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Shock-Related Deformation of Feldspars from the Tenoumer Impact Crater, Mauritania

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Shock-related textures in feldspars have been found in impactites from the Tenoumer impact structure, Mauritania. We see a range in features, from disruption of twin planes, to inclined deformation lamellae, to true Planar Deformation Features (PDF's) which occur at multiple orientations to one another. Most notably, these textures occur in samples that do not contain shocked quartz, suggesting feldspars record evidence of shock pressures lower than 8 GPa.

Introduction

The most well documented shock metamorphic effects are those changes which occur in silicate minerals, including Planar Fractures (PF's), Planar Deformation Features (PDF's), whole rock melts, impact glass, lechatelierite, coesite or stishovite and maskelynite (French 1998). Experimental simulations and modeling suggest that each of these textures form at specific pressure ranges, thus allowing for rough estimates of pressures during the impact event (Table 1).

More detailed shock barometric calibration studies of terrestrial impact craters have been carried out (Robertson and Grieve 1977; Grieve et al. 1996; Stöffler and Langenhorst 1994) and allow us to constrain shock barometry by subdividing PDF's in quartz into 4 types which form at specific narrow pressure regimes (Table 2). These studies, however, have focused almost exclusively on quartz. PDF's are known to form in feldspar but shock studies of feldspars have concentrated on the high-pressure transition to maskeylenite (Stöffler, 1966; Stöffler and Hornemann 1972) and do not address low-level shock in detail.

This study identifies a range of feldspar textures in target rocks from the Tenoumer impact crater that suggest feldspars exhibit a range of impact-related features which span a range below the 8 GPa limit of quartz deformation. Feldspars show a progression of textures related to the pressure changes experienced after impact. Thus feldspars should be a key component of future shock calibration experiments.

Background

The Tenoumer impact crater (22°55'N, 10°24'W) is a 1.9 km diameter simple crater within the paleoproterozoic and Archean rocks of the Reguibat Shield in Mauritania (French et al. 1970; Fudali 1974; Pratesi et al. 2005). The target material was dominantly crystalline igneous and metamorphic rocks, with a thin calcareous sedimentary unit. Impactites are of two types: i) crystalline basement rocks and ii) highly vassicular, glassy impact melts (French et al. 1970). Crystalline samples occur as both in-place basement and as large ejected boulders along the rim (TR-1, TR-2, TR-3, TR-4), 1-1.5 radii out from the rim (TAU), and 2-2.5 radii from the rim (TAL). Melt-matrix breccias were from further outside the structure (USNMNH 113027-41, USNMNH 113029-15, TM-1, TM-3, USNMNH 13029-61, ATD-68-1 (French et al 1970; Fudali 1974). The age of Tenoumer is disputed: 2.5 Myr ± by K/Ar dating of impact melt (French et al. 1970) or 21.4 ± 9.7 Kyr by fission track analysis of apatite in the impact melt (Storzer et al. 2003). While we favor the 2.5 Myr age for Tenoumer, for the purposes of this study, it is sufficient to classify Tenoumer as young and well preserved.

Petrography

Shock quartz was only found in the melt-matrix breccias, and has been described in detail by French et al. (1970). Shocked quartz is typically only found in individual grains entrained within the melt or within small granitic clasts also in the melt. No PDF's in quartz from the crystalline ejecta have been reported. The crystalline ejecta samples are granite to granitic gneiss of amphibolite facies metamorphic grade and resemble the basement rocks collected from inside basin (French et al. 1970; Fudali 1974; Pratesi et al. 2005). Feldspars in the crystalline ejecta, however, exhibit a range of textures uncharacteristic of unshocked feldspars. Within individual albite grains, deformation of alternating twin planes is common. Each alternate twin plane has a higher relief than the neighboring twin and under high magnification appears altered and recrystallized (Figure 1). The deformed alternate twins are often preferentially weathered and altered, but restricted to the specific twin as disruptions of the crystal lattice serve as nuclei of alteration. Within alternate twins, thin, inclined lamellae occur but do not extend into neighboring twins (Figure 2). Different grains show a range of lamellae textures: one set of lamellae, two sets of lamellae, two sets of lamellae that crosscut one another, and the development of true feldspar PDF's. Further evidence of recrystallization are individual microlitic feldspar grains that retain their initial shape and boundaries, suggesting either isotropization or full melting (Figure 3). These textures resemble the alternately isotropic twin lamalle observed by Stöffler (1966), which were interpreted as the result of orientation-dependent resistance of twin planes to the shock front. The twin deformation observed here is thus a similar response to lower-pressure shock as the twin plane has not been isotropized.

