and subordinate $\{10\bar{1}2\}$ lamellae; crossed polarizers. C–D: Quartz grain 2 ("toasted quartz") exhibiting all three rhombohedral planes of $\{10\bar{1}3\}$ lamellae, closer spacing, and more intricate interpenetration; parallel polarizers.

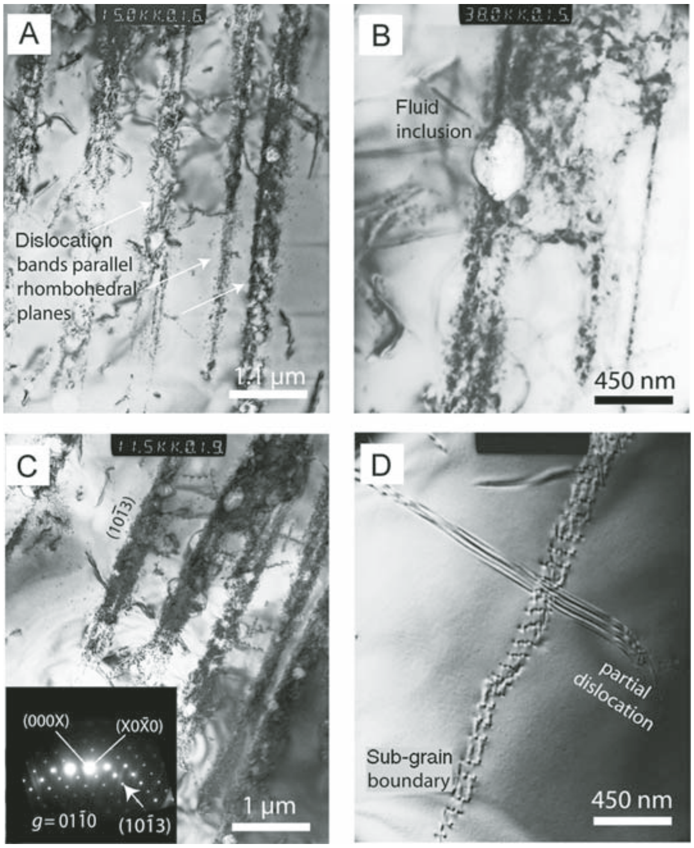

Figure 3. Bright field transmission electron micrographs (TEM) of quartz grain 1. A: Rhombohedral lamellae are straight and parallel and have varying thickness. Defect density is extremely high within lamellae. B–C: Dislocation bands along $\{10\bar{1}3\}$ contain numerous bubbles and fluid inclusions <400 nm in diameter. D: Partial dislocation and low-angle subgrain boundary.

dislocation densities, while outside of the lamellae, the dislocation density is low. Dislocations form dense and irregular tangles within the boundaries of the lamellae (Figs. 3A–3C). Some dislocations, however, have grown into the host quartz. The thickness of the lamellae varies between a few tens and hundreds of nanometers. The dislocation bands contain numerous bubbles and fluid inclusions <400 nm in diameter (Figs. 3B and 3C). Some of the inclusions are precipitated on the dislocation lines. Dislocation bands were mainly observed along $\{10\bar{1}3\}$ (Fig. 3C) and subordinately along $\{10\bar{1}1\}$ (Fig. 3A) as revealed by diffraction analysis with a diffraction vector $g = 01\bar{1}0$. Occasionally, regular subgrain boundaries were observed indicating dislocation climbing (Fig. 3D). A few partial dislocations in (0001) with typical parallel fringes were also observed and may indicate rare Brazil twins (Fig. 3D). Their formation in the basal plane of quartz requires large deviatoric stresses (4 GPa).

