LIMITS ON THE EXPANSION AND CONTRACTION OF THE MOON
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The lack of globally distributed tectonic features on the lunar surface has been used to argue against significant changes in the radius of the Moon (1) since the formation of the presently observed surface, which dates to the end of heavy bombardment about 3.9 Ga. This observation has been used to limit the maximum stresses (~100 MPa) that could be supported by the lunar lithosphere without the formation of globally distributed tectonic features (2), which in turn limits the maximum radius change to ±1 km for a purely elastic lithosphere (3). In this abstract, limits on the elastic expansion or contraction of the Moon are reexamined with respect to failure stresses necessary to produce lunar tectonic features, which have formed in the upper few kilometers of the Moon. Limits to permanent (plastic) radius changes that could have been accommodated by non-mascon grabens and wrinkle ridges are also considered. Results place more severe constraints on the expansion and contraction of the Moon since the end of heavy bombardment.

Limits to the elastic expansion and contraction of the Moon (without resulting tectonic features) can be obtained by restricting stresses due to radius changes to be less than those required for failure according to accepted criteria. The horizontal stress in an elastic lithosphere resulting from a change in planetary radius is $\Delta \sigma = \frac{E \Delta R}{R(1-v)}$, where $\Delta R$ is the change in radius, $E$ is Young's modulus, $R$ is the radius of the moon, and $v$ is Poisson's ratio. A radius change of 1 km results in a horizontal stress of about 100 MPa, assuming a Young's modulus of $10^5$ MPa (2).

An appropriate failure criterion to use for the shallow lunar crust (which is likely fractured to substantial depth) is that provided by the frictional resistance to slip on preexisting fractures (4). Application of this criterion to the Moon limits the maximum stress difference under extension to roughly 5 MPa/km depth and the maximum stress difference under compression to 15 MPa/km depth. Geometric and kinematic characteristics of grabens and wrinkle ridges suggest faults bounding these structures initiate in the shallow lunar crust (5). For example, faults bounding lunar grabens probably initiate at the base of the megaregolith, or layer of impact-ejected breccia, which is mostly 1-3 km thick (6). Faults beneath lunar wrinkle ridges (7) may initiate at the base of the mare basalts (5), which are typically up to a few kilometers thick. As a result, structural features on the Moon require failure of only the upper couple of kilometers of the lunar crust, as opposed to failure of the entire lithosphere. For these depths the maximum stresses possible before failure are about 10 MPa under extension and 30 MPa under compression. These stress limits restrict the elastic radius increase to about 100 m and the elastic radius decrease to about 300 m. Any larger changes in radius could not be accommodated elastically and would result in the formation of lunar tectonic features such as grabens or wrinkle ridges.

Limits to the expansion and contraction of the Moon that can be permanently accommodated in lunar tectonic features can be limited by considering the kinematics and distribution of structural features. Analysis of lunar grabens indicates they are bounded by inward dipping normal faults that, on average, accommodate about 150 m of horizontal extension (6). Analysis of lunar wrinkle ridges suggests they result from an average of about 200 m of shortening on thrust faults and folds (7). Most lunar grabens and wrinkle ridges are associated with mascon basins. Grabens are concentric to the edge of mascon basins; wrinkle ridges are found in the center of mascon basins. Models of the flexure of the lithosphere due to mascon loading suggest that sufficient extensional stress and strain can be generated at the edges of basins to account for concentric grabens and sufficient compressional stress and strain can be generated in the interior of
basins to account for wrinkle ridges (8, 9, 10). As a result, these structures should not be considered to form from global strain or stress fields. Nevertheless, there are a significant number of grabens and wrinkle ridges that are not related to mascon basin flexure and these could have formed from lunar expansion or contraction (even though these features are not globally distributed—all are on the lunar nearside). In addition, only tectonic features that can be confidently assigned to extensional or compressional structural deformation are considered here (i.e., grabens and wrinkle ridges); no consideration is given to less well understood features of potential structural origin such as the lunar grid or highland scarps (11). The total length of non-mascon related wrinkle ridges on the Moon is just short of 15,000 km and the total length of non-mascon related grabens on the Moon is just below 7400 km. The total radius change that can be accommodated in tectonic features is \( \Delta R = (R^2 - \Delta A/4\pi)^{1/2} - R \) where \( \Delta A \) is the cumulative change in surface area, which is simply the total length of structures times their average horizontal extension or shortening. As a result, non-mascon wrinkle ridges could have resulted from a 75 m contraction of the Moon and non-mascon grabens could have resulted from a 25 m expansion of the Moon.

From these calculations and considerations the maximum total expansion and contraction of the Moon can be determined. The implicit assumption is that the Moon could have expanded or contracted elastically up to the limits provided by the frictional resistance to sliding on preexisting fractures. Beyond this elastic limit the entire surface of the Moon is everywhere on the verge of failure, so that any additional expansion or contraction will result in failure that would form grabens or wrinkle ridges visible on the surface. As a result, the total change in lunar radius can be set by adding the elastic limit to that which could have been accommodated in non-mascon grabens and wrinkle ridges. This results in a maximum expansion of the Moon of 125 m and a maximum contraction of the Moon of 375 m since the end of terminal bombardment 3.9 Ga. These limits are substantially more restrictive than the limits of ±1 km suggested previously (3).

These limits on the change in lunar radius (+125 m/-375 m) during the past 3.9 Ga have important implications for models of the origin of the Moon. Previous conservative thermal models assumed a warm exterior and cool interior to minimize the change in radius (3). New models for the origin of the Moon from a giant impact imply a substantially more energetic, and correspondingly warmer (and partially melted) early history, which may be even more difficult to reconcile with such restrictive constraints on radius change (e.g., 12).