ESTIMATING PEAK SHOCK PRESSURES FOR LUNAR ROCKS. G.Simmons, R.Siegfried, D.Richter, Earth & Plan. Sci. Dept., M.I.T., Cambridge, MA 02139, and J. Schatz, K.Div., Lawrence Livermore Lab., Livermore, CA 94550.

Examining the crack related physical properties of lunar rocks, Todd et.al.[1] concluded that lunar rocks exhibit properties characteristic of shocked terrestrial rocks. If the normalized P-wave velocity at zero pressure is plotted as a function of crack porosity for various terrestrial and lunar rocks, Fig.1, the rocks separate into several distinct regions. The observation that lunar anorthosite, basalt and breccia separate into distinct fields on such a plot may help in understanding the origin of lunar rocks. In order to understand the way in which crack distributions are affected by shock waves, and thus determine the peak shock pressures to which the lunar samples have been subjected, we have studied a set of terrestrial rocks shocked to known peak pressure.

A suite of granodiorite samples has been obtained from the vicinity of the Piledriver underground nuclear test in Nevada where the shock pressures were monitored in the ground surrounding the shot point[2]. Our samples were cored after the device was detonated. The maximum shock pressure experienced by our samples was 52 kb.

We have measured static linear compressibility and compressional velocity in two orthogonal directions (∥ and ⊥ to the core axis) for the shocked samples and for a virgin sample collected from the area before the explosion. From the strain vs. pressure curves for our samples, we have determined a parameter that is related to the crack porosity of the sample due to cracks oriented roughly normal to the direction in which the compressibility was measured. This parameter, $\eta(\ell)$, is the zero pressure intercept of the linear part of the strain vs. pressure curve. For an isotropically cracked rock, it would be equal to 1/3 of the total crack porosity, η_c. Since a typical lunar rock has probably been exposed to shock waves from several events in different locations, the shock induced crack distribution is likely to be isotropic in lunar samples. Therefore, in order to compare our results for terrestrial rocks shocked by one event with lunar samples, we consider an effective crack porosity, $\eta_c(\text{eff}) = 3\text{Max}[\eta_c(\ell)]$. $\eta_c(\text{eff})$ is the crack porosity that one of our samples might be expected to have if it had been subjected to several shock events arriving in different directions. We use $\eta_c(\text{eff})$ and other information derived from compressibility curves and velocity measurements to characterize the crack distributions in shocked rocks. These crack distributions will then be related to the peak shock pressure to which a sample has been exposed by means of comparison with samples exposed to a known peak shock pressure. In Table 1 we list data on the Piledriver samples. From those data, we conclude that effective crack porosity exhibits a fairly regular dependence on peak shock pressure.

Effective crack porosity vs. peak shock pressure for the Piledriver samples is plotted in Fig.2. The rock with the lowest crack porosity has been subjected to a shock pressure of 19 kb. From this point to 52 kb, we see a generally linear increase of η_c(eff) with peak shock pressure. Our preliminary interpretation is that shock pressures below about 20 kb have little effect on the crack distribution in a rock. The differences in η_c(eff) among the pre-shot sample, sample 17.6, and sample 107 would be due to heterogeneity in the unshocked rock mass. This inference is consistent with the presence of several macroscopic fracture zones that have been mapped in the vicinity from which our samples were obtained. Thus we might expect some scatter in our data due to original sample heterogeneity.

