RECENT 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 extensional tectonism on the Moon largely ended ~3.6 billion years ago [1] and mare basin-related contractional deformation ended ~1.2 billion years ago [2]. The Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images (50 -200 cm pixel scale) are enabling a more comprehensive assessment of this view. New populations of lobate scarps, wrinkle ridges, and graben are being discovered at scales not previously imaged, and their morphology and stratigraphic relationships imply a complex history of deformation of the lunar crust both within mare basins and in the highlands. Mare Frigoris on the northern nearside has abundant tectonic landforms revealed in NAC images acquired with optimal lighting geometry, enabling new investigations of the region's structural landforms.

Several types of tectonic features are observed in Mare Frigoris. For example, sinuous wrinkle ridges in mare basalts have up to hundreds of meters of relief. These ridges are interpreted as folded basalt layers overlying thrust faults; however, the subsurface geometry of the faults is still debated [3,4]. Wrinkle ridges are often associated with lunar mascons – dense concentrations of mass identified by positive gravity anomalies. These superisostatic loads cause subsidence and flexural bending to form radial and concentric wrinkle ridges [5]. Examples of smaller tectonic landforms with only meters to tens of meters of relief include lobate scarps – simpler linear features formed where low-angle thrust faults break the surface – that are distributed globally and thought to originate from cooling and radial contraction of the Moon's interior [6,7]. Linear troughs or graben have also been observed on the Moon, and are interpreted to form by extension between two normal faults [1,8]. These different types of tectonic landforms frequently occur together in Mare Frigoris and provide new insight into the tectonic evolution of the Moon.

Data and Methods: The two NACs [9] acquire images with pixel scales as fine as 50 cm across a combined 5 km wide swath. Over 12,000 LROC NAC images in and around Mare Frigoris were calibrated and map projected to form a nearly continuous mosaic over the basin at ~3 m/px. Ridges, scarps, and graben were digitized as line segments in a GIS database to show the distribution of landforms and their relationships.

Results: Wrinkle ridges in eastern Mare Frigoris form a polygonal pattern, similar to other mare basins with mascons. Ridges in western and central Mare Frigoris near basin boundaries typically parallel those boundaries, while ridges towards the middle of the mare occur in parallel sets or randomly. Lobate scarps occur primarily in the highlands surrounding Mare Frigoris, often parallel to the mare/highland boundary. A ~250 km long series of lobate scarps occurs just east of Mare Frigoris and trends NW/SE. Several scarps occur as the highland continuation of mare wrinkle ridges where faults intersect the mare/highland boundary. Large linear graben are largely absent from Mare Frigoris, but smaller meter-scale graben occur almost exclusively near wrinkle ridges and lobate scarps (Fig. 1).

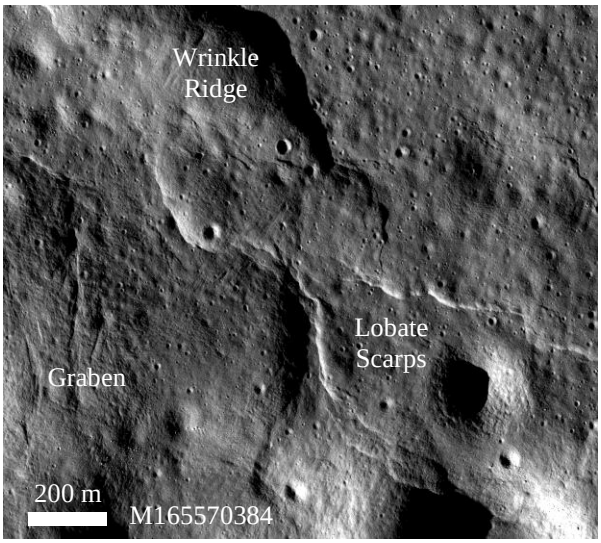

Figure 1: A wrinkle ridge transitioning to lobate scarps, with small associated sub-parallel graben.

Discussion: Although the majority of tectonic deformation within Mare Frigoris was previously thought to have occurred ~2.6-3.8 billion years ago [10,11], there is growing evidence for more recent deformation. The majority of wrinkle ridges on the Moon are proposed to be at least 1.2 billion years old [2], whereas lobate scarps are generally thought to be less than 1.0 billion years old [6,7]. At wrinkle ridge-lobate scarp transitions, the underlying faults cross the mare/highland boundary. The change in surface expression and morphology from a complex ridge to a simple fault scarp is likely due to changes in mechanical properties at mare/highland boundaries, particularly the presence or absence of layering [12,13]. The continuation of faults underlying wrinkle ridges into the highlands to form lobate scarps implies that: a) some wrinkle ridges must be younger than 1.0 Ga, b)

some lobate scarps must be older than 1.2 Ga, or c) late-stage compression reactivated pre-existing mare ridges near the basin margin and thrust faults extended into the highlands to form scarps. Although some wrinkle ridges are significantly degraded by impacts, others are morphologically crisp and crosscut small craters (Figs. 2&3), some with diameters as small as ~50 m. Lunar craters 50 m in diameter or less are Copernican in age at ≤800 ± 15 Ma [14,15], suggesting that wrinkle ridge deformation continued over a broad span of lunar history, until <1.0 Ga.

