TIMING AND CONTROLS OF TECTONIC DEFORMATION IN MARE FRIGORIS. N. R. Williams[1], J. F. Bell III[1], T. R. Watters[2], M. E. Banks[2], M. S. Robinson[1], [1]Arizona State University School of Earth and Space Exploration, Tempe, AZ 85251, USA (Nathan.R.Williams@asu.edu), [2]Smithsonian Institution National Air and Space Museum, Washington, DC 20560, USA.

Introduction: Previous work suggested that large-scale nearside basin-localized extensional tectonism on the Moon ended ~3.6 billion years ago and mare basin-related contractional deformation ended ~1.2 billion years ago [1-4]. The Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) high resolution images enable further insight to lunar tectonic history. Populations of lobate scarps, wrinkle ridges, and graben are now observed at scales much smaller than previously recognized, and their morphology and stratigraphic relationships imply a complex deformational history. For example, simple compressional highland lobate scarps with tens of meters of relief and crisp morphologies, are crosscut by few craters, indicating ages of <1 Ga [5,6]. Additionally, shallow troughs or graben with only ~1 m of relief occur near the crest or in the back-limbs of some compressional landforms. These features have short lifetimes (<50 Ma) due to regolith infilling [7].

Sinuous wrinkle ridges occur in mare basalts and have up to hundreds of meters of relief and are interpreted as folded basalt layers overlying thrust faults [8-13]. Wrinkle ridge formation has often been linked to lunar mascons – dense concentrations of mass identified by positive gravity anomalies [2,3,11]. These superisostatic loads cause subsidence and flexural bending to form radial and concentric wrinkle ridges [2,3]. These morphologically complex mare wrinkle ridges contrast with lobate scarps that are simpler linear landforms formed where low-angle thrust faults break the surface [5,6].

Here we examine the wrinkle ridges of Mare Frigoris to understand the style, magnitude, and timing of deformation.

Data and Methods: The two LROC NACs [14] acquire images with pixel scales ranging from 50 cm to 200 cm across a combined 5 km to 20 km wide swath. Over 12,000 NAC images were calibrated and map projected to form a nearly continuous mosaic over the basin. Ridges, scarps, and graben were digitized as line segments in a GIS database. Small (<100 m diameter) craters crosscut by wrinkle ridges were identified and plotted as points.

Gravity Recovery and Interior Laboratory (GRAIL) free-air anomaly maps [15] show positive anomalies indicative of mascons. These new high-resolution data allow for a more detailed comparison between tectonic features and the gravity field.

Results: The distribution and morphology of tectonic wrinkle ridges differs greatly between eastern and western Mare Frigoris. The set of wrinkle ridges in eastern Mare Frigoris (Fig. 1, black circle) exhibits a polygonal pattern and is bounded on the north and east sides by large graben. The wrinkle ridges in the eastern basin are overprinted by numerous large (up to hundreds of meters in diameter) craters and have broadly undulating slopes, suggesting a relatively old age.

In contrast, there are two distinct tectonic assemblages in western Mare Frigoris. The first tectonic pattern is a set of parallel and nearly equally spaced wrinkle ridges trending NW-SE (Fig. 1, black lines). These wrinkle ridges are also overprinted by numerous large craters and have broadly undulating slopes, consistent with an old age.

The second tectonic assemblage in western Mare Frigoris (Fig. 1, white circles) is independent of the parallel series of wrinkle ridges and is characterized by crisper morphologies indicative of recent deformation. These wrinkle ridges tend to be smaller, often only tens of meters in relief, and have sharp changes in slope. These ridges also crosscut more than 70 craters smaller than ~100 m in diameter, several being smaller than 80 m in diameter, suggesting young (<1 Ga) ages [5,6,16]. Additionally, small graben are clustered around these wrinkle ridges, suggesting recent flexure continuing to within the last 50 Ma [7]. These ridges also extend to the highlands, where they transition into morpholgically simpler lobate scarps that are also thought to be <1.0 Ga.

Discussion: Landforms in the eastern basin are consistent with the traditional mascon-induced stress model [2,3] and likely formed soon after mare basalt emplacement (2.6-3.8 Ga with most between 3.4-3.8 Ga [17,18]).

