STRENGTH AND DEFORMATION PROPERTIES OF BASALTIC LAVA FLOWS ON PLANETARY SURFACES,

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Introduction and Results.

Basaltic rocks are thought to constitute a volumetrically significant rock type on the Moon, Mercury, Mars, and Venus, in addition to the Earth. Spacecraft images of surfaces with known or suspected basaltic composition on these bodies, particularly on Venus, indicate that these rocks have been deformed in the brittle regime to form faults and perhaps dilatant cracks, in addition to folding and more distributed types of deformation [1].

Predictions of brittle fracture or other type of deformation are made by comparing calculated stresses from a tectonic model to some criterion for rock strength. Common strength criteria used in the planetary science literature for near-surface deformation include a Griffith tensile-strength criterion for intact rock [2], a Mohr envelope for intact basalt [3], and a brittle strength envelope based on Byerlee's law of rock frictional resistance [4,2,5].

However, planetary terrains of basaltic composition consist of much more than just intact basaltic rock. The aggregate basaltic material, termed the "rock mass," consists of both the intact rock and the associated fractures, faults, lithologic contacts, and other discontinuous surfaces [e.g., 6]. A basaltic rock mass is the relevant material for which strength properties must be defined and calculated model stresses must be compared to this material in order to more accurately predict brittle deformation [7]. For example, the various strengths of a rock mass are less than that of intact material of the same composition. This means that tectonic models which compare stresses to intact failure strengths overestimate the stresses required for fracture, and so underestimate the extent and magnitude of brittle deformation predicted in these models. On the other hand, rock mass shear strength can be greater than that predicted from Byerlee's law. The concept of rock mass strength is central to many engineering design studies in which calculated stresses are used to predict brittle fracture, and this experience indicates that brittle strength envelopes which assume properties for intact rock (Griffith parabolas) or sliding along a single, continuous surface (Byerlee's law) inadequately characterize the tensile, compressive, and shear strengths of rock masses.

The criterion adopted here to relate stresses to rock mass fracture is that defined for large-scale engineering projects by *Hoek and Brown* [8]. This criterion is based on a Griffith-type curve for tensile normal stress and a concave downward curve for compressive normal stress, and it is the only available criterion that explicitly considers the weakening effects of discontinuities within the rock mass on the stress state required for fracture. This criterion has been embraced by the geotechnical community for the design and construction of large engineering projects in fractured rock such as basalt [9].

Using the Hoek-Brown criterion, the strength of basalt may be approximated by

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2} \tag{1}$$

in which σ_1 and σ_3 are the greatest and least principal stresses at fracture, σ_c is the unconfined compressive strength of intact basalt, and m and s are empirical parameters that reflect the degree of block interlocking and fracturing of the rock mass. For intact rock, $s = 1$, and for pervasively fractured rock, $s = 0$. The parameter m decreases with the degree of fracturing or blockiness of the rock mass. Using representative values of $m = 4.9$ for a jointed basaltic rock mass [6], $s = 0.0021$, and $\sigma_c = 262$ MPa, the strength envelope for basaltic lava flows written using the principal stresses is

$$\sigma_1 = \sigma_3 + \sqrt{1{,}284\sigma_3 + 144} \tag{2}$$

The tensile strength of basalt whose strength is characterized by equation (1) can be obtained from

$$T_0 = \frac{\sigma_c}{2}\left(m - \sqrt{m^2 + 4s}\right) \tag{3}$$

The predicted tensile strength T_0 of the basaltic rock mass obtained using these values of σ_c, m, and s is –0.1 MPa, or nearly zero. This value contrasts with the average tensile strength of intact basalt of about –18 MPa listed in the literature.

The Hoek-Brown criterion can be recast into a depth-dependent strength envelope for brittle deformation of the rock mass. Comparison of this envelope with the standard one based on Byerlee's law indicates that a basaltic rock mass is stronger in both extension and compression than might be supposed.

Deformability properties of rocks and rock masses before bulk failure occurs are typically described by a modulus and Poisson's ratio. Young's modulus is used for rocks that respond elastically to stress. In contrast, the deformation modulus describes the often inelastic deformation properties of a fractured rock mass and is obtained from the slope of the stress-strain curve measured during an in situ field test. This modulus is invariably less than the Young's modulus for intact rock of the same composition and mineralogy. Poisson's ratio for a basaltic rock mass is somewhat larger than that for unfractured intact basalt. Typical values of these parameters are given in Table 1.

The deformation properties of a basaltic rock mass in the near-surface environment of Venus are of particular interest given abundant evidence for faulting and folding of near-surface rocks there [1]. The strength parameters discussed above are appropriate for rock material deformed under ambient pressure (~0 MPa) and temperature (20°C) conditions. These parameters must be modified for application to Venus. In particular, the deformation modulus appears to increase with temperature, perhaps by as much as a factor of two at 450°C; the other parameters may be reduced slightly for this temperature. Estimates of the strength parameters for Venus are listed in Table 1.

Conclusions.

Strength properties of basaltic rocks presented here differ significantly depending on the scale of observation. This well-known effect [e.g., 10,11] is incorporated into the empirical brittle strength envelope defined by *Hoek and Brown* [8]. This rock mass envelope is generally intermediate between the envelope for intact rock (Modified Griffith criterion) and that for the frictional resistance of a through-going surface (Byerlee's law); the latter two end-member approaches provide imprecise estimates of the strengths of a basaltic rock mass under compression or extension.

An important finding of the present work is the marked reduction in strength parameters for a basaltic rock mass relative to the intact material under the same conditions. For example, tensile strength of the rock mass is reduced to nearly zero, uniaxial compressive strength is reduced by an order of magnitude, and the modulus is reduced by a factor of two relative to intact basalt for conditions of ambient temperature and no confining pressure. These reference values and associated strength envelopes should provide better estimates of rock mass strengths for use in planetary tectonic modeling of near-surface deformation on any of the terrestrial planets.

Table 1. *Strength Parameters for Basaltic Rocks on Planetary Surfaces*

Parameter	Intact	Rock Mass	Venus Rock Mass
Young's modulus, GPa	73	–	–
Poisson's ratio	0.25	0.3	0.3
Deformation modulus, GPa	–	20	~40
Tensile strength, MPa	–18	~0.1	~0.1
Compressive strength, MPa	262	12	<12
Cohesion, MPa	66	4.5	4

References. [1] Solomon et al., *JGR, 97,* 13,199–13,255, 1992. [2] Tanaka and Golombek, *Proc. Lunar Planet. Sci. Conf., 19th,* 383–396, 1989. [3] Smrekar and Solomon, *JGR, 97,* 16,121–16,148, 1992. [4] Melosh, *Proc. Lunar Sci. Conf., 7th,* 2967–2982, 1976. [5] McGovern and Solomon, *Lunar Planet. Sci., XXIII,* 885–886, 1992. [6] Bieniawski, *Engineering Rock Mass Classifications,* Wiley, 1989. [7] Hoek, *Géotechnique, 33,* 187–223, 1983. [8] Hoek and Brown, *J. Geotech. Eng., 106,* 1013–1035, 1980. [9] Pan and Hudson, in *Rock Mechanics and Power Plants,* Balkema, 95–103, 1988. [10] Barton, in *Scale Effects in Rock Masses,* Balkema, 31–55, 1990. [11] Scholz, *The Mechanics of Earthquakes and Faulting,* Cambridge, 1990.