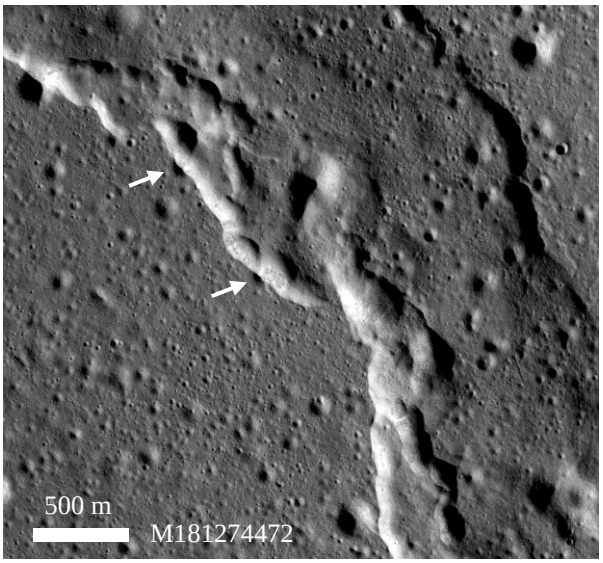

Figure 2: Wrinkle ridges crosscutting 105 m and 70 m diameter impact craters (arrows).

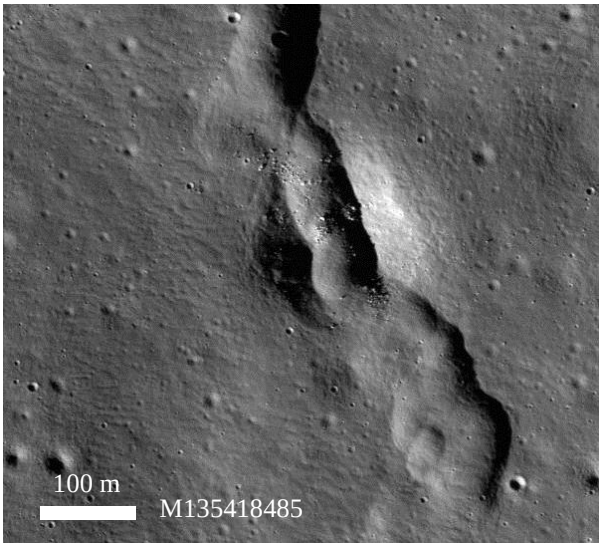

Figure 3: A wrinkle ridge crosscutting and shortening a ~170 m diameter impact crater.

Another constraint for recent tectonic deformation comes from small (meter-scale) troughs and graben [8]. Numerous clusters of small graben occur in and around Mare Frigoris near or atop lobate scarps and wrinkle ridges. The graben are usually oriented either parallel or perpendicular to the nearest scarp or ridge. In a predominantly compressional stress regime, small graben may result from localized back-limb extension simultaneous to ridge or scarp growth. Small graben such as those found in Mare Frigoris are typically only meters to a few tens of meters wide and likely only a few meters deep, and elsewhere on the Moon have been estimated to have maximum ages of ~50 Ma [8]. In order for the observed small graben to form concurrently with their associated ridges and scarps, the neighboring landforms must have also been active within the last ~50 Ma, although the majority of their deformation may have occurred earlier.

Conclusions: Deformation within Mare Frigoris has continued until much more recently than previously thought. Although some wrinkle ridges have been significantly degraded by impacts and are inferred to be over 2.6 billion years old in Mare Frigoris [10,11], others appear morphologically crisp and have been active in the recent past (<1 Ga). Lobate scarps are also morphologically crisp, and sometimes transition into wrinkle ridges at mare/highland boundary. The apparent continuity of faults across that boundary suggests that scarps and ridges overlying those faults may have been active during the same time, creating a paradox between previous age estimates for those landforms. Small graben oriented parallel or perpendicular to nearby scarps and ridges further suggest that deformation in Mare Frigoris has continued to within the last tens of millions of years and is perhaps active today.

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