Also within alkali feldspar grains, irregular microcline inclusions occur regularly. The microcline inclusions are higher relief and show highly diffuse and irregular boundaries with the host feldspar (Figure 4). This texture matches textures of experimentally shocked feldspars at low shock pressures (Velde and Boyer 1985), and has been noted from other impact structures (eg, Gardnos, French 1997; Vredefort, Gibson and Riemold 2005; and Manson, Short and Gold 1996).

X-ray Mapping and Micro-Raman Spectroscopy

In order to support the interpretation of an impact related formation process of the deformed feldspars, microraman spectroscopy and microprobe elemental analyses were carried out. X-ray maps indicate no significant compositional differences between the alternately deformed twin planes (Figure 5). In some cases, slight enrichments in Na occur along the twin boundaries but this is likely due to later alteration which would occur along the twin boundary, especially if crystal defects exist in the crystal structure. The similarity in composition of the twins rules out the possibility that the optical textures are simply the result of chemical differences or exsolution. In the case where twin planes include inclined deformation lamellae, slight compositional of the lamellae differences can be seen but not of the twins themselves.

Microraman spectroscopy has shown that in experimentally shocked feldspars, multiple levels of disruption of the crystal lattice occur before the transition to maskelynite (figure 6) (Velde and Boyer 1985). In addition to a detectable broadening of raman shift at characteristic peaks, Velde and Boyer noted optical irregularities with individual grains similar to the high relief, diffuse inclusions seen in the Tenoumer impactites. Following their method, microraman spectra of the high-relief inclusions and alternately deformed albite twins were acquired. Spectra were acquired using a Horiba Jobin-Yvon T64000 Raman spectrometer with a Ti-sapphire laser at 514 nm. Both the high relief inclusions and the deformed alternate twins show raman spectra consistent with low shock. (Figure 7). High relief inclusions (Figure 7A) show broadening in the spectra centered around 480 and 510 nm. Deformed alternate twins (Figure 7B) show broadening at low wavelengths between 480 and 510 nm and at 1110 nm as well as more prominent broadening at 1180 nm. This is consistent with low-shock, between stage 2 and 3 of Velde and Boyer.

Discussion

While shock in feldspars has been reported previously, here we see textural evidence of a progression of features suggestive of different levels of shock deformation. More importantly, these textures in feldspar occur in samples that contain both shocked and unshocked quartz grains. This suggests that feldspars are recording effects of pressures below the 8 GPa limit for shocked quartz. Therefore, feldspar can provide information about the low-shock spectrum of the impact cratering process and have the potential to be more powerful barometers than quartz alone.

In order to fully understand this deformation, however, experimental simulations and calibrations are needed. The combination of quartz and feldspar barometers has the potential to greatly enhance our ability to expand impact cratering research to a wider range of environments both on Earth elsewhere in our solar system. In addition to recording low-shock regimes, feldspars are a more abundant planetary material and would be applicable to feldspar-rich environments such as those found on Mars and the Moon.

Table 1. Shock metamorphic features and the corresponding pressures at which they form. From Montanari and Koeberl (2000) and references within.

Shock Metamorphic Features	
Feature	**Pressure (Gpa)**
PF's (Planar Fractures)	>8
PDF's (Planar Deformation Features)	20 - 35
Stishovite	Dec-35
Coesite	>30
Diaplectic glass	35 – 50
Lechatelierite and Ballen	>50

Table 2. Shock barometry based on experiments in quartz. From Robertson and Grieve (1997).

Shock Deformation Levels in Quartz		
Deformation Type	**Characteristic Index**	**Mean Pressure (GPa)**
A	c{0001}	8.8
B	$\omega\{10\bar{1}3\}$	12
C	$\{22\bar{4}1\}$, $r\{10\bar{1}1\}$ $z\{0\bar{1}11\}$, $\xi\{11\bar{2}2\}$	15
D	$\{10\bar{1}2\}$	23

Figure 1. Feldspar grain (USNMNH 113029-12) in the melt breccia (ppl) showing alternating higher relief twins.

