TECTONIC MAPPING OF MARE FRIGORIS USING LUNAR RECONNAISSANCE ORBITER CAMERA IMAGES. 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 (nrwilli2@asu.edu), [2]Smithsonian Institution National Air and Space Museum, Washington, DC 20560, USA.

Introduction: Previous work suggests that extensional tectonics on the Moon largely ended ~3.6 billion years ago [1] and contractional deformation ended ~1.2 billion years ago [2]. NASA's Lunar Reconnaissance Orbiter Camera (LROC) unprecedented high resolution images are enabling a fresh 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. Western and central Mare Frigoris (55°N to 67°N and 50°W to 15°E) have abundant tectonic landforms revealed in high-resolution LROC image coverage, enabling new investigations of the region's structural landforms.

Several types of tectonic features have been observed in Mare Frigoris and elsewhere on the Moon. For example, sinuous wrinkle ridges in mare basalts have 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 associated with lunar mascons – dense concentrations of mass identified by positive gravity anomalies. The thick basaltic lava thought responsible for lunar mascons causes subsidence and flexural bending to form wrinkle ridges and graben [5]. No mascon-like gravity anomaly has been observed with Mare Frigoris, yet large wrinkle ridges deform the mare basalts. Examples of other, smaller tectonic landforms with only meters to tens of meters of relief include lobate scarps – 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]. Some small-scale troughs or graben also occur near or superposed on some ridges and may indicate flexure induced extension concurrent to ridge and scarp formation [8].

Data and Methods: LROC consists of two Narrow Angle Cameras (NACs) and one Wide Angle Camera (WAC) [9]. The NACs acquire images with resolutions as fine as 50 cm/pixel across an approximately 5 km wide swath, whereas the WAC acquires multispectral images with a coarser resolution of ~100 m/pixel but with a wider field of view for regional and global contexts. Over 300 NAC images in Mare Frigoris were calibrated and map-projected using ISIS and then imported into a GIS database. Landforms were digitized by drawing line segments over the centers of ridges and graben, or along the crests of scarps. Locations, lengths and orientations of landforms were calculated and plotted.

Results: Approximately 3,000 km of wrinkle ridges, 270 km of lobate scarps, and 40 km of small troughs or graben were mapped in and around Mare Frigoris using LROC NAC images (Fig. 1). Wrinkle ridges in Frigoris occur both near and distal to the basin perimeter. Ridges typically trend East-West, sub-parallel to the basin's long axis (Fig. 2). Several complex wrinkle ridges are observed to transition into simpler lobate scarps at mare/highland boundaries (Fig. 3). Scarps in Frigoris occur primarily in the highlands, tend to strike ENE/WSW, and often but not always follow the boundary between mare and highlands (Figs. 2, 4). Small troughs or graben mapped in Frigoris occur in several clusters adjacent to or on top of ridges and scarps, and are often oriented nearly parallel or perpendicular to the nearest ridge or scarp (Fig. 5).

Discussion: The presence of wrinkle ridge-lobate scarp transitions in Frigoris suggests a possible genetic relationship between the two landforms. Ridges are generally considered to have formed shortly after lava emplacement in Frigoris (possibly ~2.6-3.8 Ga [10]). Lobate scarps, often considered to be among the youngest tectonic features on the Moon, have ages estimated to be < 1.0 Ga [5,6]. If formation of the ridge-scarp transitions was concurrent, either a) some wrinkle ridges are younger than previous estimates, b) some lobate scarps are older than 1 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. The crisp morphology of some tectonic landforms with few superposed but many crosscut craters suggests some wrinkle ridges may be much younger than the ancient flood basalts. Further study is needed to better constrain the ages of these young lunar tectonic landforms. The presence of wrinkle ridges in mare basalts not associated with mascons – in Mare Frigoris, Oceanus Procellarum, and small basins like Karrer and Kugler craters – indicates subsidence and contraction in areas without superisostatic loads. The sources of compressional stress in these regions need to be more fully explored.

References: [1] Lucchitta B. K. and Watkins J. A. (1978) LPS 9, 3459-3472. [2] Hiesinger et al. (2003) JGR, 108, E001985. [3] Schultz R. A. (2000) JGR, 105, 12035-12052. [4] Watters T. R. (2004) Icarus,

171, 284-294. [5] Solomon S. C. and Head J. W. (1980) Rev. Geophys. & Space Phys., 18, 107-141. [6] Binder A. B. and Gunga H. C. (1985) Icarus, 63, 421-441. [7] Watters T. R. et al. (2010) Science, 329, 936-940. [8] Watters T. R. et al. (2012) Nature Geosci., in press. [9] Robinson M. S. et al. (2010) Space Sci. Rev. 150, 81-124. [10] Hiesinger H. et al. (2010) JGR, 115, E03003.