The dashed line in Fig.2 indicates the virgin unshocked crack porosity of the rock mass. If the shock-induced crack porosity is assumed to become important above some critical shock pressure P_c, then the effect of shock cracks can be represented by a curve starting from [η_c(eff) = 0, P_c] and increasing with increasing shock pressure. One possible such curve is indicated in Fig.2(curve C), which would yield the total crack porosity curve indicated by the solid line (curve A). Further measurements on additional samples in the 25 to 50 kb peak shock pressure range should serve to define better any such relation. From the high crack porosities of lunar samples ($\leq$.5%) we infer that they have been subjected to peak shock pressures large compared to the 52 kb maximum for our samples. One may estimate roughly the pressures involved by a simple linear extrapolation of our data. If our speculation regarding the existence of a critical shock pressure P_c at which crack effects begin is correct, extrapolation of curve (A) would yield peak shock pressures of 80, 140, and 300 kb for the lunar anorthosites, basalts, and breccias, respectively. If we reject this interpretation due to lack of supporting data, and assign the scatter at low pressure to heterogeneity of samples, then the relation between η_c(eff) and pressure is that of curve D and extrapolation to higher crack porosities yields pressures of 100, 200, and 500 kb for the three regions of Fig.1.

Further study of crack-related properties of shocked rocks may help us to better understand the relations between physical properties and peak shock pressures. In particular, the fact that lunar samples group in Fig.1 according to rock type raises such interesting questions as this - do the breccias have a high crack porosity because they have been shocked repeatedly, because they have been shocked strongly, or because of the particular response of breccias as a rock type to shock waves?

1-Todd, Richter, Simmons, and Wang (1973) Unique characterization of lunar samples by physical properties. In "Proc. Fourth

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2-Borg, I.Y. (1970) Survey of Piledriver results and preliminary interpretation of three postshot cores in and near the cavity. In LRL Report No. UCRL-50865.

Table 1. Properties of Piledriver Samples.

Sample	Peak Shock Pressure (kb)	Effective Crack Porosity (%)	Velocity of P-Waves: Parallel to core	Velocity of P-Waves: Perpendicular to core
Pre-shot	0	0.102	4.96	5.22
17.6	10	0.132	4.79	4.86
107	19	0.087	4.91	5.20
200	40	0.231	4.48	4.29
234	49	0.384	3.51	3.64
311	52	0.396	3.50	4.26

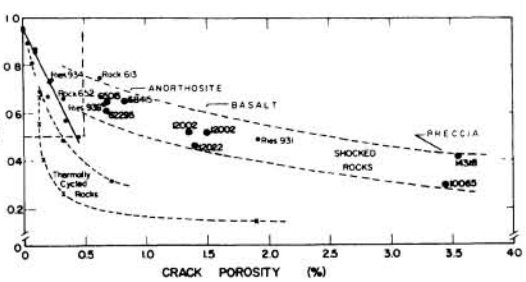

Fig.1. Effect of microcracks in rocks on the velocity of compressional waves. The ratio of the velocity at a confining pressure of 1 bar to that at 10kbar is $V_p(1)/V_p(10)$. The solid line represents typical terrestrial igneous rocks. Thermally cycled igneous rocks and shocked rocks separate into two distinct and widely separated fields. The three Ries rocks are granitic samples from the Ries Crater in Germany. The lunar samples separate into distinct groupings with the zone of shocked rocks. The small rectangle in the upper left hand corner of the diagram indicates the region of the new measurements. (Modified form Todd et al.)

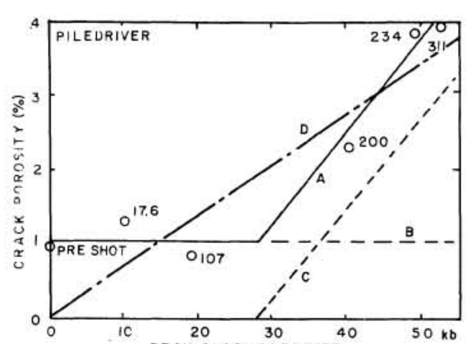

Fig.2. Effective crack porosity as a function of peak shock pressure for Piledriver granodiorite samples. In one interpretation, curve A (total crack porosity) is the sum of curves B (initial crack porosity) and C (shock-induced crack porosity). In another interpretation, the scatter at low pressure is attributed to sample heterogeneity and curve D is the correct relation.