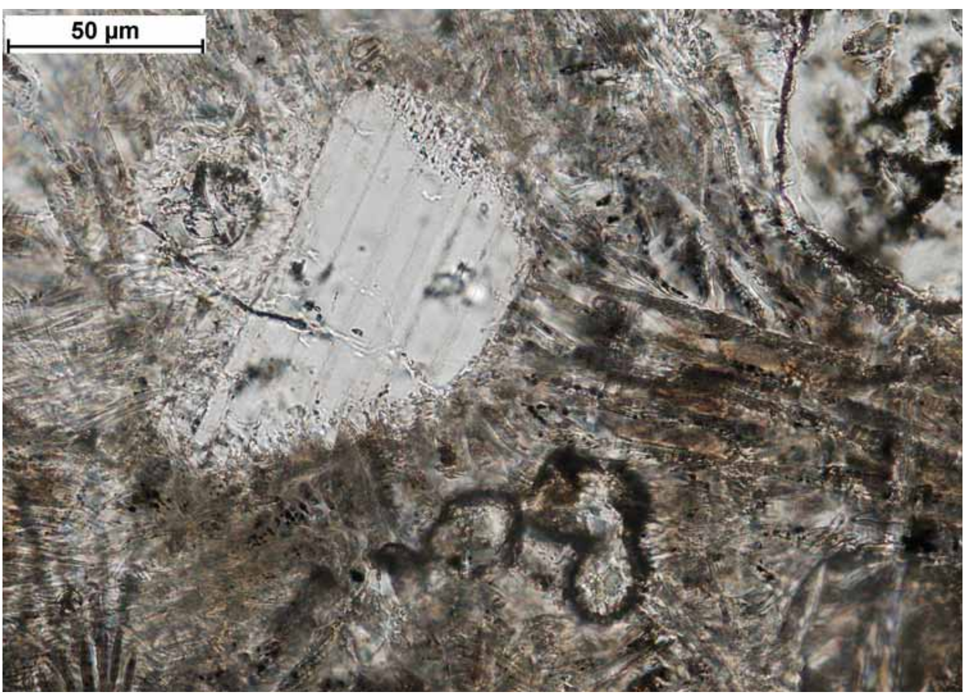


Figure 2. Feldspar grain (xpl) in sample TAL showing inclined deformation lamellae that occur every other twin plane

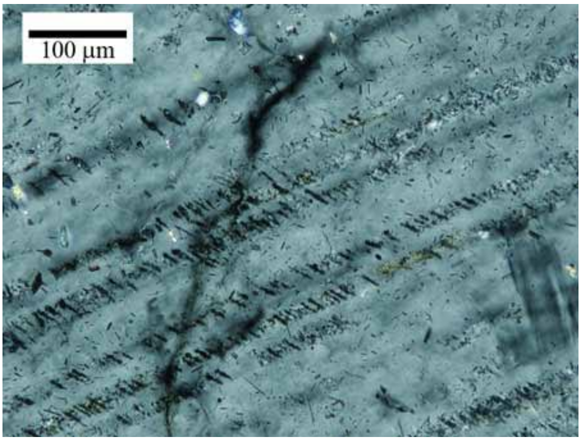


Figure 3. Progression of shock-related features in feldspar grains. A) USNMNH 113029-14, ppl, well-defined inclined deformation lamellae in every other albite twin plane B) USNMNH 113029-12, xpl, multiple sets of deformation lamallea occurring in alternate twin planes C) USNMNH 113029-14, ppl, multiple sets and orientations of PDF's throughout the entire feldspar grain, D) USNMNH 113029-14, ppl, recrystallized melted grains, that retained its initial grain margin.

