Small Graben and Recent Tectonic Deformation in Mare Frigoris

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Introduction and Motivation

- Previous work suggested that mare basin-related extension on the Moon largely ended ~3.6 Ga[1] and contractional deformation ended ~1.2 Ga[2,3]
- Lunar Reconnaissance Orbiter Camera (LROC) enables the discovery of tectonic landforms at scales not previously imaged[4,5,6]
- Landform morphology[7,8] and stratigraphic relationships imply a complex history of deformation on the Moon

Landforms

a. Lobate Scarp: A simple curvilinear, asymmetric hill formed by near-surface fault[4,5,7,8] (Fig. 1a)
b. Wrinkle Ridge: A complex of curvilinear, asymmetric hills formed by folding over a blind fault or faults[2,9,10] (Fig. 1b)
c. Graben: A trough formed between two normal faults[1,6] (Fig. 1c)

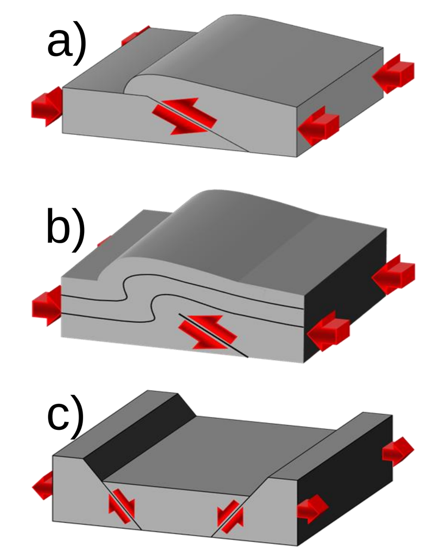

Fig. 1: Block diagrams of a) lobate scarp, b) wrinkle ridge, and c) graben

Data and Methods

- LROC Narrow Angle Camera (NAC)[11] images with meter-scale resolution
- Nearly continuous NAC image coverage from 45°N to 65°N and 45°W to 45°E
- Map tectonic landforms using ArcGIS both in the mare and in the adjacent highlands
- Identify any preferred orientations for groups of landforms
- Infer principal stress components from surface traces

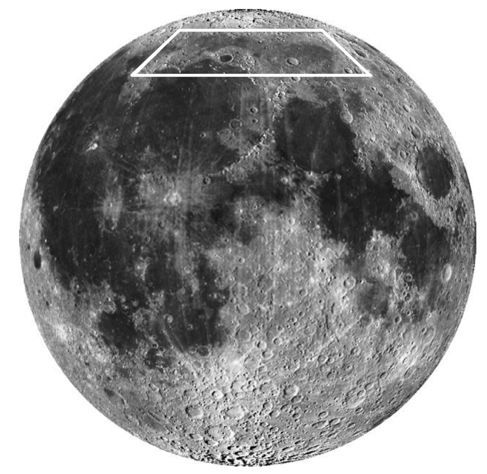

Fig. 2: LROC WAC global orthographic projection centered on 0°N, 0°E showing the location of Mare Frigoris (trapezoid)

