Introduction: Mare Tranquillitatis is anomalous: The mare units are amongst the oldest [1], but the wrinkle ridges that deform these units are significantly younger [2]. Most other mare have ridges that occur well within the span of mare unit ages, often in the early part of that span (Fig. 1). Here we argue that the thermo-chemical evolution of the Moon interacted with the unique setting of Tranquillitatis (atop the Procellarum-bounding rift (PBR) system [3]) and the edge of the Procellarum KREEP Terrain (PKT) geochemical province [4]) to produce a strongly time-dependent profile of support for the load of Mare Tranquillitatis on the lunar lithosphere.

Setting: Mare Tranquillitatis is located at the eastern edge of the geochemically delineated PKT terrain. It comprises two distinct geophysical provinces. The western province overlies linear gravity anomalies indicating thinned crust, parts of a proposed Procellarum-bounding rift system [3]. The basalt units of the eastern province are superposed on a block of normal-thickness (i.e., not basin-thinned) nearside crust, and have been described as a volcanic shield: the Cauchy Shield [5]. The Mare Tranquillitatis region lacks any substantial geophysical evidence for constituting a relict impact basin of dimensions comparable to the so-named mare units [6], and we are skeptical of scenarios based solely on surface-derived observations that attempt to justify such an assignment.

Observations: We use age determinations of mare units [1] and wrinkle ridges [2] from crater counts and geophysical observations such as topography and gravity [e.g., 6] to formulate and evaluate scenarios for the geologic and tectonic evolution of Mare Tranquillitatis. We assign various mare considered here to the following categories and sub-categories: 1) Basin (B), topographically relaxed basin (RB), and non-basin (NB). 2) Associated with PBR or not. 3) Within PKT, at its boundary (PTKB), or not associated.

In most cases, the entire span of the wrinkle ridge ages falls within that of the basalt unit ages, and the mean of the wrinkle ridge ages is older than the mean of the basalt unit ages (Fig. 1). These “Class I” include Fecunditatis (RB), Crisium (B), Serenitatis (B, PBR, PKTB), Oceanus Procellarum (NB [3], PKT), and Imbrium (B, PKT). However, for three locations, the wrinkle ridge ages extend significantly beyond the basalt unit ages and the mean of the latter is younger than that of former: Tranquillitatis (NB, PBR, PKTB), Nubium (RB, PBR, PKT), and Humorum (B, PBR, PKTB). All three of these “Class II” locations are on the PBR. Significantly, these locations span the range of not a basin, relaxed basin, and basin, although the mean age offset toward younger ridges decreases along that continuum. We conclude that there is an association between youth of wrinkle ridge ages with respect to basalt ages and position on the Procellarum-bounding rift.

There is a “Class III” consisting of Frigoris (NB, PBR, PKT), for which wrinkle ridge mean age is very close to the mare mean age, and the former does not extend beyond the latter. Imbrium from Class I could plausibly be re-classified to this class. Frigoris shares NB and PBR classifications with Tranquillitatis but additionally occurs within PKT. The similarities and contrasts of Frigoris and Tranquillitatis have been evaluated [7], but their joint NB status has not resulted in similar age dating results. That Mare Frigoris apparently behaves similarly to most other basin-filling mare provinces and differently than Tranquillitatis suggests that the chemical and thermal anomalies associated with PKT inhibit dissociation between mare unit and wrinkle ridge formation (but see Nubium for an exception).

Figure 1. Ranges of wrinkle ridge ages [2] and basalt unit ages [1] (red and blue horizontal bars, respectively) ranked by the mean age of the former. Mean ages are also shown in the vertical red solid and blue dashed lines, respectively.

Modeling Technique: To examine scenarios for creating rift-parallel compression at the FAT Mare, we create Finite Element Method (FEM) models of the lunar lithosphere in COMSOL Multiphysics Finite Element Method (FEM) package. We have previously reported results of the lithospheric response to
emplacement of mare units in a rift setting with initially isostatic rift valley topography [7]. Such models can produce several km of vertical deflection and rift-normal compressive stresses that predict rift-parallel faulting, as generally seen in Tranquillitatis. However, they do not explicitly explain the delayed onset of wrinkle ridge formation with respect to mare unit emplacement. Timescales for this response scale with the characteristic (Maxwell) relaxation time $\tau_M$ (viscosity $\eta$ divided by shear modulus $\mu$), perhaps $10^3$ or so times $\tau_M$, yielding can be of the order $10^7$-$10^8$ years, but the response is monotonically increasing, with significant stresses built up as early as $10$s of $\tau_M$. What is needed is a delay period between loading and the onset of its response. This might arise by the superposed effects of declining rift-generated extension [7], but the details of this scenario are poorly constrained.

We now consider a second class of stress-generating models: thermoelastic stress from cooling of the lunar interior. These are inspired by the modeling of [8], who considered the effects of the dissipation of impact-induced heating beneath lunar impact basins. These workers found stress and topography-altering effects that occurred on timescales of up to $10^5$ years, consistent with the offset timescale of mare units vs. wrinkle ridges seen at Tranquillitatis (Fig. 1). This timescale is set by the thermal diffusivity $\kappa$ of the lunar interior, itself determined by the ratio of thermal conductivity $k$ to the product of density $\rho$ and specific heat $C_p$. We also consider the effects of concentrating heat-producing elements into the crust or a sub-crustal KREEP-rich layer using parametrizations of lunar radiogenic heat generation rates [9].

**Results:** We find that thermoelastic models of cooling of lunar interior thermal anomalies in a Tranquillitatis rift-like setting can predict subsidence and rift-normal compression of sufficient magnitude to produce rift-parallel compression, in a manner similar to the flexural loading models presented previously [7]. Further, the timescales of such models are on the $10^2$-$10^5$ year range, consistent with those needed to explain the observed basalt-ridge time offset at Tranquillitatis [1, 2; Fig. 1]. However, for this basic scenario, the monotonicity problem remains, beyond assuming an ad hoc thermal anomaly history in the mantle.

Models that consider heat generation in the uppermost interior of the Moon [e.g., 9] and its effects on crustal and mantle thermal evolution offer a promising way around the monotonicity problem. In such models, the initial response to the emplacement of a rift-filling mare unit is heating the unit from below, with concomitant generation of (a small amount of) uplift and significant horizontal extensional stresses. We are working on scenarios that model the subsequent cooling of both the mare and the crust, eventually reversing the stress and deformation trends to produce low topography and rift-parallel wrinkle ridges as seen at Tranquillitatis.

**Discussion:** If heating from radiogenic element-enhanced crustal and KREEP layers is important for places like Tranquillitatis, then determinations of lunar crustal thickness [e.g., 10] should be investigated. We note that “Class II” mare like Tranquillitatis and Nubium are associated with thicker crust beneath them than basin-filling mare like Crisium and Serenitatis. On the other hand, Class II Humorum has similar crustal thickness and PBR status to Serenitatis and yet quite different relationships of mare emplacement to wrinkle ridge timing. Clearly, the details of each particular setting will have to be explored, such as the asymmetric heating Tranquillitatis might encounter being on the edge of the PKT terrain.

Another potential complication is the potential loss of an early tectonic record by vigorous resurfacing; similar to the way the early history of volcanic edifices is lost and only the most recent units are seen. It is possible that wrinkle ridge activity at Tranquillitatis started similarly early and contemporaneous to basalt unit emplacement at other lunar mare provinces (Fig. 1), but was covered and erased by subsequent volcanic units. However, such latter units would have to be thick enough to remove 100s of m of ridge relief while somehow not generating ridges via their own loading, seemingly merely deferring the time offset problem.