LITHOSPHERIC STRENGTHS OF THE TERRESTRIAL PLANETS

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Knowing the strength of a planet's lithosphere is a prerequisite to both placing limits on the stresses possible within a lithosphere and providing an accurate failure criterion. Unfortunately, efforts to determine the strengths of planetary lithospheres have been hampered by the lack of an accepted criterion for the earth. Recently, however, a relation has been identified [1] that accurately predicts the maximum stress levels found in the brittle portion of the earth's crust [2]. In this abstract, we briefly describe this relation, and apply it to the terrestrial planets. Even given the large uncertainties in determining the important parameters for geophysically poorly understood planets, our application places strong constraints on limiting stress levels and reasonable failure criteria for the lithospheres of the terrestrial planets.

For rocks in the brittle regime, sliding will occur on pre-existing fractures at stresses less than those required to break intact rock. Under these conditions, deformation is governed by Byerlee's law [1,2], $\sigma_1=\mu\sigma_3+b$, where σ_1 and σ_3 are, respectively, the maximum and minimum principle effective stresses (stress minus pore pressure), μ is the coefficient of friction, and b is a constant. Laboratory friction measurements show that μ and b are constant (except for a slight change at 135 MPa) over a wide range of stress, and are virtually independent of rock type, displacement, surface conditions, and temperature. As temperature increases, ductile flow dominates rock deformation. Flow laws for many rocks and minerals have been experimentally determined for stresses up to 1-2 GPa and strain rates down to 10^{-8}/sec. These results can be extrapolated to geological strain rates via creep equations, which generally are of the form $\dot{\varepsilon}=A(\sigma_1-\sigma_3)^n\exp(-Q/RT)$, where $\dot{\varepsilon}$ is the strain rate, R is the gas constant, T is absolute temperature, and A, Q, and n are experimentally determined constants.

The failure criterion for a given depth in the lithosphere will be determined by the weaker of the frictional or ductile strength at that depth. The yield stress increases with depth according to Byerlee's law until it intersects the crustal flow law. It then decreases exponentially until it reaches the moho, where the mantle flow law causes an abrupt increase in yield stress followed by another exponential decrease. The total yield strength of the lithosphere can be defined as the integral of the yield stress vs depth curve [3].

The parameters to which strength calculations are most sensitive are crustal thickness (c), internal temperature, and composition. In these calculations we use a density of 2.8 Mg/m^3, $\dot{\varepsilon}=10^{-15}$/sec, and flow laws from [4-6].

Earth: Strength analyses for the earth (e.g. [2,3,7,8]) have been carried out assuming a quartzite flow law within a 35 km continental crust and olivine below. For a thermal gradient of 15°/km this model yields a compressive strength (S_c) of 8.3 (in units of 10^{12} nt/m) and a tensile strength (S_t) of 5.4. Using a diabase flow law appropriate for the 10 km crust of an oceanic lithosphere results in strengths of S_c=30 and S_t=12. For comparison, a 100 km lithosphere with a uniform yield stress of 100 MPa would have a strength of 10^{13} nt/m.

Moon: For a 60 km anorthosite crust and a thermal gradient of 3.9°/km at the surface decreasing to 1.5°/km at 300 km [9] results in strengths of S_c=204 and S_t=100.

Mercury: Assuming a thermal gradient of 5°/km [10] and an anorthosite crust of 35 km (based on a volumetric analogy with the moon) yields S_c=138 and S_t=74. These strengths do not change unless c>70 km.

Mars: A thermal gradient of 9°/km [9] and a diabase crust [11] were assumed for Mars. An upper limit of 100 km has been suggested for the thickness of the martian crust based on gravity studies [12]. S_c varies from 67 for c<40 km, to 33 for c=100 km. S_t ranges from 27 to 12 over the same interval. If liquid water exists as a pore fluid, these strengths are lowered by about 20%.

Venus: Venus is the most poorly constrained of the planets. While it is reasonable to assume a diabase crust [13], its thickness is unknown and the thermal gradient is a matter of some debate [14]. If we adopt a gradient of 12°/km [15], the strengths decrease from S_c=11, S_t=5 for c=0 to S_c=6, S_t=4 for c>35 km. A similar analysis has been done by Solomon and Head [16] for the crust alone.

The moon has by far the strongest lithosphere, nearly 7 times stronger than terrestrial oceanic lithosphere. It is followed in order of decreasing strength by Mercury, Mars, the earth, and Venus. Tensional strengths tend to be about half the corresponding compressional strengths. Crustal thickness has no effect on strength for reasonable values of c on the moon and Mercury, but can cause variations of a factor of two on Mars, a factor of three on the earth, and over an order of magnitude on Venus. Venus' lithosphere is also the most sensitive of the planets studied to uncertainties in internal temperature because the brittle-ductile transition is so close to the surface; strength decreases by an order of magnitude for a doubling of the thermal gradient.

We are currently conducting a similar study for the outer planet satellites.

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