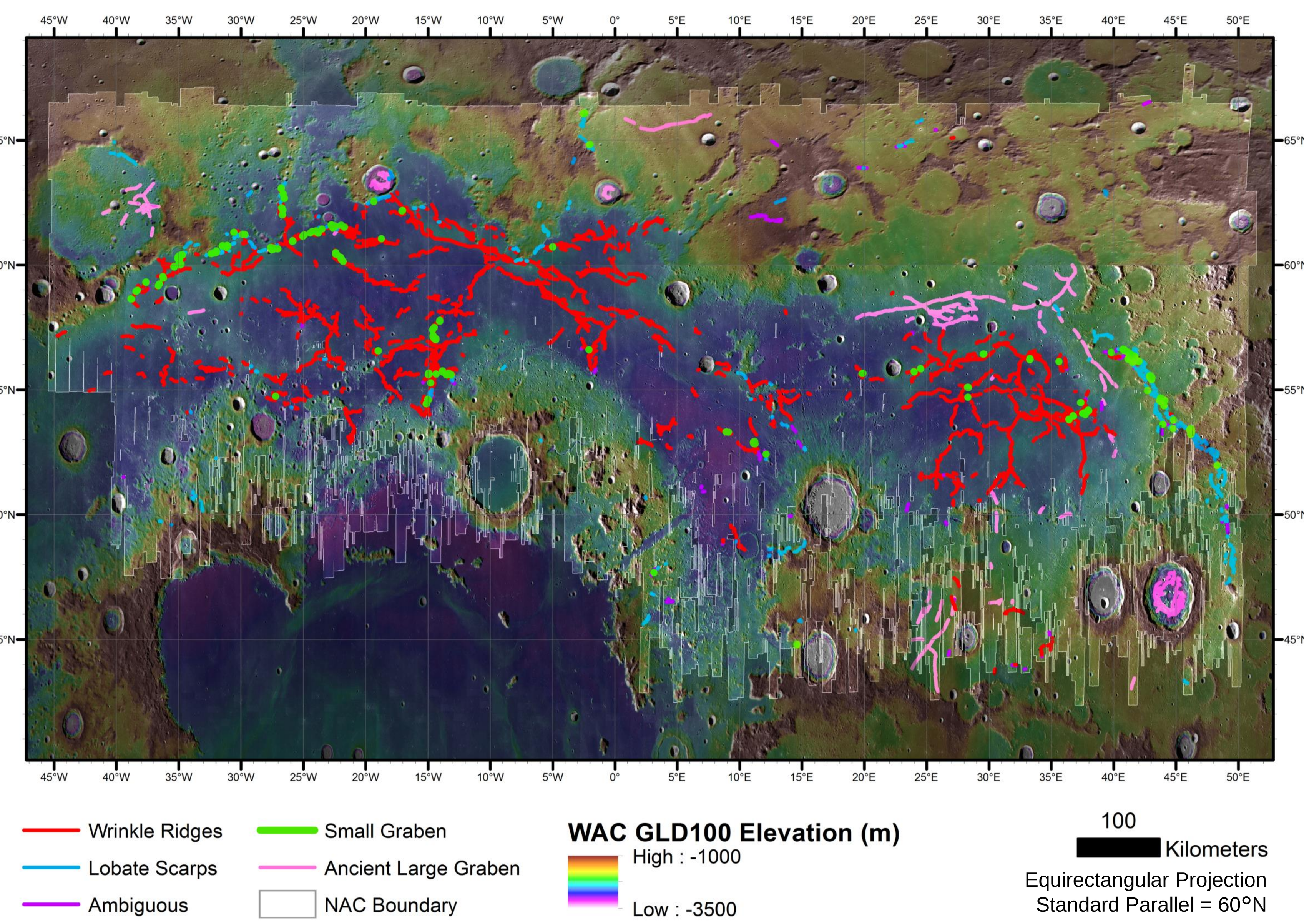

Fig. 3: Tectonic map of Mare Frigoris over LROC WAC DEM[12]

Perpendicular Graben

- Graben bounded by normal faults should extend 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 a normal fault and parallel to the long axis of the graben
- Conversely for thrust faults, σ_{max} is perpendicular to the strike of the thrust fault and σ_{min} is parallel to its strike
- Small graben perpendicular to ridges/scarps share the same principal stress component orientations and likely formed in the same stress field

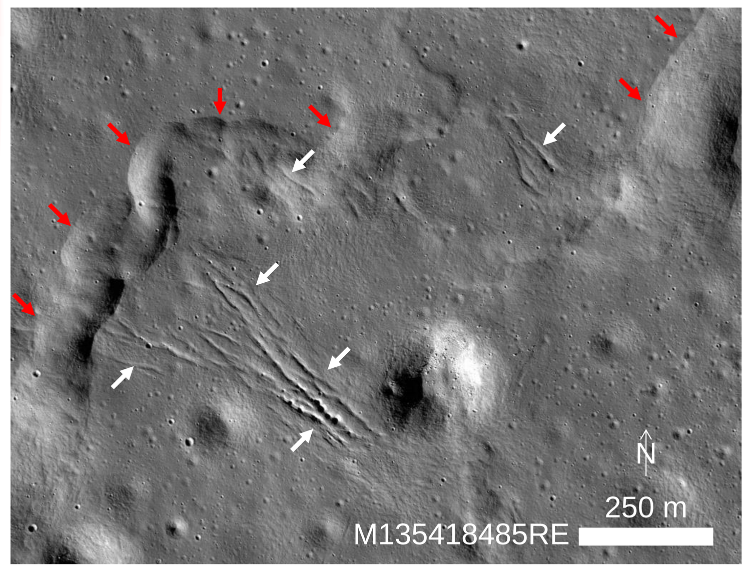

Fig. 4: Small graben (white arrows) nearly perpendicular to a wrinkle ridge (red arrows) at 60.40°N, 34.83°W

