

RHEOLOGY OF THE LUNAR LITHOSPHERE AND THE ORIGIN OF FLOOR-FRACTURED CRATERS.

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Introduction: Lunar floor-fractured craters are impact craters that underwent modification by magmatic intrusion or viscous relaxation [1-3]. In the magmatic intrusion hypothesis, a laccolith uplifts and fractures the pre-existing crater floor. In the viscous relaxation hypothesis, the crater topography subsides because of thermal anomalies associated with older basin forming events [1,4]. Studies that have tested the viscous relaxation model suggest that the lunar lithosphere is simply “too rigid” for viscous relaxation to have occurred, thereby favoring the magmatic intrusion hypothesis [5]. Understanding the formation mechanism of floor-fractured craters is essential to constraining the lithospheric and thermal evolution of the Moon.

Motivation: Dombard and Gillis (2001) approximated the rheology of the lunar lithosphere using the strain rate ($\dot{\epsilon}$) of Columbia dry diabase and present-day heat flow measurements to conclude that the lithosphere is too rigid for viscous relaxation to have contributed to the formation of floor-fractured craters [5]. However, anorthosite, which makes up the lunar primary crust is likely a better approximation for the lunar lithosphere. Additionally, since floor-fractured craters are of pre-Nectarian and Nectarian age, present day heat-flow measurements are not representative of that of pre-Nectarian and Nectarian periods when the lunar geothermal gradient was likely higher.

Methods: We constructed strength envelopes of the lunar lithosphere by adopting the method of Ranalli and Murphy (1987) [6]. The upper portion of the crust is brittle, and its strength is governed by Byrelee’s law [7]. The lower portion of the crust is ductile, and its strength is governed by power law creep [8]. In other words, the strength of the upper crust is pressure dependent, whereas the strength of the lower crust is temperature dependent [6].

The strength of the upper crust is defined by:

$$\sigma_1 - \sigma_3 = \alpha \rho g z \text{ (Eq.1; [7])}$$

where σ_1 and σ_3 are maximum and minimum stresses respectively, ρ is the density of the crust, $\alpha = 3.0, 1.25$, or 0.75 for thrust, transcurrent, and normal faulting respectively, g is the gravitational acceleration (1.625 m/s^2), and z is the depth (in km). Here we adopt $\alpha = 0.75$.

The strength of the lower crust is defined by:

$$\sigma_1 - \sigma_3 = \left(\frac{\dot{\epsilon}}{A} \right)^{\frac{1}{n}} \cdot \exp \left(\frac{Q}{nRT} \right) \text{ (Eq. 2; [8])}$$

where $\dot{\epsilon}$ is the strain rate (in s^{-1}), Q is the activation energy (in kJ mol^{-1}), R is the gas constant (in $\text{kJ mol}^{-1} \text{K}^{-1}$), T is the temperature (in K), and A is the empirically determined pre-exponential constant (MPa s^{-1}). In the ductile regime, $\dot{\epsilon}$ is in the range of $10^{-14} - 10^{-16} \text{ s}^{-1}$. Here, we adopt $\dot{\epsilon} = 10^{-14} \text{ s}^{-1}$ to estimate the upper bound of the lithospheric strength [6].

Table 1: Creep parameters of anorthosite and diabase [9]

Material	A (MPa s ⁻¹)	n	Q (kJ mol ⁻¹)
Anorthosite	3.2×10^{-4}	3.2	238
Diabase	2.0×10^{-4}	3.4	260

We adopt the lunar geotherm at 4 Ga estimated by Mohit and Phillips (2006) for crustal thicknesses of 30km, 45km, and 60km with their corresponding heat flow estimates of 41, 33, and 29 mWm^{-2} (Fig. 1; [10]).

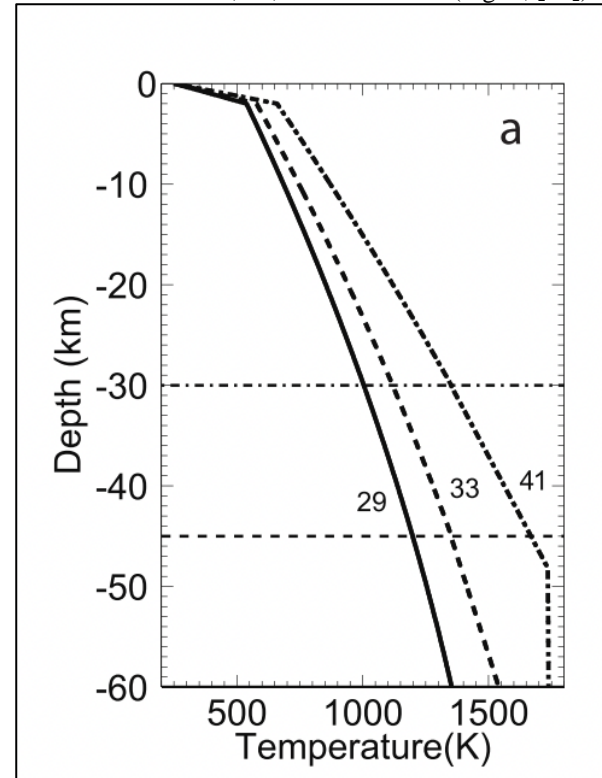


Figure 1: Lunar geotherm at 4Ga estimated for heat fluxes of 41, 33, and 29 mWm^{-2} corresponding to crustal thicknesses of 30km, 45km, and 60km respectively [10].

