EMPLACEMENT AND TECTONISM OF THE NON-BASIN LUNAR MARE PROVINCES TRANQUILLITATIS AND FRIGORIS.

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Introduction: Two of these things are not like the others: the lunar basaltic volcanic provinces Mare Frigoris and Mare Tranquillitatis do not fill circular impact basins like most other prominent Mare units, but rather fill troughs that may reflect deep and primordial rifts [1]. We consider scenarios to account for the unusual characteristics that the FAT (Frigoris And Tranquilitatis) Mare have in common, but also for the differences between them.

Similarities. The main basaltic volcanic units of the FAT Mare are not circumscribed by the rims of impact basins (as for Mare Serenitatis, Imbrium, Crisium, etc.), although they encompass smaller basins (e.g., East Frigoris and Lamont [2]). Both overlie linear gravity anomalies indicating thinned crust, parts of a proposed Procellarum-bounding rift system [1]. Tectonically, the western portions of both Frigoris [3] and Tranquillitatis [4] exhibit wrinkle-ridge trends approximately parallel to the gravity anomalies and topographic lows, although the pattern at the former has an en-echelon component that can depart significantly from rift-parallel [3]. Eastern Frigoris may comprise a small mare-filled impact basin (perhaps partially relaxed), and wrinkle ridge trends within it have mixed orientations reflecting contributions from mare basin filling [3]. Modest rift-parallel systems of grabens are seen along the margins of eastern Frigoris [3] and western Tranquillitatis [4].

Contrasts. There are strong compositional contrasts: Western Mare Tranquillitatis units have very high titanium content, Mare Frigoris units in general do not exceed 2 wt% TiO_2 (the exception being the western-most unit where TiO_2 content reaches 6 wt%; [5])). Eastern Tranquillitatis is distinct from the rest of that province in terms of geology, comprising a volcanic shield (the "Cauchy Shield" of [6]) cut by two prominent surface extensional features (Rimae Cauchy) and with wrinkle ridges mostly confined to its periphery. Scattered around and within Mare Frigoris are isolated, late-stage (or post-mare?) pyroclastic volcanic domes and calderas with flows of limited extent. In addition to evidence of cryptomare units [5]. The distinction is also expressed geophysically, with eastern Tranquilitatis exhibiting "normal"-thickness crust rather than the thinned crust typical beneath mare units. Further, this terrain has no analog in Frigoris.

Conundrums: 1) If rifts produced the expected rift-perpendicular extension in the crust, the presence of rift-parallel ridges at FAT is counterintuitive. The nominal expected syn-rift stress state is the most compressive principal stress σ_c oriented vertical (σ_v) and most extensional principal stress σ_e oriented rift-perpendicular (σ_{pe}), with the intermediate σ_i oriented rift-parallel (σ_{pa}). (Note: this stress state is consistent with the orientations of grabens observed at the western margin of Tranquillitatis). Global contraction would superimpose a global isotropic horizontal compression σ_g on both horizontal stresses: as σ_g increased, σ_{pa} would be the first horizontal stress eligible to become σ_c, first putting the region into the strike-slip regime, followed by σ_{pe} surpassing σ_v such that σ_v was now σ_e, with a resulting prediction of rift-*perpendicular* faulting, counter to observation. Clearly, a phenomenon different from merely a cessation of rifting followed by global contraction is required to explain the observations. 2) Tranquillitatis has on average the oldest mare surface unit ages [7] but also exhibits by far the youngest wrinkle ridge ages [8]. This difference suggests that Tranquillitatis resisted falling into compression for substantially longer than any other mare unit.

Modeling Technique: To examine scenarios for creating rift-parallel compression at the FAT Mare, we create Finite Element Method (FEM) models of the response of the lunar lithosphere to emplacement of mare units in a rift setting using the COMSOL Multiphysics package (Fig. 1). We calculate stresses in plane-strain geometry, applying a uniaxial compaction "Poisson" state of lithospheric pre-stress [see 9], reflecting an expected bias toward horizontal extension at rifts. Initial topography of the lithosphere's surface takes a super-Gaussian profile with maximum depth of 6 km at the symmetry axis (x = 0 km). The crust-mantle boundary is isostatically compensated, and the mantle component of the lithosphere has constant thickness, to reflect heating and weakening of the rifted mantle. Basal boundary conditions include flexural restoring and prestress-balancing forces.

Results: Subsidence from mare unit emplacement in plane-strain geometry produces rift-perpendicular compression in the mare load (blue horizontal arrows at top of Fig. 2) that acts in opposition to any pre-existing rift-perpendicular extension in the lithosphere. High differential stress magnitudes in the mare are consistent with pervasive compressive faulting striking parallel to the rift axis, consistent with the observed orientations of wrinkle ridges at the FAT Mare.