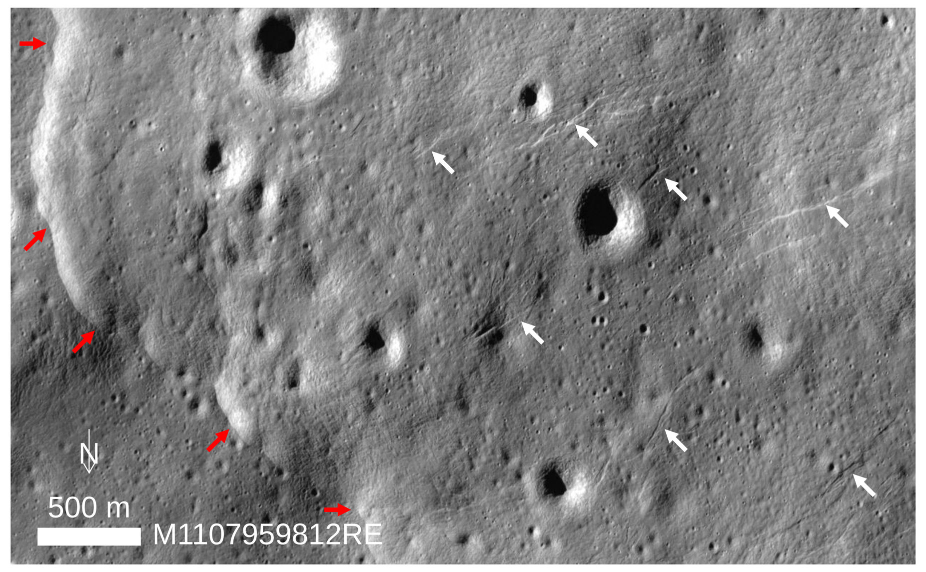

Fig. 5: Small graben (white arrows) nearly perpendicular to a lobate scarp (red arrows) at 53.35°N, 46.23°E

Parallel Graben

- Bending in response to slip on a thrust fault causes an extensional normal stress (σ_{min}) perpendicular to the fold axis in near surface materials, causing extension parallel to the fault
- Since wrinkle ridges are interpreted as folds overlying thrust faults, we expect some graben to be parallel to ridges, and to a lesser degree graben may also be parallel to lobate scarps as well
- The presence of parallel graben suggests some folding and flexure in Mare Frigoris

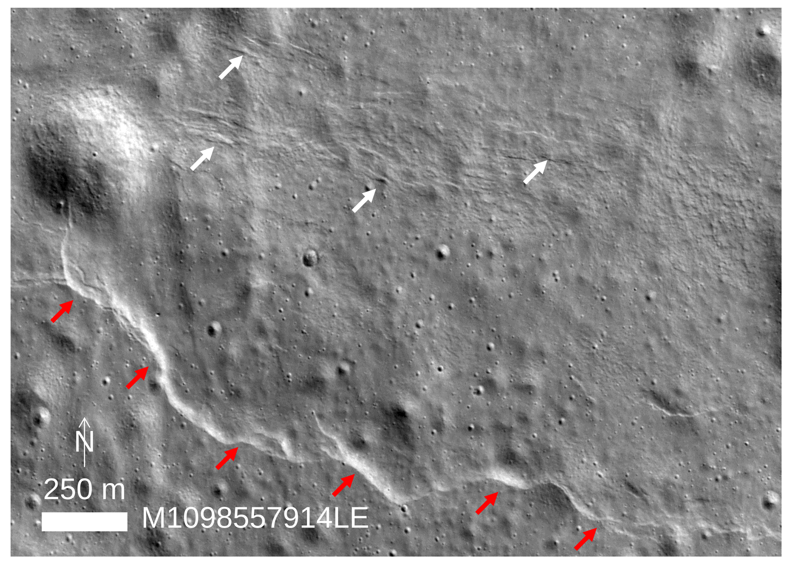

Fig. 6: Small graben (white arrows) nearly parallel to a lobate scarp (red arrows) at 56.14°N, 42.00°E

