Timing and Controls of 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 and contractional deformation ended ~1.2 Ga[1-4]
- Wrinkle ridges are often associated with mascons (large positive gravity anomalies),[2,3,5] yet ridges occur in Mare Frigoris even where a large mascon is not observed
- Lunar Reconnaissance Orbiter Camera (LROC) enables the discovery of tectonic landforms at scales not previously imaged[6,7]
- Landform morphology and stratigraphic relationships imply a complex history of deformation of the Moon

Landform Classifications

a. Lobate Scarp: A simple curvilinear, asymmetric hill formed by near-surface fault[5,7-10] (Fig. 1a)

b. Wrinkle Ridge: A complex curvilinear, asymmetric hills formed by folding over a blind fault or faults[2,3,5,11-15] (Fig. 1b)

c. Graben: A trough formed between two normal faults[1,6,11] (Fig. 1c)

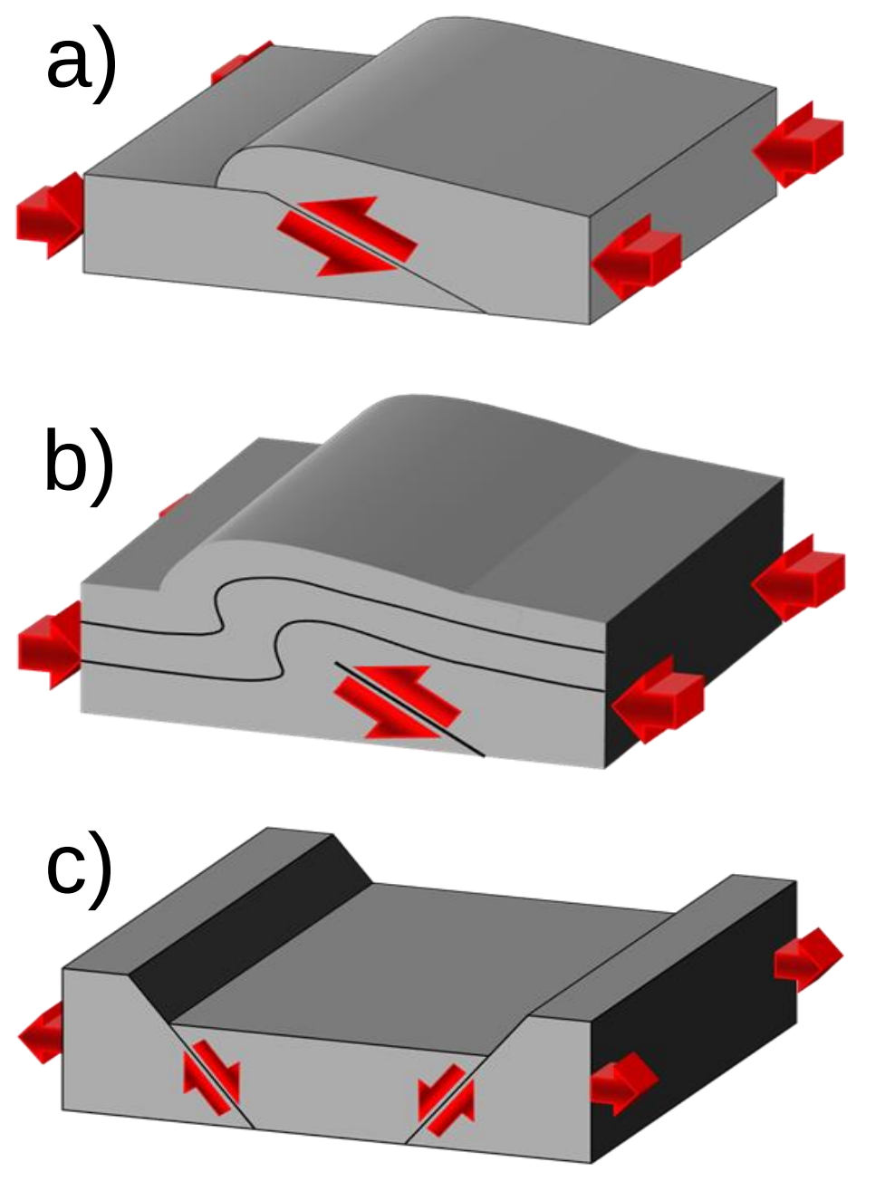

Fig. 1: Block diagrams of a) lobate scarp, b) wrinkle ridge, and c) graben

Data and Methods

- LROC Narrow Angle Camera (NAC) images with meter-scale resolution[16]
- Nearly continuous NAC image coverage from 45°N to 65°N and 45°W to 45°E
- Map tectonic landforms using ArcGIS
- Correlate landform distribution with GRAIL free air gravity anomaly[17]
- Find and measure small crosscut craters and classify degradation state to determine age[18]

