VISULIZATION OF HIGH- AND LOW-RATE COMPRESSIVE FAILURE OF QUARTZ. J. Kimberley[1], Kaliat T. Ramesh[1], Olivier S. Barnouin-Jha[2], P.K. Swaminathan[2] C.M. Ernst[2]. [1]Dept. of Mechanical Enginerring, Johns Hopkins University, Baltimore, MD 21218 (jamie.kimberley@jhu.edu, ramesh@jhu.edu). [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 (olivier.barnouin-jha@jhuapl.edu, pk.swaminathan@jhuapl.edu, carolyn.ernst@jhuapl.edu)

Introduction: Quartz is one of the most common minerals in rocks on Earth and on other non-icy planetary bodies. Apart from the generation of microstructural features such as planar fractures and planar deformation features, which are associated with the high pressure and loading rates associated with shock loading [1,2], not much is known on the fracture behavior of this material during large scale impacts, where much of the rock does not necessarily encounter high pressures and loading rates. Here we provide experimental evidence that planar fractures can be generated during unloading form uniaxial compression at stresses and loading rates lower than those typically associated with shock loading. We therefore, provide experimental results that can be used to better understand fracturing during large scale cratering events on the Earth and planets.

Experimental method: Cube shaped specimens with 5mm edge length were cut from larger natural quartz crystals from Brazil. Specimens were subjected to uniaxial compression along the $[11\bar{2}0]$ direction (i.e., perpendicular to the *x*-cut face) at a quasistatic loading rate of 25 MPa/s and dynamic loading rates up to 125 MPa/μs. The quasistatic compression experiments were conducted using a MTS servohydraulic uniaxial testing machine, while the dynamic compression experiments were conducted using a Kolsky (split-Hopkinson) bar apparatus [3,4] as shown in Fig. 1. For all experiments images were recorded in real time to capture the evolution of failure in the specimen. For both the quasistatic and dynamic loadings two subsets were performed: 1) load to catastrophic failure, 2) load–unload. In case 1 the specimen stress is increased until the specimen explosively crushes into a fine powder. In case 2 the specimen was loaded to a stress that is below the catastrophic failure stress and then unloaded.

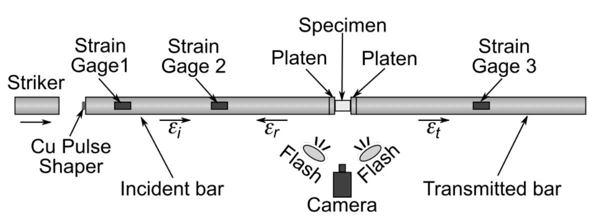

Fig. 1: Experimental configuration of the Kolsky bar used for the dynamic compression experiments.

Load-to-failure experiments: For specimens compressed quasistatically the failure stress was measured to be 2.3 GPa. Images captured during the experiment show no damage in the specimen until the catastrophic failure stress is reached at which point the specimen explosively crushed into a fine powder. Under dynamic loading the failure stress was measured to be 2.5 GPa. No damage was observed up to the point of catastrophic failure, similar to observations in quasistatic experiments.

Prior work on the fragmentation of brittle solids under compressive loading [5,6] has shown that there is often a large increase in failure strength as the applied loading rate is increased above a material dependent transition rate. The similar failure stresses and failure modes observed in our quasistatic and dynamic compression experiments would indicate that despite an increase of six orders of magnitude in the loading rate, the highest rates still lie below the transition rate. Theoretical predictions of the transition stress rate have been based upon the low rate failure strength and ratio of crack propagation velocity to specimen length [5], or the defect spacing [7]. The real time imaging of our experiment allows for the direct measurement of crack speed, which combined with the specimen geometry and quasi-static failure strength results in a predicted transition loading rate of 440 MPa/μs [5], confirming that our experiments lie below the transition loading rate.

Load–unload experiments: In experiments where the specimen was compressed to a level below the failure strength and then unloaded, crack propagation was observed only during the unloading portion of the experiment. Fig. 2 shows the stress–time history and the corresponding high speed images captured during a dynamic compression experiment. The specimen was loaded to 1.3 GPa, well below the failure stress, over a period of ~50 μs and then unloaded over a similar duration. Cracks were seen to grow in frames 3-8 which correspond to the mechanical unloading of the specimen.