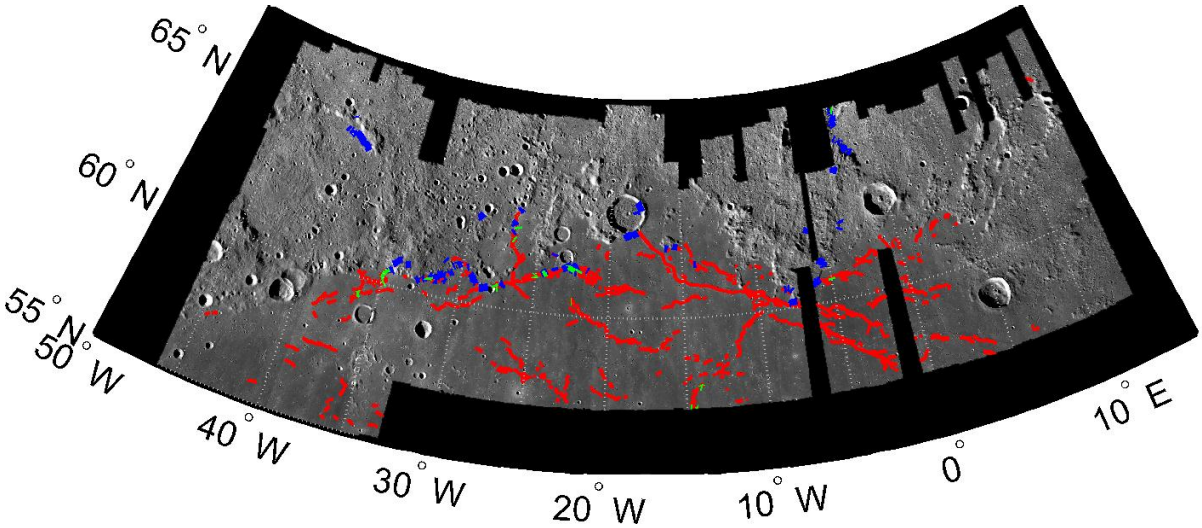

Fig. 1: Tectonic map of ridges (red), scarps (blue), and troughs (green) in western and central Mare Frigoris overlain on WAC mosaic of area examined.

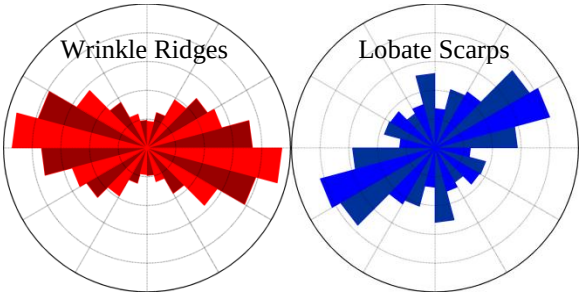

Fig. 2: Length-weighted distribution of mapped Frigoris tectonic landform orientations.

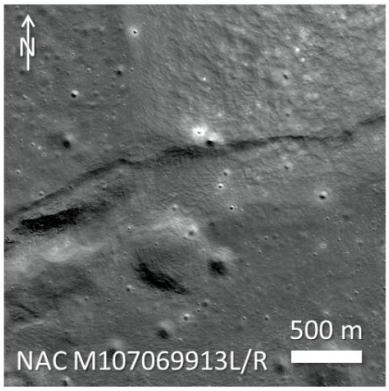

Fig. 3: A mare wrinkle ridge (left) transitions into a highland lobate scarp (right).

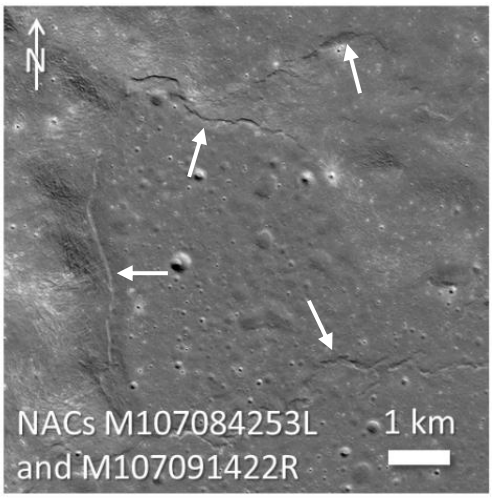

Fig. 4: Ridges and scarps (white arrows) deform along and away from the mare-highland boundary.

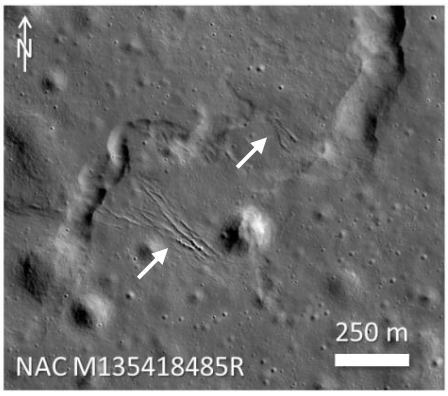

Fig. 5: Extensional troughs (white arrows) adjacent to a mare wrinkle ridge