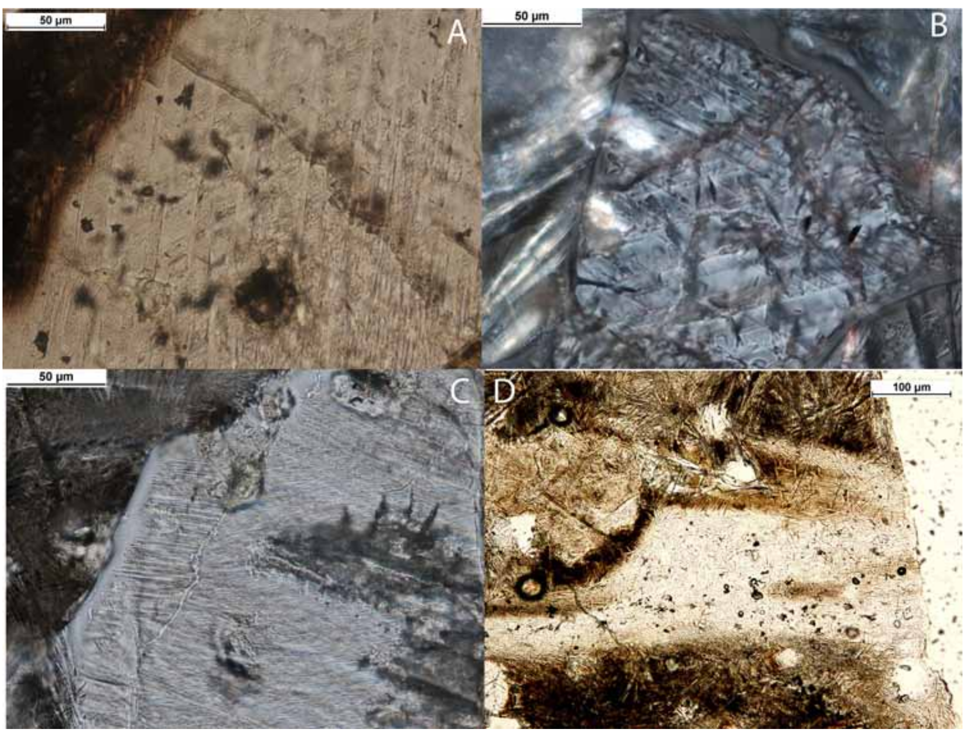


Figure 4. Microcline inclusions in alkali feldspar in ppl (A) and xpl (B). The microcline inclusions are higher relief than the host feldspar, and have diffuse disequilibrium boundaries.

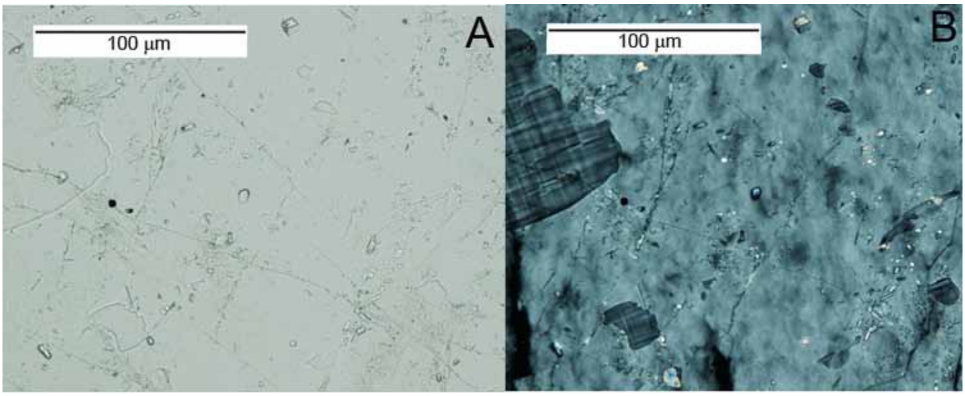


Figure 5. Microprobe X-ray elemental maps of alternating deformed albite twin planes in sample TAL. A) Baskscatter, B) Iron, C) Aluminum, and D) Sodium. Compositional differences between twins are minor, and likely due to secondary alteration.

