Extensional contributions to lunar stress fields from mantle phase transformations

Craig R. Bina[1] and Mark S. Robinson[2]
[1]Dept. of Earth and Planetary Sciences, Northwestern University, Evanston, IL 60208, U.S.A.
(craig@earth.northwestern.edu)
[2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, U.S.A.
(robinson@ser.asu.edu)

1. Introduction

Throughout much of its history, the lunar surface is believed to have experienced a globally compressive stress regime arising primarily from thermal contraction [1], leading to compressive surface features such as the lobate scarps [2] generally interpreted as the result of thrust faulting. Recently, high-resolution imaging of the lunar surface by the LRO mission revealed evidence of local extension, in the form of graben structures [3,4] whose locally extensional stress regimes are attributed to flexure or magmatic intrusion. Also recently, high-resolution gravity mapping by the GRAIL mission revealed evidence of global extension, in the form of elongated linear gravity anomalies attributed to deep-seated magmatic intrusion of dikes arising from global expansion [5] during an early phase of lunar thermal evolution [1]. Here we propose an alternative mechanism for local or global extensional stress contributions, arising from the interplay between mantle petrological stability fields and lunar thermal evolution.

2. Petrological background

The plagioclase-spinel-garnet (Pl-Sp-Gt) lherzolite phase transformations are petrologically unusual in that their phase boundary curvatures in P-T space exhibit opposing concavities. Among the reactants (Ol, Pl) of the lower-P transition, from plagioclase to spinel lherzolite, plagioclase has a relatively high entropy, while the products (Sp, En, Di) are nearly pure phases at low T, so that $\Delta S<0$. At higher T, the products contain solid solutions (En+Ts, Di+Ts+cEn), so that $\Delta S>0$, leading to phase boundary concavity d2P/dT2<0. The opposite is true for the higher-P transition, from spinel to garnet lherzolite, where at low T the reactants (Sp, En, Di) are nearly pure phases while the products contain garnet solid solution (Py+Gr), so $\Delta S>0$. At higher T the reactants also become solid solutions (En+Ts, Di+Ts+cEn), so $\Delta S<0$, yielding phase boundary concavity $d2P/dT^2>0$. This pattern persists for complex systems bearing sodium, chromium, and ferrous and ferric iron. As a result, warm, young geotherms or selenotherms may intersect the Pl-Sp lherzolite boundary at two different pressures, while colder, older T profiles cross the Sp-Gt lherzolite boundary at increasing depths, yielding density reversals during cooling that have been invoked terrestrially to explain flattening of old oceanic lithosphere [6] and temporal variations during subsidence of tectonic basins [7]. We propose that these same phase boundaries may contribute to extensional stresses near the surface during lunar thermal evolution.

3. Results and discussion

Fig. 1 shows time-varying selenotherms from two lunar cooling models [8,9] superimposed on calculated lherzolite phase boundaries for three terrestrial pyrolitic mantle compositions [7]. While phase relations for lunar mantle (yet to be computed) may differ in detail, it is clear that selenotherms remain close to the Pl-Sp lherzolite boundary for much of lunar history, so that local or regional heating may drive transformation to Pl lherzolite and consequent surficial extensional stress. Furthermore, much lunar cooling proceeds on the ΔS>0 side of the Sp-Gt lherzolite boundary, driving global downward expansion of the Sp lherzolite stability field and consequent surficial extensional stress. Fig. 2 shows schematically, by finite-element modeling [10], the generation of surficial extensional stresses by regional subsurface expansion. Similar thermo-petrological considerations may be applicable to larger bodies, such as Mars or Mercury.

References

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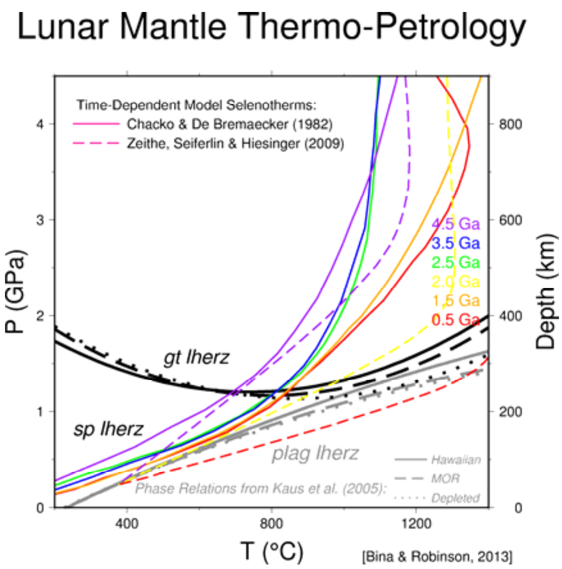

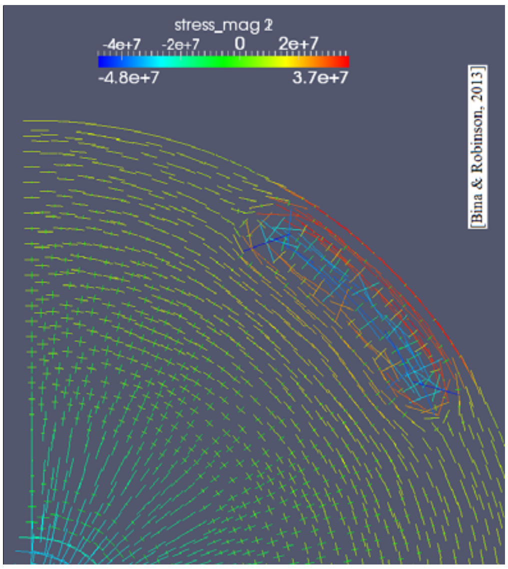

Fig. 1. Selenotherms from 2 cooling models [8,9] with phase fields for 3 mantle compositions [7].

Fig. 2. Finite-element modeling (using Elmer [10]) of principal stresses from subsurface expansion.