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;
[2]Smithsonian Institution National Air and Space Museum; (nrwilli2@asu.edu)

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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]
- Wrinkle ridges are often associated with mascons (large positive gravity anomalies),[3] yet ridges occur in Mare Frigoris even though a large mascon is not observed
- Lunar Reconnaissance Orbiter Camera (LROC) enables the discovery tectonic landforms at scales not previously imaged[4,5,6]
- Landform morphology[7] and stratigraphic relationships imply a complex history of deformation of 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[6] (Fig. 1c)

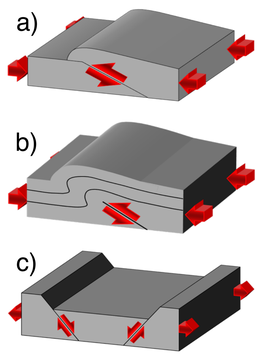

Fig. 1: Block diagrams of a) lobate scarp, b) wrinkle ridge, and c) graben

Data and Methods

- LROC Narrow Angle Camera (NAC) 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
- Determine principal stress relationships for different types of landforms
- Find and measure small crosscut craters and classify degradation state to determine age[11]

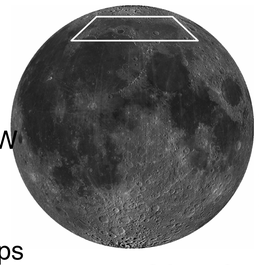

Fig. 2: LROC WAC global context of Mare Frigoris (trapezoid)

Landform Distribution

- Radial and concentric graben in eastern Mare Frigoris similar to pattern in other circular mare mascon basins
- Several landforms parallel to basin boundaries in NW Mare Frigoris, suggest stress localized
- Numerous ridges in southern Mare Frigoris argue against a basin origin by giant slump[12]
- Sets of parallel ridges in western and central Mare Frigoris trend NW/SE inconsistent with typical mascon stress fields; perhaps from Procellarum basin[13]
- ~250 km en echelon series of scarps at eastern end of basin
- Influenced by basin loading, boundary conditions, and/or changes in mechanical properties[3,9,10]

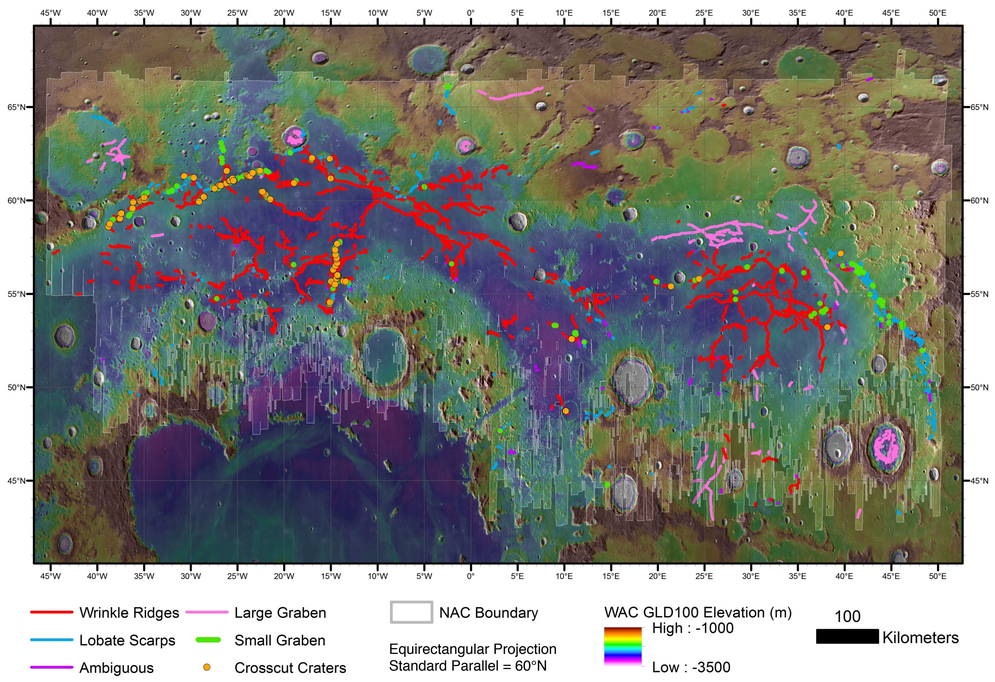

Fig. 3: Tectonic map of Mare Frigoris over LROC WAC DEM[14]

