THE ROLE OF DIFFERENTIATION IN THE STRESS HISTORIES OF THE TERRESTRIAL PLANETS: IMPLICATIONS FOR THE MOON AND MARS;

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Introduction Volumetric changes throughout the interior of an evolving solid planet will inevitably be felt at the surface as stresses, potentially making themselves manifest as extensional or compressional tectonic features. The interpretation of global tectonic features in terms of interior evolution has traditionally focused on thermal expansion and core segregation (*e.g.*, 1, 2). Our purpose here is to point out that silicate differentiation can also cause a net volume increase and to assess the importance of such differentiation in the histories of the terrestrial planets, particularly the Moon and Mars.

The expansion accompanying differentiation results mainly from the transformation of garnet into less dense minerals. For this to work, Al_2O_3-bearing melt must originate in the garnet stability field and refreeze at shallower depth outside this field. It is *not* necessary that the igneous product be extruded onto the surface or that it form the conventionally defined crust. The effect is well known for the Earth (3), where a net expansion due to differentiation $\frac{\Delta V}{V}\big|_d = 4.55\%$ results if 25% of a typical pyrolite is converted to basalt. This of course has no tectonic implications, since the basalt is eventually recycled into the mantle and the Earth's volume does not increase with time by this mechanism. In contrast, Venus may have accumulated a 100–170-km basaltic crust (4), which, with the above $\frac{\Delta V}{V}\big|_d$, corresponds to an increase in planetary radius of 18–30 km. If the lithosphere were perfectly elastic with $E \simeq 100$ GPa, tensile stresses of ~ 0.4–0.7 GPa could result; in reality such stresses are more than sufficient to cause failure. The significance of this result is hard to appraise for two reasons. First, Venusian tectonism has been interpreted as having both extensional and compressional components (5). Second, some of the basalt may have been extruded onto the surface, both reducing the level of stress produced and burying the evidence of tectonism associated with differentiation. Silicate differentiation is likely to have been overwhelmed in the evolution of Mercury by the contraction associated with the partial freezing of that planet's large metallic core (6). Our results below suggest, however, that $\frac{\Delta V}{V}\big|_d$ may have been nearly as important as thermal expansion for the Moon and possibly for Mars. The case of the Moon is especially intriguing, since its apparent lack of significant global tectonism has strongly constrained its radius to $\lesssim \pm 1$-km change in the last 3.8 Ga (7). This is usually interpreted to require that the Moon formed with a hot exterior and a large, cold core, resulting in a delicate balance between cooling above and radiogenic warming below (1). Motivated by current interest in "giant impact" models of lunar formation, we show that much hotter initial states are permitted if $\frac{\Delta V}{V}\big|_d$ is included in the volume budget. Less can be said with certainty about Mars, but $\frac{\Delta V}{V}\big|_d$ might contribute appreciably to global (or local) expansion and thus play a part in the observed extensional tectonics.

We start by making a hopefully robust estimate of $\frac{\Delta V}{V}\big|_d$ for each body. Applying a set of simplified mineralogical schemes to a wide range of published compositions, we calculate the STP densities of primordial mantle, basalt, and residue left after melt extraction. From these, plus the maximum attainable melt yield X_{max}, we can estimate $\frac{\Delta V}{V}\big|_d$. Our neglect of minor minerals and (P,T) effects is justified by the large uncertainty in the compositions that should be used. We can then compare the importance of the calculated $\frac{\Delta V}{V}\big|_d$ with that of $\alpha\Delta T$ in a number of simple ways. In the case of the Moon, we also find it worthwhile to investigate a specific thermal model in order to determine the influence of $\frac{\Delta V}{V}\big|_d$ on the tectonic constraints for the initial state. Details of the lunar calculations were presented in (8).

Calculation of Densities We "simplify" the published compositions by removing minor elements, leaving only SiO_2, MgO, Al_2O_3, FeO, and CaO. We then project the simplified compositions onto the mineral assemblages Ol-Opx or Sp-Cpx-Ga (source and residue), and Ol or Qz-Opx-Cpx-An (basalt). We assume that the Mg:Fe ratio is the same in Ol, Sp, and Ga (but not Cpx), and we ignore all other solid solutions (3).

Our models of the lunar composition, numbered in order of decreasing Ca and Al content, are Mo1="adjusted" model Mo1 from (9), Mo2=model 1 from (10), Mo3= adjusted Mo2 from (9), Mo4=model from (11), Mo5=model 3 from (10), and Mo6=model 4 from (10). (Reference 10 is a compilation from other sources.) Our models for a primary lunar melt are MoB1=Ol basalt 12009 plus 10% Fo_{75} (12), and MoB2=Apollo 15 green glass (13). Fig. 1 is a plot of $\frac{\Delta V}{V}\big|_d$ against X_{max} for each combination of models. Clearly, $\frac{\Delta V}{V}\big|_d$ depends mainly on X_{max}, which in turn is limited by the availability of CaO except for the very Ca-rich Mo1 and Mo2. The values $\frac{\Delta V}{V}\big|_d = 3\%$ and $X_{max} = 0.4$ will be taken as representative for the Moon.

