DYNAMIC STRENGTH EXPERIMENTS ON BASALT WITH APPLICATIONS TO CRATERING ON MERCURY. A.M. Stickle[1], J. Kimberley[2], and K.T. Ramesh[1], [1]The Johns Hopkins University, 3400 N Charles St., Hackerman 200, Baltimore MD 21218, angela.stickle@jhu.edu, [2]New Mexico Institute of Mining and Technology, Department of Mechanical Engineering, 801 Leroy Place, Socorro, NM 87801.

Motivation for Experiments: Bodies throughout the solar system exhibit anomalous crater morphologies that are not easily explained (e.g., crater transitions on Mercury or strange morphologies on icy bodies [e.g., 1-3]). One possible variable influencing these strange morphologies is the material strength. Here, we show that new models of dynamic material behavior could provide clues into puzzling observations of Mercury's cratering record.

Experiments on rocks show that the "strength" is a function of confining pressure, temperature, strain rate, strain, porosity, and sample size [e.g., 2]. The onset of material failure is typically defined to occur when a scalar measure of stress in the material, such as principal stress or equivalent (Mises) stress, reaches a critical value (e.g., the material strength). It is important to note that there are a multitude of "strengths" for a given material that may arise from different loading conditions (stress states). For example, most rocks exhibit significantly higher strength under compression than tension. Thus, even if a scalar measure of strength could be used, determining the appropriate measure to use is not trivial.

Traditionally, descriptions of material strength have followed from ideas of isotropic plasticity modeling: a single scalar value of strength is assumed to exist beyond which the material will fail. In ductile materials, this failure is usually driven by dislocation movement under shear stress. However, the failure mechanism in brittle rocks is different, and a scalar measure may not be able to accurately capture the complex response in a brittle solid under multiaxial loading. The failure of rocky materials under impact conditions will occur in a rapidly evolving, multi-axial stress state. Thus, robust models of impact on terrestrial planets rely on robust measures of dynamic strength under general states.

Experimental Methods: During an impact event, the target material will experience various stress states, stress paths and high strain rates. For example, a given region of the material may first experience large dynamic compression, followed by release to a lower compressive stress, subsequent shearing (during the excavation stage) and even subsequent tensile loading. The damaged state of the material evolves with the rapidly evolving loading, and is likely to be best represented by a damage tensor and an evolution law for the damage. Thus, dynamic failure experiments are needed to determine the material response of the rock (e.g., basalt) under more general stress states. Such experiments include compression Kolsky bar experiments with in situ visualization to identify the failure mechanism (Fig. 1), dynamic torsion experiments [5] using a torsional Kolsky bar, and confined dynamic compression experiments within modified Kolsky bars to understand confinement effects [6]. Moderate dynamic tensile states can be achieved using Brazilian disk tests

Using results from such experiments, a failure envelope for basalt at high-rates can be determined. This data can be used to fit existing material models used in impact simulations, and some of the complex stress state experiments (such as confined dynamic compression) themselves provide validation for computational models. Further, impact experiments at the AVGR (with a setup as described in [7]) provide information about damage evolution and a means to test the accuracy of new material models.

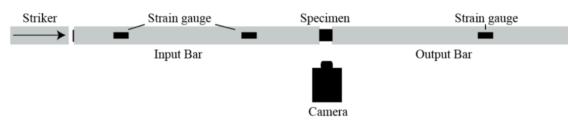

Fig. 1 Schematic configuration for the Kolsky bar used in dynamic compression and tension experiments

As a first step in this process, the uniaxial compressive strength of basalt was measured over a range of strain rates. Quasistatic compression experiments were conducted using a MTS servohydraulic uniaxial testing machine, and the dynamic experiments were performed using a Kolsky bar (also called a Split Hopkinson Pressure Bar) (Fig. 1). The specimens were loaded until failure and the damage evolution tracked using high-speed photography (Fig. 2).