DISCUSSION

Planar deformation features are impact diagnostic and cannot form in any other geological environment (e.g., Goltrant et al., 1991, 1992; Langenhorst and Deutsch, 1994; Stöffler and Langenhorst, 1994). Microanalyses of thin straight lamellae within quartz grains (Figs. 2 and 3) of the Kayenta Formation from Upheaval Dome, using optical microscopy, Raman, SEM, and TEM, suggest that they are annealed and decorated planar deformation features. Their orientation dominantly along $\{10\bar{1}3\}$, and subordinately along $\{10\bar{1}2\}$, $\{10\bar{1}1\}$, coincides with the most frequent planar deformation feature orientations reported in literature. The appearance of the planar deformation features at the TEM scale is similar to observations by Goltrant et al. (1991, 1992). The latter distinguished four types of planar deformation features at the TEM scale and showed that the dense dislocation tangles within the lamellae are reorganized planar deformation features that resulted from the annealing of originally amorphous material assisted by the presence of a fluid phase. The occurrence of highly chaotic dislocation tangles, however, indicates that crystal defects could not be annihilated by climbing and that cation diffusion was thermally hindered. This suggests that the investigated rocks may have experienced moderate temperatures insufficient for dislocation climb. A temperature in the range of 100–150 °C is believed to be the sum lithostatic overburden of at least 1.6 km (Kenkmann et al., 2005) and mild postshock heating of the target rock. The documentation of planar deformation feature lamellae provides evidence for the impact origin of Upheaval Dome. It supports earlier strong indications of the impact origin of Upheaval Dome based on geophysical (Kanbur et al., 2000), structural (Shoemaker and Herkenhoff, 1983; Kriens et al., 1997, 1999; Huntoon, 2000; Scherler et al., 2003; Kenkmann et al., 2005), and microstructural data (Kenkmann, 2003; Okubo and Schultz, 2007).

According to the shock pressure calibration by Stöffler and Langenhorst (1994), the frequency of planar deformation feature orientations changes with shock intensity. The orientations $\{10\bar{1}3\}$ and particularly $\{10\bar{1}2\}$ and $\{10\bar{1}1\}$ indicate shock pressures >10 GPa in nonporous rocks. The unaffected refraction indices of the investigated quartz grains give an upper limit of shock pressure of 25 GPa.

These shock pressures are in conflict with previous pressure estimates and with best-fit numerical simulations. Kenkmann (2003) derived effective confining pressures in excess of 250 MPa for the White Rim Sandstone, and Okubo and Schultz (2007) assumed maximum pressure magnitudes of 4.6 GPa in the Wingate Sandstone. Numerical models for Upheaval Dome propose pressures between 3.3 GPa and less than 1 GPa (Kenkmann et al., 2005; their Fig. 19) for the studied sample location. The occurrence of shocked material at the outer flank of the central uplift is unexpected and therefore requires explanation.

It is known that the impact angle affects the distribution and magnitude of shock waves generated by an impact (Dahl and Schultz, 1999). The peak pressure in a propagating shock wave usually follows a power-law decay curve, but the magnitude in the down-range direction can be higher in comparison to the up-range direction. Recent experiments have shown that shock-induced damage beneath oblique craters in the down-range direction is stronger than in the up-range direction (Ai and Ahrens, 2005). Strain-rate measurements in oblique impact experiments have shown that their magnitude is about twice in the target down-range direction at the same peak stress (Dahl and Schultz, 1999). Likewise, oblique impacts are capable of producing much stronger shear waves (Dahl and Schultz, 2001) than vertical impacts of the same size. Based on the structure of Upheaval Dome, an impact from the northwest (Kenkmann et al., 2005; Scherler et al., 2006) is most likely. Hence, the shocked quartz grains of the northeast periphery of the central uplift stem from the cross-range crater sector, where high shear strains but not elevated shock pressures can be expected. Alternative explanations for the occurrence of isolated high shock pressures favor local pressure excursions formed by a shock-induced collapse of pore space (Kieffer et al., 1976) and impedance mismatches between feldspar and quartz. Note that the investigated quartz grain 1 is surrounded by fractured feldspar.

CONCLUSIONS

We have documented multiple sets of thin planar lamellae, dominantly with $\{10\bar{1}3\}$ orientation, which we identify as decorated planar deformation features, in quartz grains of the Upheaval Dome structure, Utah, USA. TEM analyses revealed that the lamellae are dislocation bands with extremely high dislocation densities that contain numerous fluid inclusions precipitated on the dislocations. The original amorphous material of the lamellae was devitrified by thermal annealing.

The documentation of planar deformation features provides the definite evidence for the impact origin of Upheaval Dome. The documented planar deformation feature lamellae suggest shock pressures of ~10 GPa and probably more at 1.3 km distance from the crater center. This order of pressure magnitude is in conflict with previous pressure estimates by a factor >3. Possible explanations for such elevated shock pressures include (1) local pressure excursions formed by shock-induced collapse of pore space, (2) impedance mismatches between feldspar and quartz, and (3) oblique impact trajectories.

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