For Mars, we use models Ma1–Ma6 from (9) (again, a compilation), Ma7=model from (14), and Ma8=model from (15). Our Martian basalts are generalized from (16), where melts are estimated for a bulk composition with Ol-Opx-Cpx-Ga mineralogy and for one in the Ol-Cpx-Sp-Ga field. We use the melt appropriate to each of our calculated bulk mineralogies, varying only the Mg:Fe ratio to reflect that of the source. Ma3 and Ma6 lie very close to the Opx-Sp boundary (the "full" Ma6 contains Sp (16), but our simplified version contains Opx), across which the nature of the melt, hence X_{max} and $\frac{\Delta V}{V}\big|_d$, change radically. We therefore calculate $\frac{\Delta V}{V}\big|_d$ for Ma3 and Ma6 using both melt models. Fig. 2 shows the results. For Mars, $\frac{\Delta V}{V}\big|_d$ depends on X_{max} but also very strongly on the melt type. The much more Al_2O_3rich melt predicted for the Sp-Ga wehrlite source leads to larger $\frac{\Delta V}{V}\big|_d$ for a given melt yield. Whether this dichotomy is real, and on which side the Martian mantle actually falls, are facts that must be determined if the role of $\frac{\Delta V}{V}\big|_d$ in Martian tectonics is to be fully understood.

Comparison of Differentiation and Thermal Effects In addition to $\frac{\Delta V}{V}\big|_d$, the role of differentiation in a planet's stress history depends on the thickness of basalt that can be accumulated within the stability field of the low-density minerals, and on the amount and timing of melt formation. The first two factors can be assessed semiquantitatively; the third can be determined only in the context of a thermal evolution model. The importance of $\frac{\Delta V}{V}\Big|_d \simeq 3\%$ may be seen by dividing it by α (17): differentiation is equivalent to heating the source region by nearly 10^3 K. The contraction $\alpha \frac{1}{2} \Delta T \sqrt{\kappa t} \simeq 5.5$ km expected from the cooling of the Moon's outer regions over $t = 3.8$ Ga may be offset by differentiating $\sim 0.26 V_{Moon}$ (*e.g.*, a 1100-km sphere). We can thus imagine an initial state with a 640-km-deep magma ocean and an interior just below the solidus which nevertheless leads to an acceptable radius history, provided the timing is right. The volume of magma produced is $\sim 0.1 V_{Moon}$, which fits into the plagioclase stability field (9) even with a 70-km anorthosite crust above it. This is also about 100 times the estimated volume erupted (9), a large ratio but perhaps not implausible given that the melt is not buoyant with respect to the crust.

The conclusions for Mars are less dramatic. The depth to which the low-density phases are stable is a limiting factor, and it is uncertain because of temperature and composition dependences. The bottom of the plagioclase field may be as shallow as ~ 35 km and the top of the garnet field may be at 70–120 km (16, 18); the latter may be relevant, since most of the density decrease for basaltic composition occurs there. Assuming a gabbro layer 100 km thick, $\frac{\Delta V}{V}\Big|_d = 1\%$, and $X_{max} = 0.2$, we calculate a radius increase of ~ 2.5 km, comparable with the thermal expansion for a number of published thermal models (*cf.* 9). Stresses of the order of 0.1 GPa, sufficient to cause tensional failure, could be set up in an elastic lithosphere. Correspondingly larger values obtain for a spinel-containing mantle. It is also possible that much of the extensional tectonism on Mars is regional, related to Tharsis volcanism. The differentiation effect we have calculated could equally well contribute to such regional expansion.

Lunar Thermal Model We have investigated (8) a simple conductive thermal evolution model for the Moon, following (1) in most particulars (both to simplify and to facilitate comparison). It corroborates the estimates made above and lets us assess the timing of differentiation. We parameterize the initial state by a depth Z_0 above which the temperature is at the solidus and a central temperature T_c. Fig. 3 shows this parameter space, hatching indicating the models excluded because they exhibit too much expansion or contraction (or both). Including $\frac{\Delta V}{V}\Big|_d$ permits $T_c \lesssim 1200$ K at modest magma ocean depths Z_0. Such an initial state—part molten, part "warm"—could be consistent with an impact formation model in which a protolunar disk spawns a large number of moonlets that cool before coalescing.

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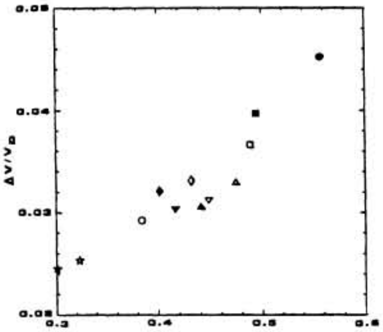

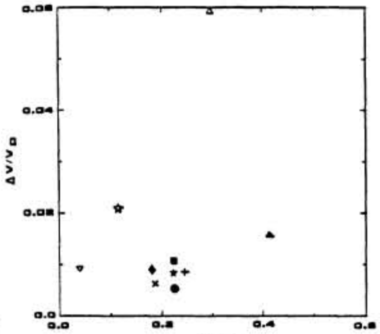

Figure Captions Figure 1. Differentiation volume change vs. melt yield for the Moon for various combinations of bulk composition and melt composition. Symbol shape indicates bulk Moon model: circle=Mo1, square=Mo2, triangle=Mo3, inverted triangle=Mo4, diamond=Mo5, star=Mo6. Shading indicates melt model: solid=MoB1, open=MoB2. Figure 2. As Fig. 1, but for Mars. Circle=Ma1, square=Ma2, triangle=Ma3, inverted triangle=Ma4, diamond=Ma5, star=Ma6, plus=Ma7, cross=Ma8. Open=melt appropriate for spinel-garnet wehrlite, solid=for garnet lherzolite. Figure 3. Parameter space (central temperature vs. magma ocean depth) for lunar thermal models. Parameter values leading to lithospheric failure (not observed) indicated by hatching. Dashed boundaries outline region of acceptable values if differentiation effect is neglected.