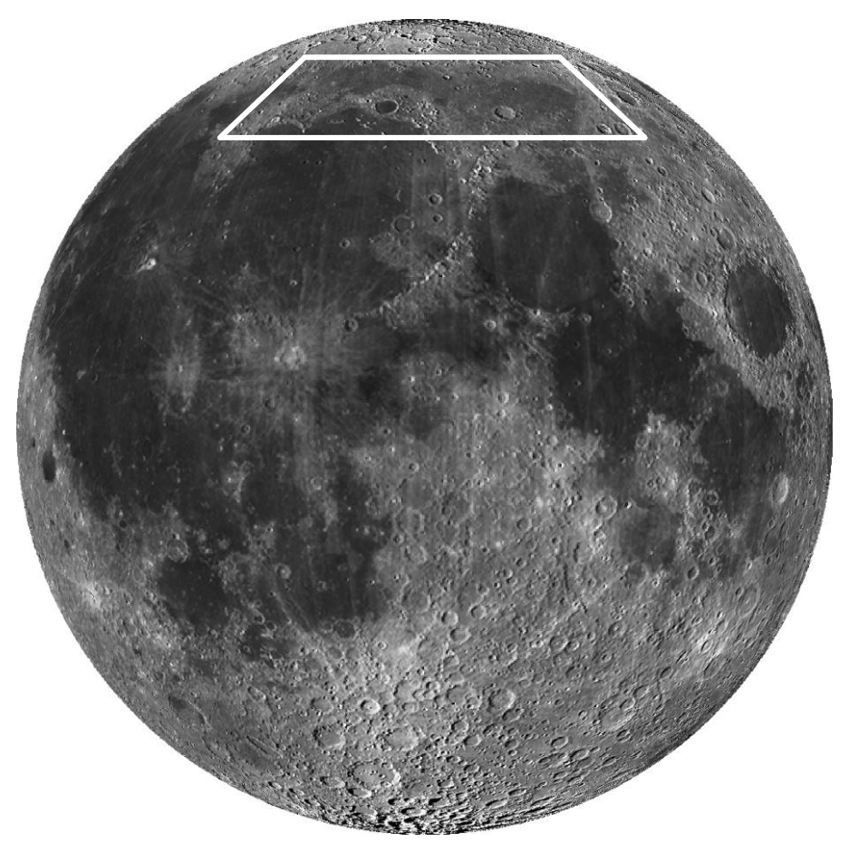

Fig. 2: LROC WAC global context[19] of Mare Frigoris (trapezoid)

Landforms in Western Mare Frigoris

- Parallel set of wrinkle ridges that trend NW/SE (black lines)
  - These ridges are overprinted by numerous large craters (up to hundreds of meters in diameter) and have broadly undulating slopes, indicating a relatively old age
  - Likely formed soon after mare basalt emplacement (2.6-3.8 Ga with most between 3.4-3.8 Ga[20,21])
  - Parallel ridges are not consistent with mascon-induced flexure[2,3] and the negative or very small positive gravity anomaly[17], nor do the askew orientations suggest an Imbrium outer ring collapse[20]
- 2 other clusters of tectonic landforms (white circles) occur independent of the parallel series of ridges
  - These wrinkle ridges and lobate scarps tend to be smaller, often only tens of meters in relief, and have sharp changes in slope, suggesting a relatively young age
  - Many small graben found in the back limbs of these crisp ridges/scarps

