LIMITS ON THE BRITTLE STRENGTH OF PLANETARY LITHOSPHERES UNDERGOING GLOBAL CONTRACTION. Christian Klimczak[1], Paul K. Byrne[1,2], and Sean C. Solomon[1,3], [1]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA, cklimczak@ciw.edu; [2]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX 77058; [3]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA.

Summary: An assessment of the near-surface brittle strength of the lithospheres of Mercury, the Moon, and Mars reveals that all of these bodies could have accommodated substantial amounts of global contraction prior to the onset of thrust faulting. In particular, their lithospheres were sufficiently strong so as not to be markedly deformed until they experienced changes in radius of as high as 1.6 km (Mercury), 1.1 km (the Moon), and 2.2 km (Mars). As a consequence, these figures should be added to estimates to radius changes derived from thrust fault analyses, increasing the total estimates of global contraction of Mercury to as much as ΔR = 7.9 km, of the Moon to at least 1.2 km, and of Mars to 6.0 km.

Introduction: Global contraction is a planet's response to the secular cooling of its interior. Such cooling is a major source of compressional tectonics and is responsible for widespread thrust faulting on one-plate planetary bodies such as Mercury, the Moon, and Mars. Recent estimates of Mercury's radius change (ΔR) due to global contraction, inferred from tectonic mapping, are ~4.2 to 6.3 km [1], but earlier, more conservative estimates for ΔR were as low as ~1.0 km [2,3]. Current estimates of ΔR for the Moon are no higher than ~0.1 km [4], whereas Mars is thought to have reduced its radius by as much as ~3.8 km [5]. Generally, these estimates are much lower than predictions made by thermal history models of these bodies. Results from tectonic observations [4] and thermal history models [6,7] for the lunar radius change in particular differ by up to two orders of magnitude. However, radius change estimates from thrust fault mapping do not account for the fact that planetary lithospheres can accommodate some portion of the compressive stresses from global contraction without failure, so that actual radial decreases are probably higher than previously determined from mapping.

Approach: To account for the brittle strength of planetary lithospheres in estimates of radius change, stresses caused by global contraction are compared with critical stresses for rock failure. For that comparison, near-surface stress conditions are assumed, as thrust faulting is expected to be initiated at shallow depths. Near-surface horizontal stresses (σ_H) on a planet of radius R caused by planetary radial change (ΔR) can be estimated in its simplest form [8] as:

$$\sigma_H = 2G\left(\frac{1+\nu}{1-\nu}\right)\frac{\Delta R}{R}, \tag{1}$$

where G is the shear modulus and ν is Poisson's ratio of the planetary lithosphere. The radius decrease due to global contraction results in horizontal stresses that are compressive. These stresses are thought to be the driving force for the widespread thrust faulting observed on Mercury, the Moon, and Mars.

The critical values of the principal stresses —the threshold above which rock failure occurs— for the traditional Coulomb failure [e.g., 9] are given as:

$$\sigma_1 = \sigma_c + q\sigma_3, \tag{2}$$

where σ_c is the unconfined or uniaxial compressive strength of the material, q is a variable relating to the coefficient of internal friction, μ, by $q = \sqrt{\mu^2+1} + \mu$, and σ_1 and σ_3 are the greatest and least compressive stresses, respectively. In a tectonic setting governed by global contraction, σ_1 acts in the horizontal plane and can be obtained by eq. (1), whereas σ_3 acts vertically and is equal to the lithostat $\sigma_v = \rho g z$, where ρ is the rock density, g is the surface gravitational acceleration, and z is the depth below the surface. For near-surface conditions, σ_3 can be assumed to be zero.

Solutions for eq. (2) pertain to intact rock, but planetary lithospheres behave instead as a rock mass [10]. Rock masses [11] on planetary surfaces consist of the intact rock and associated structural weaknesses, such as fractures, impact damage zones, and lithologic contacts that all tend to weaken the overall material. A rock mass rating (RMR), a standardized procedure in geoengineering measured on a scale from 0 to 100 where 100 represents intact rock, can account for the degree and condition of weaknesses as well as for pore pressure conditions within the rock [e.g., 11] to evaluate likely rock strength parameters on the lithospheric scale [10].