About timing: The timing of wrinkle ridge formation then becomes the issue: At Frigoris, the wrinkle ridges are produced [8] within several hundred million years of surface mare unit emplacement [7], consistent with formation of ridges directly from loading stress, given reasonable mantle asthenospheric relaxation times. However, at Tranquillitatis, the up to 2.4 Ga timespan between oldest surface unit emplacement [7] and the end of ridge formation [8] requires that pervasive compressional faulting not occur for an extended period of time after unit emplacement. (removal of faults by resurfacing is not viable given the very old surface unit ages). This finding suggests that extension lasted much longer at Tranquillitatis than at Frigoris, implying a hotter, more active rift segment at the former. Further, the gap between earliest surface unit emplacement and *earliest* wrinkle ridge formation at Tranquillitatis (several hundred million years) is comparable to the complete time period between earliest surface unit emplacement and *latest* ridge production at Frigoris.

Resolution of Conundrums: 1) Loading by mare units and deep rift zone cooling mechanisms provide the rift-parallel compression needed to explain the first-order orientations of the FAT Mare wrinkle ridges. Contributions from despin-tidal evolution of the Moon might provide a secondary influence, and the relative timing between rifting activity and the onset of global compression from lunar contraction may affect timing of wrinkle ridge formation relative to mare unit emplacement. 2) Tranquillitatis is different from other lunar mare provinces, obviously from the round ones filling impact basins but also from the non-basin Frigoris. Wrinkle ridges are formed by a combination of mare loading (flexure/membrane response of the lithosphere) and global contraction. But if western Tranquillitatis, as a component of the proposed Procellarum-bounding rift [1], was a site of focused extension, then it may have required more time to convert the state of stress from extension to compression. Further, contributions to the stress state from cooling of regional thermal anomalies (e.g., the ostensibly hot rift) could also contribute to both the intensity and timing of faulting at Tranquillitatis. A scenario positing a longer-lived thermal anomaly at this site could forestall the effects of both loading subsidence and global contraction until later in the Moon's evolution, accounting for the time discrepancy. Further modeling will incorporate thermoelastic effects from heating/cooling and temperature-dependent viscoelastic rheology to explore temporal aspects of FAT Mare evolution.

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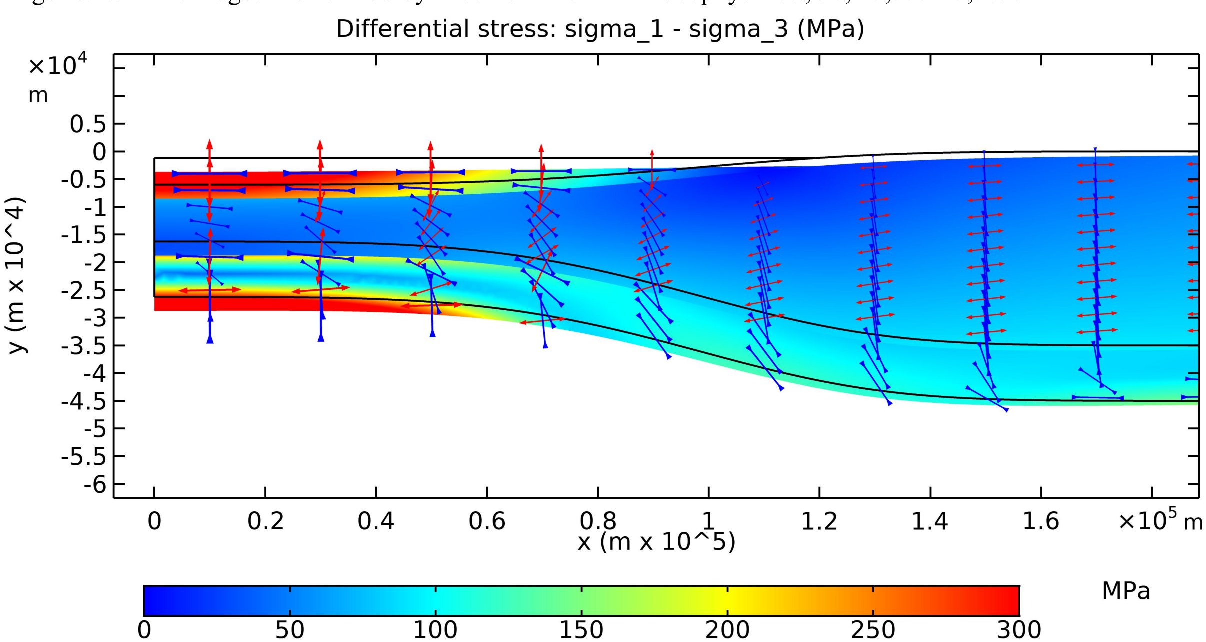

Figure 1: State of lithospheric stress and deformation for a plane-strain FEM 3-component (mantle and crustal lithosphere plus mare fill load) model of mare unit emplacement within a lunar rift. Color shows differential stress (greatest minus least principal stress) in MPa, blue and red arrows indicate principal compression and extension, respectively. The black-lined frame and colored region show pre-loading and deformed configurations, respectively. The wedge-shaped frame segment at upper left and the mostly red-colored deformed segment corresponding to it is the mare basalt load.