MICROCRACKS IN SHOCKED ROCK. G. Simmons, R.W. Siegfried, Department of Earth and Planetary Sciences, MIT, Cambridge, MA 02139, D. Richter, Rock of Ages Corp., Barre, VT 05641, and F. Hötz, Geology and Geophysics Branch, NASA, Johnson Space Center, Houston, TX 77058.

INTRODUCTION. Microcracks in a dozen samples of shocked granite from the block studied previously by Hötz [1] have been examined with the techniques used previously [2,3,4] to study microcracks in lunar samples. The purposes of this investigation are (1) to obtain data on microcracks known to have been produced by shock and (2) to use those data for the interpretation of the microcracks in the returned lunar samples. Our techniques and terminology are described elsewhere: for DSA [5,6] and for microscopic observations of crack sections [3,4,7]. With DSA we estimate the porosity contained in microcracks as a function of the pressure at which the cracks close and the effective orientation of the cracks. With the SEM, we observe the microcracks directly.

DIFFERENTIAL STRAIN ANALYSIS. Samples of dimensions $1 \times 1 \times 2$ cm and that had experienced maximum shock pressure ($P_{\text{max}}$) of 2 to 20 kb were used for differential strain analysis (DSA). Typical strain curves and the derived spectra are shown in figures 1 and 2, respectively. Both strain and crack spectra are second order tensors and we used a sufficient number of gauges to determine the full set of components. These spectra differ significantly from the spectra obtained previously by us [3] for five lunar samples; a typical example is shown in figure 3. The major difference between the spectra for shocked terrestrial rocks and for lunar samples is the width of the spectra. The cracks that contain most of the porosity in terrestrial samples are closed at $P < 0.5$ kb, but significant porosity is contained in the cracks in lunar samples that close at $P > 0.5$ kb.

The differences in crack spectra in shocked terrestrial samples and the returned lunar samples may be due to (1) differences in $P_{\text{max}}$, (2) differences in the duration of the shock wave, (3) effects of shock on material residing in the lunar regolith, and (4) effects of shock waves on unconfined material during excavation. We believe explanations number 3 and 4 to be more likely than 1 or 2. The differences in $P_{\text{max}}$ between terrestrial samples and our set of lunar samples are not great. The range of $P_{\text{max}}$ for the tombstone samples is 2 to 20 kb, for the Piledriver samples 10 to 50 kb [8] and for the samples studied by Siegfried et al. [9] 5 to 10 kb. The value of $P_{\text{max}}$ for the set of lunar samples studied by us is probably not greater than 50 kb because mineralogic effects associated with higher pressures are not present. Our assessment of the effect of shock duration on lunar material in situ is based on (A) the Piledriver samples [8] do not have broad spectra and (B) shock waves of 3 and 6 μsec durations increase crack porosity but do not broaden the spectrum to $P > 1000$ bars [9]. We suspect that shock waves in unconfined material may produce the broad spectra. Perhaps shock waves associated either with the event that excavated the lunar samples from depth to the regolith or with later impacts on the lunar regolith have produced them.

OBSERVATIONS WITH SCANNING ELECTRON MICROSCOPE. Material adjacent to the DSA blocks were used to prepare crack sections for microscopic observations. With the SEM, we have studied samples with values of $P_{\text{max}} = 2, 5,$ and $30$ kb and found: Three different types of cracks are present in these samples -
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preshock cracks, shock-induced cracks, and spall cracks. Preshock cracks are uniformly distributed in the granite block. Shock-induced cracks (SHIC) are larger and more abundant in samples with higher $P_{\text{max}}$. Spall cracks are most abundant in the 2 kb sample. In each sample, relatively large volumes of crack-free material are bounded completely by microcracks. Cleavage cracks are rare. Differences in the quantity of cracks in different minerals are not significant (with the possible exception of micas).

A subset of the preshock cracks is easily recognized, viz., those microcracks that are partially healed or that show significant changes in width along the crack without a significant change in direction.

The SHIC's in this set of samples consist of several subsets of parallel to subparallel cracks. The orientation of each subset is constant throughout the granite block even though $P_{\text{max}}$ ranges from 2 to 30 kb. The SHIC range in width from several microns to ~0.1 mm; the width correlates with $P_{\text{max}}$. At higher values of $P_{\text{max}}$, the SHIC's often isolate small blocks 10 to 30 mm across and strips 50 to 200 mm long by 10 to 30 mm wide; similar effects are not seen in the lunar samples. The quantity of debris in the SHIC is small. The term 'debris' is used for material 0.1 to a few microns in size, present in the cracks, and physically isolated from the material bounding the microcrack.

Macroscopic cracks are present in samples that were near the back-side of the granite at the time of shocking even though $P_{\text{max}}$ was <3 kb. They are 10 to 50 mm wide and centimeters long, can be seen with the unaided eye, and are due to tensile stresses associated with rarefaction waves reflected from the free boundary of the original block. Such cracks are termed spall cracks and have these diagnostic features: (1) they are considerably wider than either shock-induced cracks or the preshock cracks; (2) they contain large quantities of debris; and (3) their walls contain structures not seen in other microcracks (e.g., grooves similar in appearance, although different in scale, to the glacial grooves produced in bedrock). The microcracks in lunar samples do not contain these features and we infer that they are not spall cracks.

CONCLUSIONS. The microcracks in shocked terrestrial rocks differ significantly from the microcracks in returned lunar samples.

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Fig. 1. Differential strain data for a shocked granite sample. $P_{\text{max}} = 6.3$ kb. Propagation direction was 1-direction.

Fig. 2. Crack closure pressure distribution for same sample of fig. 1.

Fig. 3. Typical crack closure pressure distribution for lunar samples. After [3].

Figure 3 courtesy Proc. Lunar Sci. Conf. 8th (1975) Pergamon Press Ltd.