The parallel set of wrinkle ridges in western Mare Frigoris are not associated with a mascon, and the orientations do not appear to be influenced by the nearest mascon in Mare Imbrium, nor do the askew orientations suggest an Imbrium outer ring collapse [18]. The preferred orientation of this parallel set of ridges could result from either A) a difference between horizontal stress components throughout western Mare Frigoris, or B) similarly oriented buried topography or structural weaknesses that pre-date basaltic emplacement. Similar to the landforms in eastern Mare Frigoris, the parallel western ridges appear to be old and likely formed during or after basalt emplacement >2.6 Ga.

The young population of wrinkle ridges, lobate scarps, and small graben in western Mare Frigoris poses an interesting question: what caused those features to form and why so recently? Without a mascon to induce flexure and subsidence, another source of compressional stress is required within the past ~1 Ga. The lobate scarps that are distributed globally across the highlands are thought to form as a result of a global compressional stress from cooling and radial contraction of the Moon's interior [5,6,19,20,21]. Such a stress should also pervade the mare basins, yet lobate scarps are very rare within the maria. Both lobate scarps and wrinkle ridges are inferred to be the surface expressions of thrust faults, with the distinction being that wrinkle ridges have greater complexity, likely due to additional folding in layered basalts [8,9,22]. We propose that the presence of some young, morphologically crisp wrinkle ridges may also help accommodate recent global compressional stresses. Zones of weakness near the edges of mare basins may localize young wrinkle ridges, and potentially explain the existence of several ridges that transition to lobate scarps at the mare/highland boundary [9,11,23].

Conclusions: Mare Frigoris is a tectonically diverse region with a complex deformational history. While the older wrinkle ridges in the mare appear to be consistent with deformation due to mascon loading; the younger features are considered to be the result of compressional stresses resulting from global contraction.

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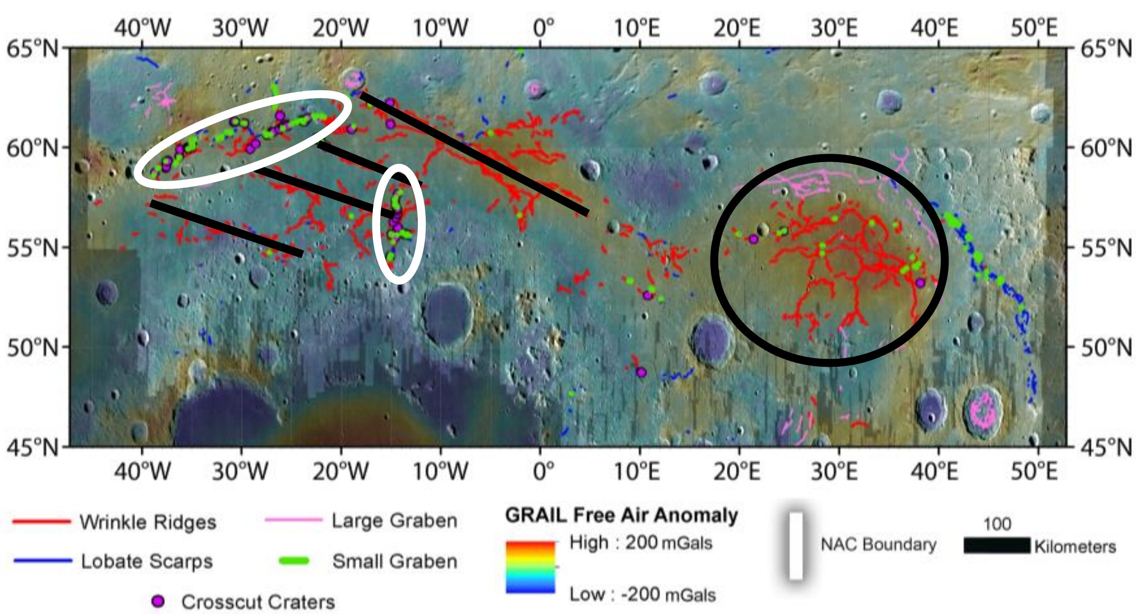

Fig. 1: Tectonic map of Mare Frigoris overlaid on GRAIL free air anomaly [15] and shaded relief. The black circle indicates the eastern tectonic assemblage, black lines indicate the older western assemblage, and white circles indicate the younger western assemblage.