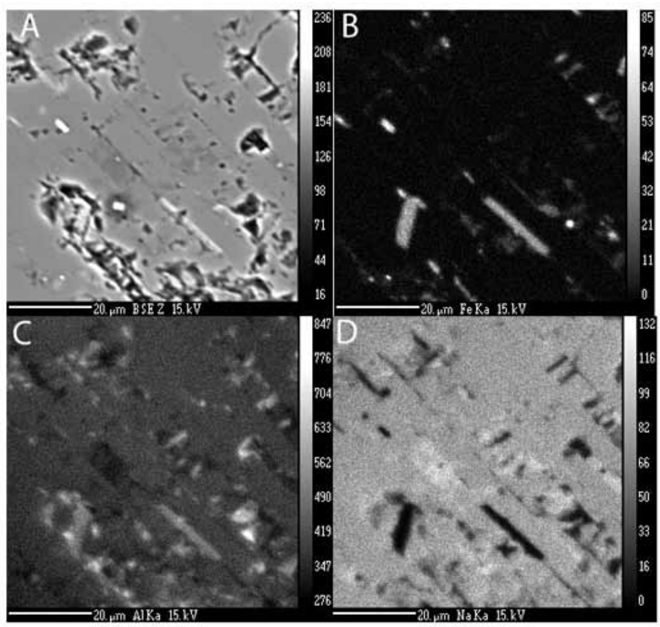


Figure 6. Microraman spectra of experimentally shocked feldspar showing multiple levels of deformation from undeformed (line 1) to maskelynite (line 5). From Velde and Boyer 1985

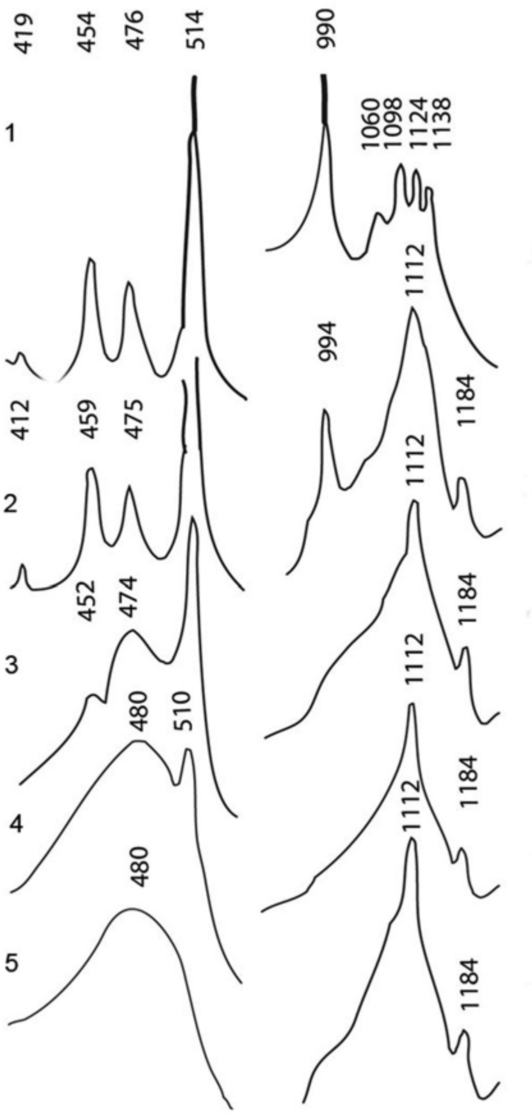
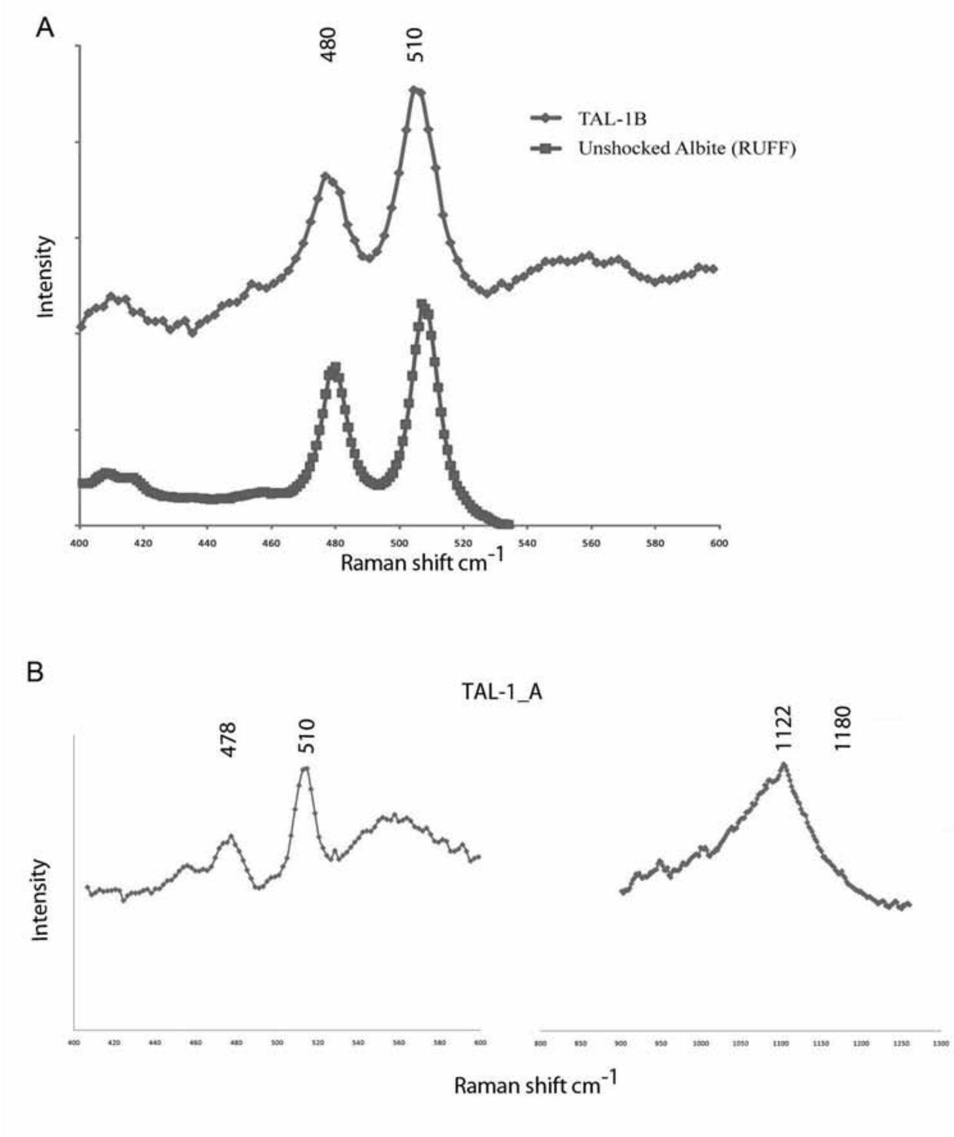