Ridge-Scarp Transitions

- Several complex wrinkle ridges transition to simpler lobate scarps at mare-highland boundary
- Wrinkle ridges previously thought to form shortly after lava emplacement >1.2 Ga globally[2] and >2.6 Ga in Mare Frigoris[12]
- Lobate scarps thought to be <1.0 Ga globally[4,5,7]
- Previous age ranges for ridges and scarps don't overlap[2,4,5]
- Yet at least some displacement on faults across mare-highland boundary was likely concurrent

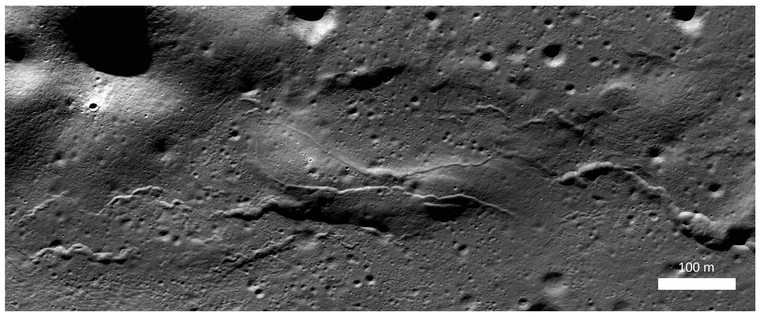

Fig. 4: Complex ridge-scarp transition in SW Mare Frigoris

Crosscut Craters

- Small craters quickly destroyed from impact gardening
- Craters ≤80 m in diameter are ≤1.0 Ga[11]
- Crosscut craters are older than superposed structures
- Wrinkle ridges now observed crosscutting craters as small as 21 m, some still showing bright ejecta
- Calibrated degradation rates for small craters[11] suggest observed crosscut craters as young ~40 Ma (±3x)
- Seismic shaking would decrease retention age, so crosscut craters will appear older and more degraded

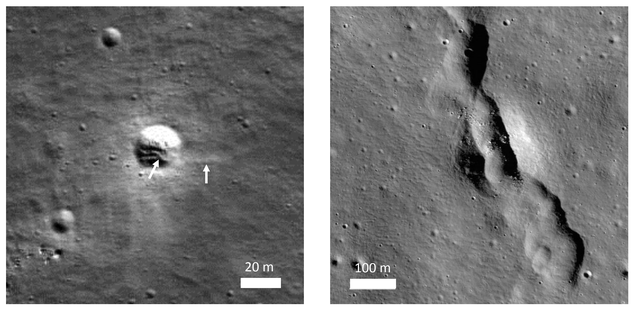

Fig. 5: Examples of small craters crosscut by wrinkle ridges

Small Graben

- Meter-scale graben occur near some ridges/scarps
- Usually either parallel or perpendicular to nearest ridge or scarp
- Inferred principal stresses consistent with flexure or back-limb extension during nearby ridge/scarp growth
- Some have pit crater chains similar to Vitello graben[6]
- Similar meter-scale graben estimated to be <50 Ma[6]
- Suggests associated ridges/scarps active within <50 Ma

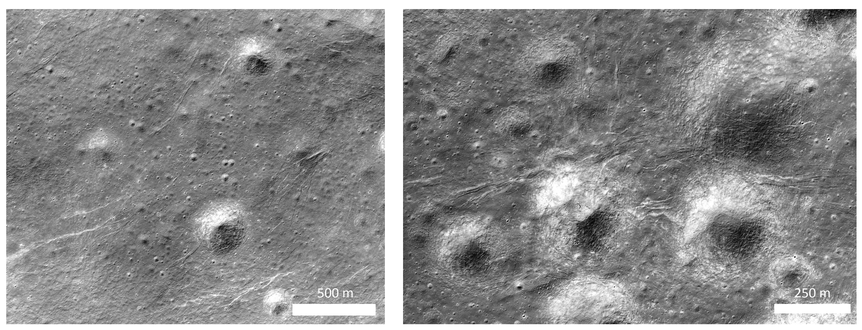

Fig. 6: Small graben near eastern Mare Frigoris

Conclusions

- More recent tectonism in Mare Frigoris than previously identified
- Identified many crisp lobate scarps (<1.0 Ga globally)
- Identified numerous small graben (~50 Ma globally) associated with some scarps and ridges
- Small crosscut craters suggest that some wrinkle ridges were active within last 1.0 Ga and as recently as 40 Ma
- Wrinkle ridges may have accommodated strain from late-stage global radial contraction

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