We constructed strength envelopes for the lunar lithosphere at 4Ga (i.e., pre-Nectarian period) assuming both anorthosite and diabase rheologies for the three crustal thicknesses mentioned above. The lower crust begins at a depth of 15km where a viscosity

discontinuity occurs and thereby defines the boundary between the upper and lower crust [10].

Results:

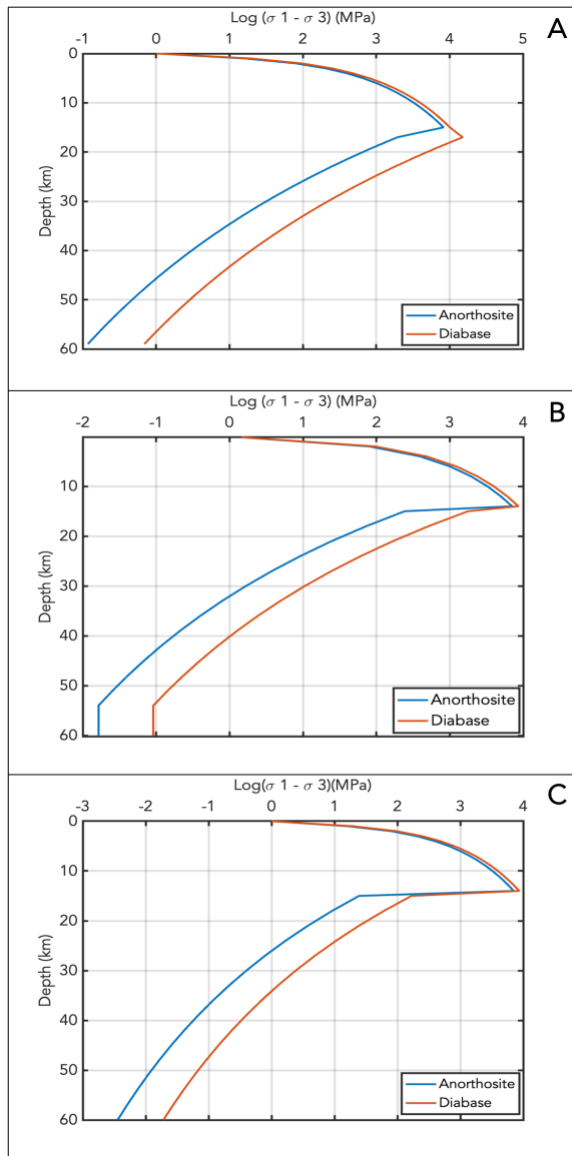


Figure 2: Crustal strength envelopes for three cases: (A) crustal thickness = 30km; $T(15) = 800\text{K}$, (B) crustal thickness = 45km; $T(15) = 900\text{K}$, and (C) crustal thickness = 60km; $T(15) = 1000\text{K}$. $\Delta T/\Delta Z = 50\text{K/km}$ in all three cases.

Discussion and Conclusion: We constructed lithospheric strength envelopes for the pre-Nectarian period (4Ga) from the lunar geothermal gradient computed by [10] for crustal thickness of 30km, 45km, and 60km. In each case (Fig 2. A-C), there is no strength difference between anorthosite and diabase in the upper crust ($0 < z < 15\text{km}$). However, the strength of anorthosite

is an order of magnitude lower than that of diabase in the lower crust ($z \geq 15\text{km}$), where the rheology is temperature dependent. Since the primary crust of the Moon is composed of anorthosite rather than diabase, its relative lower strength suggests that the conditions in the lower crust at 4Ga were favorable for viscous relaxation. Furthermore, [11] observed that 76% of floor-fractured craters are spatially associated with the oldest basins (i.e., pre-Nectarian age). The strength envelope estimates for anorthosite coupled with the spatial distribution of floor-fractured craters are consistent with the viscous relaxation hypothesis. Hence, viscous relaxation cannot be ruled out as a plausible formation mechanism for floor-fractured craters as concluded by previous studies [2,5].

However, here we have only computed strength envelopes for a single layer crust (i.e., anorthosite or diabase) using a theoretical selenotherm estimated for the pre-Nectarian period. Additionally, we have assumed an extensional tectonic regime (where $\alpha = 0.75$ for normal faulting in q. 1). Further work is needed to estimate the selenotherm for the Nectarian and Imbrian periods and compute strength envelopes for the lithosphere for the corresponding geologic timescales. Several questions remain: how do the lithospheric strength envelopes vary for a two-layered crust? At what period in the lunar geologic history does the tectonic regime change from extensional to compressional? Is viscous relaxation of the lithosphere plausible in those cases and does it contribute to the formation of floor-fractured craters across geologic timescales?

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