Figure 7. Microraman spectra of microcline inclusions (A, blue line) and deformed twins (B) relative to a standard (red line). Spectra show peak broadening similar to low-level experimental shock.



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About the Author

Steven Jaret is currently in his first year of a Ph.D. program in geology at Harvard University. A 2009 University of Tennessee graduate, Steven received a degree in earth and planetary sciences. Steven transferred to the UT in fall 2006, and entered the Department of Earth and Planetary Science and the Chancellor's Honors Program. He quickly became involved in his department as a regular attendee at weekly brown-bag lunch seminars and outreach activities and was the undergraduate president of the GeoClub in 2007-2008. He also participated in research projects that included a study of eucrite meteorites with Dr. Hap McSween and a senior thesis involving rocks from the Tenoumer impact crater with Dr. Linda Kah. While at Tennessee, he had the opportunity to present his work both at Tennessee's Exhibition for Undergraduate Research and Creative Achievement and at the international Lunar and Planetary Science Conference

About the Advisor

Dr. Linda Kah is an associate professor in the Department of Earth and Planetary Sciences. Her primary research interests involve understanding changes in ocean-atmosphere composition during early Earth history and how these changes may have affected the evolution of eukaryotic life. During these endeavors, Dr. Kah has been fortunate to have had two field seasons in Mauritania, West Africa, where she collected materials for Steven's undergraduate research. At UT, Dr. Kah has a strong commitment to UT's undergraduate population, and has served as an advisor within both the Department of Earth and Planetary Sciences and the College of Arts & Sciences Advising center. She has also served as a research mentor to numerous undergraduates and is very proud to have seen several continue their success in graduate school and beyond..