The brittle strength of a rock mass is given by:

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}, \tag{3}$$

where m and s are the so-called Hoek-Brown parameters that reflect the degree of block interlocking and fracturing of the rock mass [12].

If $\sigma_1 = \sigma_H$ and $\sigma_v = 0$, then the limits of the brittle strength of planetary lithospheres can be assessed with respect to stresses from global contraction for near-surface stress conditions by setting eq. (1) as equal to eq. (2) or (3). Solving for ΔR then yields the minimum value of radius decrease of a given planet for brittle failure to occur. These radius changes have not, so far, been included in estimates of global contraction from thrust fault mapping [1–5].

Results: For basaltic rocks with rock strength parameters (cohesion, coefficient of internal friction, and unconfined compressive strength) consistent with laboratory measurements of terrestrial and lunar basalts [e.g. 13] (Table 1), intact lithospheres on Mercury, the Moon, and Mars could stay intact and still accommodate planetary radius changes of 6.4 km, 4.5 km, and 8.9 km, respectively (Table 1).

Table 1. Typical rock strength properties for basaltic rocks and the corresponding radius changes. Variables denoted with an asterisk indicate values adjusted with RMR.

Properties	Mercury	Moon	Mars
C_0 (MPa)		~ 66	
μ		0.7 – 1.2	
σ_c (MPa)		254 – 364	
ΔR (km)	6.36	4.53	8.85
σ_c^* (MPa, RMR 45)		11.96	
σ_c^* (MPa, RMR 75)		63.34	
ΔR_{min}^* (km)	**0.30**	**0.21**	**0.42**
ΔR_{max}^* (km)	**1.59**	**1.13**	**2.20**

Of course, the lithospheres of these planetary bodies are not intact, as geologic layering and the impact process have introduced major weaknesses of various degrees, decreasing rock densities near the surface [14]. Therefore, the strength parameters for intact rock must be adjusted by using RMR.

It is apparent from Figure 1 that the calculated planetary radius change decreases exponentially with decreasing RMR values. Basaltic rock masses are found to have typical RMR values between 45 and 75 [15], corresponding to a fair to good rock mass quality. Within the bounds of these RMR values, Mercury's radius could have decreased by 0.3–1.6 km before the onset of major thrust faulting (Table 1). Prior to brittle failure on the Moon, the lunar lithosphere would have been able to accommodate a radius change of 0.2–1.1 km (Table 1), a value more than an order of magnitude greater than that estimated from fault mapping [4]. Brittle failure in the martian lithosphere would not have occurred until $\Delta R^* = 0.4$ km to 2.2 km.

These results show that the response of planetary lithospheres to global contraction does not begin with the formation of thrust faults, and that substantial amounts of planetary radius change can be taken up prior to the onset of widespread compressional tectonic activity.

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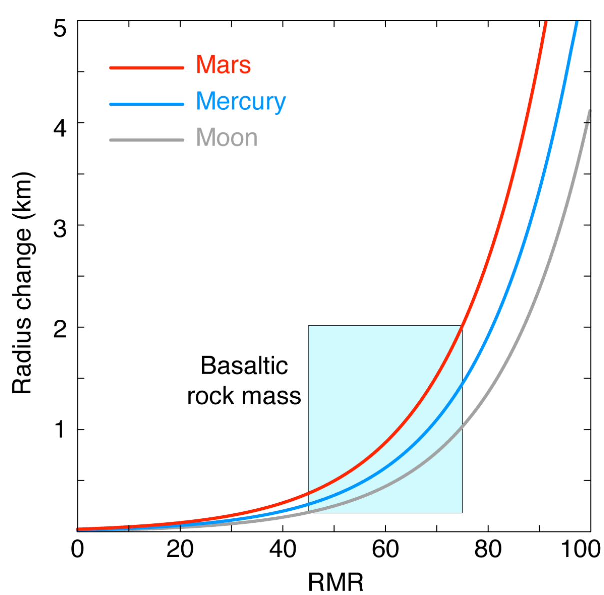

Figure 1. Planetary radius change from global contraction for Mercury, the Moon, and Mars as a function of rock mass rating. Basaltic rock masses generally have RMR values between 45 and 75 [15]. An RMR of 100 represents intact rock.