After testing, the specimen of Fig. 2 was fractured into several mm-sized pieces. The largest of these pieces is shown in Fig. 3(a). Here the axis of compression was normal to the page. The right side of the fragment is bounded by a large planar fracture surface that was identified to be the $(\bar{1}101)$ crystallographic plane, as indicated in Fig. 3(b). This plane has previ-

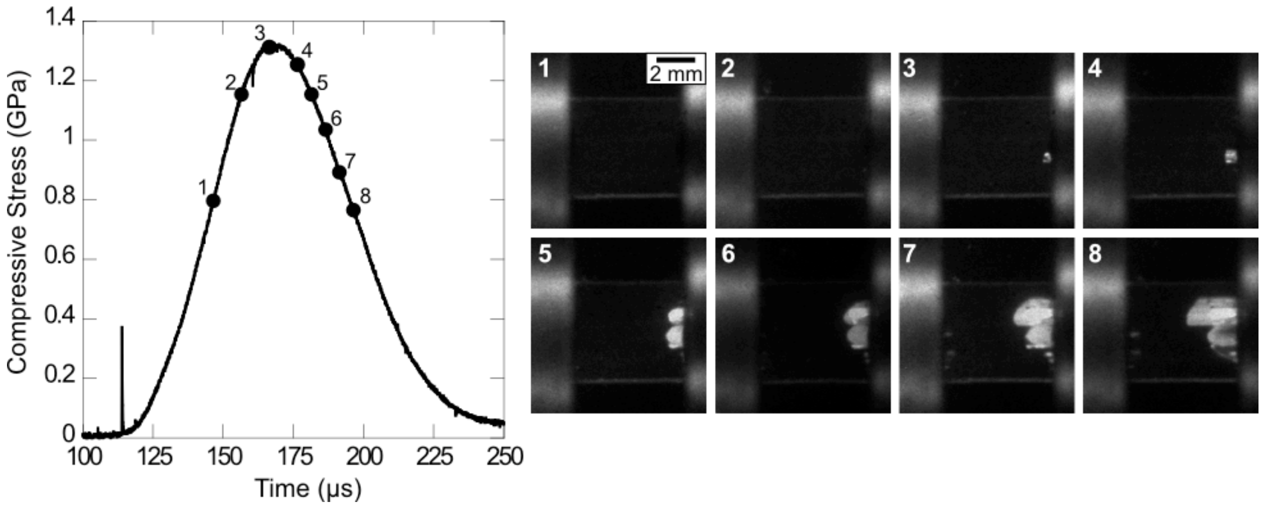

Fig. 2: Stress–time history and corresponding high-speed images for a specimen dynamically loaded below the catastrophic failure threshold stress and unloaded. Compression is in the horizontal direction. Images were captured using reflected light so that cracks show up as bright features in the images. Crack growth is observed in frames 4-8, which correspond to the mechanical unloading of the specimen.

ously been reported as a cleavage plane in quartz [8,9], thus there may be a natural tendency for planar fractures to occur on this plane.

Similar response was observed in specimens subjected to quasistatic compression, with several planar fractures growing during the unloading phase of the experiment. After testing, the specimen remained in one large piece despite cracks spanning the majority of the specimen. These planar cracks were identified to be of the same type identified in the dynamic experiments, *i.e.,* $(\bar{1}101)$.

The appearance of planar fractures of type (0001) and less commonly type $\{10\bar{1}1\}$ have been correlated with very weakly shocked samples of quartz bearing rock, and are used as an indicator of the shock state[1]. $\{10\bar{1}1\}$ fractures become more common at increased shock amplitude, but are also accompanied by planar deformation features. Our experimental results show that planar fractures of the $\{10\bar{1}1\}$ type can be generated under compressive stresses and loading rates well below those associated with shock compression.

Through direct visualization of crack growth during unloading our results indicate another mechanism of fracture in quartz bearing rocks subjected to compressive loading that is not normally accounted for. As a consequence rocks may be weaker than expected after unloading. This may affect the modification stage of crater formation and have implications for related phenomena such as the transition from simple to complex craters.

References:

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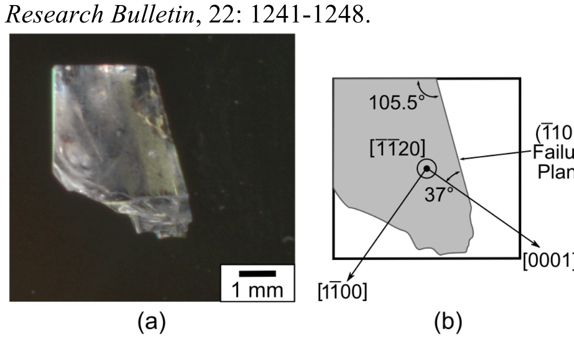

Fig. 3: (a) Postmortem micrograph of a piece of the specimen from the dynamic load–unload test, loading axis was into the page. (b) Shows the location of the fragment with respect to the original specimen geometry and the coordinate axes. The right side of the fragment shows a distinct fracture plane.