Small Graben and Recent Tectonic Deformation in Mare Frigoris

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Previous work suggested that extensional tectonics on the Moon ended ~3.6 Ga [e.g. Lucchitta and Watkins, 1978] and mare basin-related contraction ended by ~1.2 Ga [e.g. Hiesinger *et al*., 2003]. New populations of small graben are being discovered alongside lobate scarps and wrinkle ridges in Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images (50-200 cm/pixel) [Watters *et al*., 2010; 2012]. Mare Frigoris on the northern nearside (~45°N-60°N, 40°W-40°E) is one such area with abundant tectonic landforms now revealed by LROC. We determined that principal stress components for small graben are consistent with local stress fields during the growth of their associated wrinkle ridges and lobate scarps. We discovered over 40 clusters of small graben ubiquitously associated with compressional landforms in Mare Frigoris and suggest that compression and localized extension continued in that mare basin until much more recently than previously thought.

Contractional tectonic landforms on the Moon consist of wrinkle ridges and lobate scarps, interpreted to be surface expressions of thrust faults [e.g. Watters and Johnson, 2010]. Linear troughs are also observed and interpreted to be graben formed by extension [Watters *et al*., 2012]. In Mare Frigoris, we found small graben ubiquitously atop or in back-limbs of lobate scarps and wrinkle ridges, and graben are usually either parallel or perpendicular to the strike of their associated scarp/ridge.

Assuming horizontal principal stress components, graben bounded by normal faults should form in the direction of greatest extensional stress (or least compressive stress, σ_{min}). The greatest compressive stress (σ_{max}) is perpendicular to the direction of slip on the normal faults, and parallel to the graben's long axis. Conversely for thrust faults, σ_{max} is perpendicular to the strike of the thrust fault and σ_{min} is parallel to its strike. Thus, small graben perpendicular to ridges/scarps (e.g. 60.40°N, 34.83°W) share the same principal stress component orientations and likely formed in the same stress field.

Our stress component models further imply that small graben parallel to compressional features (e.g. 60.03°N, 34.86°W) form as a result of flexural bending. Bending in response to slip on the fault is expected to cause an extensional normal stress (σ_{min}) perpendicular to the fold axis in the near surface materials. Since wrinkle ridges are interpreted as folds overlying thrust faults, we expect parallel graben on the back-limbs of ridges. Folding and flexure resulting from recent growth of the ridges in Mare Frigoris is suggested by the small parallel graben.

Based on the rate of filling of boulder tracks, small graben with depths of ~1m should infill in <50 Ma [Watters *et al*., 2012]. Due to the very good spatial correlation and consistent stress fields for the subset of wrinkle ridges with graben in Mare Frigoris, we infer some wrinkle ridges in Mare Frigoris were active within the past 50 Ma. Although large graben and many other ridges formed earlier in lunar history, this new evidence suggests that compressional tectonic deformation in Mare Frigoris did not completely shut off by 1.2 and 3.6 Ga, resp., and may continue today.