
New shock compression and release adiabat measurements are reported for the ilmenite-rich mare basalt 70215 (1). These are the first shock wave measurements for a rock type uniquely indigenous to the mare basins, and the associated release adiabat data are the first reported for any basic rock. The high titanium basalts appear to be the densest samples in the present lunar collection. We have measured bulk densities on a series of 7 aliquots ranging in mass from 0.4 to 5 grams and these have bulk densities in the range 3.32 to 3.34 g/cm$^3$ (higher than previously reported (2,3)) and an intrinsic (crystal) density of 3.385 ± 0.004 g/cm$^3$ (measured for 4 aliquots) in agreement with Mizutani and Osako (4). The initial density is of special interest in that the high-titanium basalts are among the oldest (~3.8 Gy) mare rocks exposed on the lunar surface and also have the shallowest inferred depths of origin (5). The observed high densities suggest the possibility that subsurface equivalents and/or the antecedent cumulates from which these basalts were formed, are responsible for the mascon gravity anomalies. In addition to Hugoniot states measured in the two pressure ranges, 7 to 16 GPa and 117 to 123 GPa, release adiabat data are shown in Fig. 1 and 2. Lexan plastic (6) (1.196 g/cm$^3$) and Na-Ca glass (7) (2.491 g/cm$^3$) were used as buffer materials to obtain these adiabat points centered in the above, low-pressure and high-pressure ranges, respectively. Although the data set at low pressures is extremely limited, the release adiabats centered at 12 and 16 GPa appear to be initially steep. This observation implies that shock waves in the amplitude range would be expected to suffer more rapid spatial attenuation than expected if the Hugoniot curve itself were representative of release adiabats. Moreover we infer from previous data for pyroxene (8) and plagioclase (9), and the observation that the calculated post-shock density upon release from 12 GPa is $\approx$3 g/cm$^3$, (whereas upon release from 16 GPa it is $\approx$3.7 g/cm$^3$) that shock-induced transitions in the predominantly pyroxene, ilmenite and plagioclase assemblage occurs above $\approx$14 GPa. Significantly, the present results did not display the 4 to 5 GPa elastic precursor (i.e., Hugoniot elastic limit, HEL) previously observed in plagioclase (9), gabbroic anorthosite (10), in the weathered and somewhat glassy Vacaville basalt (11), and inferred by us to be evident in the capacitor (but not optical) measurements of McQueen et al. (12) for terrestrial diabases. The 0.4 GPa HEL value indicated in Fig. 1 and 2 represents an upper bound. The Hugoniot data at 120 GPa give an average density of 5.69 g/cm$^3$. These data, and the associated release data at $\approx$90 GPa, imply the formation of a shock-induced high-pressure mineral assemblage with an apparent zero-pressure density of 5.2 g/cm$^3$. The density at 120 GPa can be explained theoretically by adding specific volumes of constituent minerals inferred from individual mineral Hugoniots, assuming the following minerals composition, mass fractions and zero-pressure densities: En $\approx$30Wo $\approx$33Fs $\approx$16, 0.579, 3.30 g/cm$^3$; (Fe $\approx$87Mg $\approx$13) TiO$_2$, 0.184, 4.68 g/cm$^3$; Ab $\approx$16An $\approx$84, 0.145, 2.74 g/cm$^3$; Fo $\approx$68Fa $\approx$32, 0.064, 3.54 g/cm$^3$; and SiO$_2$, 0.027, 2.65 g/cm$^3$. To obtain the densities of solid-solutions, ideal mixing was assumed
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using linear-shock-velocity-particle velocity fits to the existing shock wave data. The appropriate equation-of-state for the equivalent diopsidic, titaniferous and aluminous pyroxene is poorly constrained and points out the need for more shock data for Ca- and Tschermak's molecule-bearing pyroxene. Using a similar methodology, good fits to the Hugoniot data (12) for Westerly granite and Centreville diabase were obtained. The latter, and an estimate of the density of 3.5148 (gabbroic anorthosite), are indicated in Fig. 2. The present results have important implications for both the degree of shock metamorphism expected for impact processes and the extent of ejecta transport on mare surfaces with high-titanium basalt composition. Although the impact-induced flows have yet to be explored in detail, previous calculational results (13) suggest that some qualitative differences may be expected for impacts on mare (versus highland terrane) surfaces. The higher shock impedance of Ti-rich basalt (relative to highland crust) means that more material will be shock metamorphosed for a given population of impacting objects. Also, the markedly lower dynamic yield strength of mare rocks will also result in greater excavation, and in effect shift crater-diameter versus cumulative number curves (14). Thus, we expect that when mare and highland surfaces of the same age exposed to the same meteoroid flux, (i.e., specified by a mass, composition and impact velocity distribution function) are compared, the mare surface will appear, on the basis of crater size versus number, to be older. Since it is already well established that the present mare have considerably younger apparent crater ages than the ejecta blankets produced by excavation of the mare basins, we expect that future work will demonstrate an even more rapid decay of the meteoroid infall rate than has been previously inferred for the first 1.5 Gy of lunar history.

ACKNOWLEDGEMENTS: This research was supported under NASA Grant NSG 9019. Contribution No. 2860, Division of Geological and Planetary Sciences, California Institute of Technology.

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Fig. 1 Low-pressure Hugoniot and release adiabat data for Ti-rich mare basalt 70215 - in pressure-particle velocity plane.

Fig. 2 Hugoniot and release adiabat data for 70215 in pressure-density plane. Gabbroic anorthosite (10) 15418 at 120 GPa, and Centreville diabase (12) are shown in comparison to calculated curves.

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