Results and Discussion: The strength of brittle materials is highly rate-dependent [8-13]. Fig. 3 shows a comparison of the measured uniaxial compressive strength of basalt over a range of strain rates, and it is clear that the strength increases markedly with increasing rate. Dynamic Brazilian disk experiments by Housen [14] show similar results for basalt and granite in tension. This dependence is seen for both terrestrial and meteorite materials [e.g., 8-11, 13]. Further experiments, as described above, will expand this work to a general stress state for basalt. We are constructing a general failure model for brittle materials, and basalt in particular, for use in large-scale impact simulations.

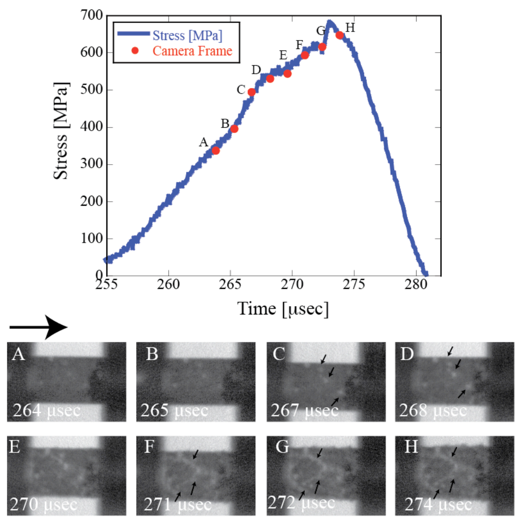

Fig. 2 Results from a typical, dynamic, unconfined compression experiment on basalt. (top) stress v. time; (bottom) images of the specimen failure following uniaxial compression.

Impact cratering is a dominant physical process throughout the solar system, and numerical models provide one of the best means to study large-scale cratering processes. Laboratory experiments provide information about impact processes at small scales. However extrapolating to larger scales is often difficult and requires the use of scaling laws [e.g., 8, 15-16] or sophisticated numerical models. These models must be validated with observational evidence in order to provide confidence that they accurately represent what occurs during the rapidly evolving and complicated stress states following an impact. Further, predictive models for damage evolution following planetary impacts also require accurate, sophisticated constitutive models. The accuracy of these models relies heavily validation with detailed laboratory experiments. One of the best means to validate these models is to quantitatively compare damage and deformation in the target material [e.g., 17]. The data provided by this suite of dynamic failure experiments under specific stress states provides a means for significant advances in understanding of the impact process via the deformation behavior of materials.

A newly developed scaling law for brittle solids in compression [18] allows these measurements to be extrapolated to the high rates appropriate to bodies such as Mercury. The high impact velocities on Mercury (~42 km/s [19]) result in very high strain rates at the impact site, and our results show that the material may well be substantially stronger at these rates than traditionally believed (or accounted for in simulations of impact on other bodies with slower average impact velocities).

Observations of the cratering record on Mercury's surface, especially compared with the records of the Moon or Mars, illuminate several puzzling features. There are more secondaries on Mercury than would be expected [4], and those that are seen are much larger than other bodies [4, 20-21] Further, the simple-to-complex transition diameter is larger on Mercury than would be expected for a 1/g variation [e.g., 22]. These observations are consistent with a stronger target material.

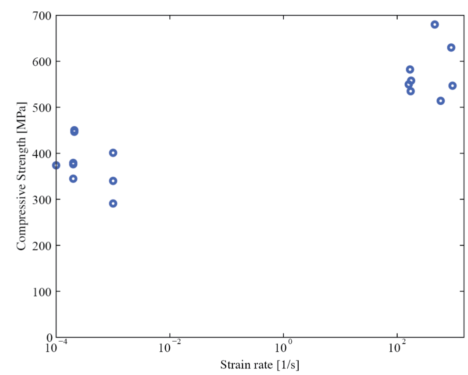

Fig. 3 Rate dependence of unconfined compressive strength for basalt. The gap in data between strain rates 10^{-2} and 10^{2} is due to limitations of the testing equipment.

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