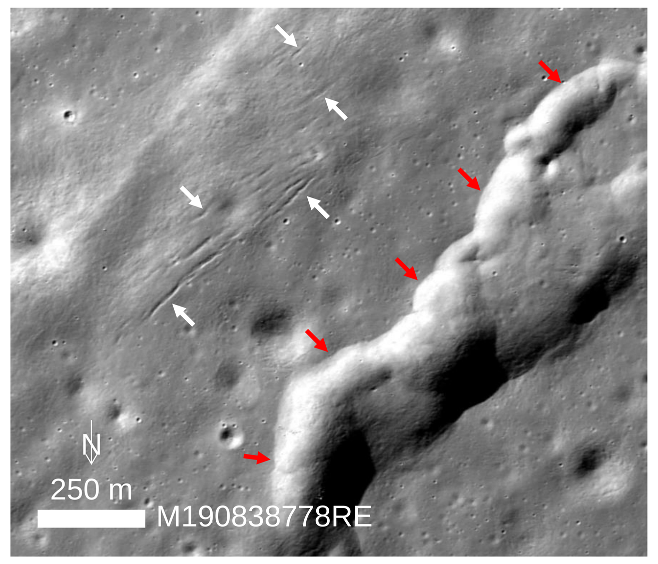

Fig. 7: Small graben (white arrows) nearly parallel to a wrinkle ridge (red arrows) at 60.03°N, 34.86°W

Tectonic Map Results

- Over 40 clusters of small graben distributed throughout Mare Frigoris and the neighboring highlands
- Small graben ubiquitously associated with wrinkle ridges and lobate scarps in Mare Frigoris
- Typically only meters to a few tens of meters wide and at most a few meters deep
- Small graben with <1 m of vertical relief should infill in <50 Ma based on analysis of boulder tracks[13], and if still visible are presumed to be young[6]

Graben Orientations

- Difference in azimuth measured between small graben and their nearest ridge/scarp
- Graben are preferentially at high angles (nearly perpendicular) to nearby ridges and scarps
- Minor preference for graben to be nearly parallel to ridges and scarps
- Moderate orientations likely due to regolith heterogeneities and curvature of associated ridge/scarp

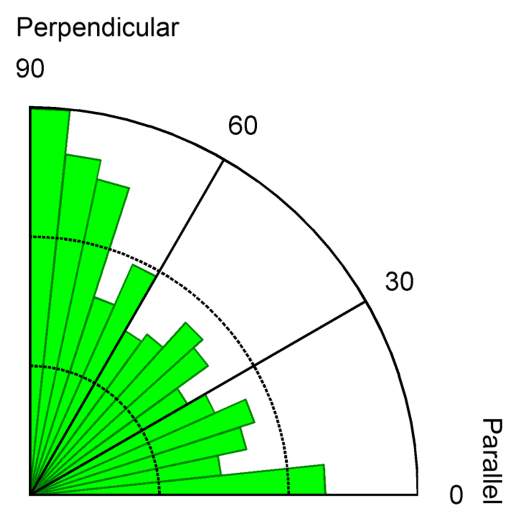

Fig. 8: Length-weighted histogram of azimuthal differences between graben and nearest ridge/scarp

Conclusions

- Graben nearly perpendicular to nearby wrinkle ridges and lobate share the same principal stress component orientations with those ridges and scarps
- Graben nearly parallel to nearby ridges and scarps suggest folding and flexure in back-limbs of those ridges and scarps
- Small shallow graben are young, perhaps <50 Ma for those with <1 m of vertical displacement and relief
- Very good spatial correlation and consistent stress fields suggest the associated wrinkle ridges and lobate scarps were also likely active within the past 50 Ma
- Tectonic deformation in Mare Frigoris did not completely shut off by ~1.2 Ga, and may continue today

References

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