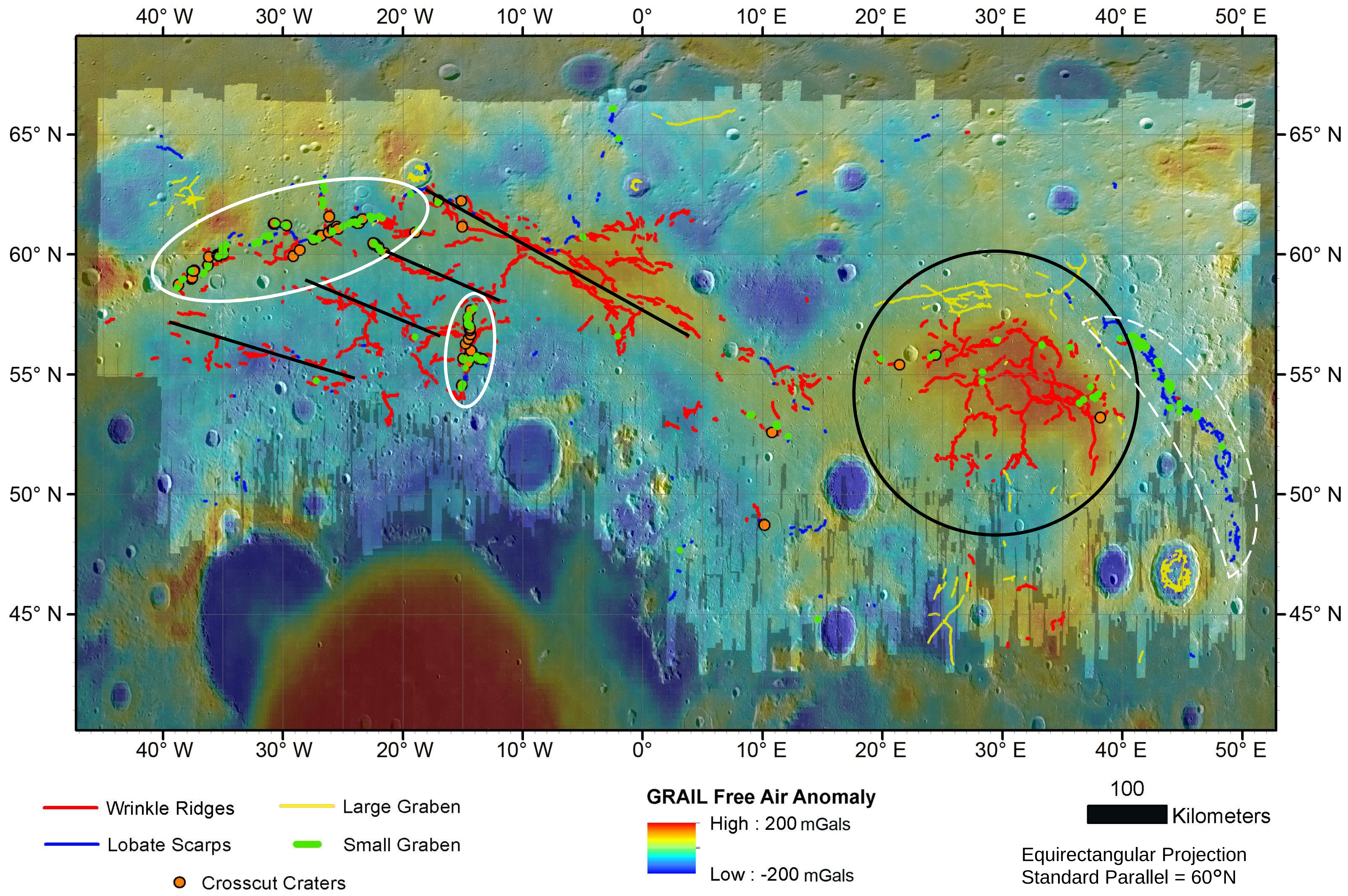

Fig. 3: Tectonic map of Mare Frigoris over GRAIL Free Air Gravity Anomaly[17] and LROC WAC shaded relief[19]

Landforms in Eastern Mare Frigoris

- Polygonal pattern of wrinkle ridges bounded on the north and east sides by large arcuate graben (black circle)
  - These ridges and large graben are overprinted by numerous large craters (up to hundreds of meters in diameter) and have broadly undulating slopes, indicating a relatively old age
  - Likely formed soon after mare basalt emplacement (2.6-3.8 Ga with most between 3.4-3.8 Ga[20,21])
  - Consistent with the traditional mascon-induced flexure[2,3] and correlated with positive gravity anomaly[17]
- Two ~250 km sub-parallel series of en echelon, lobate scarps (dashed white wedge) extends into the highlands from eastern Mare Frigoris, with numerous small-scale graben in the back limbs of scarps
  - Like other lobate scarps globally, this series is inferred to have formed within the last 1.0 Ga as a result of a global compressional stress from cooling and radial contraction of the Moon's interior[5,7,22-24]

Absolute Age Constraints from Small Crosscut Craters

- Small craters quickly destroyed from impact gardening
- Craters ≤80 m in diameter are ≤1.0 Ga[18]
- Wrinkle ridges observed crosscutting at least 70 craters 21-100 m in diameter, a few still showing bright ejecta
- Calibrated degradation rates for small craters[18] suggest observed crosscut craters as young as ~40 Ma (±3x)
- Seismic shaking would decrease retention age, so ages are likely overestimated

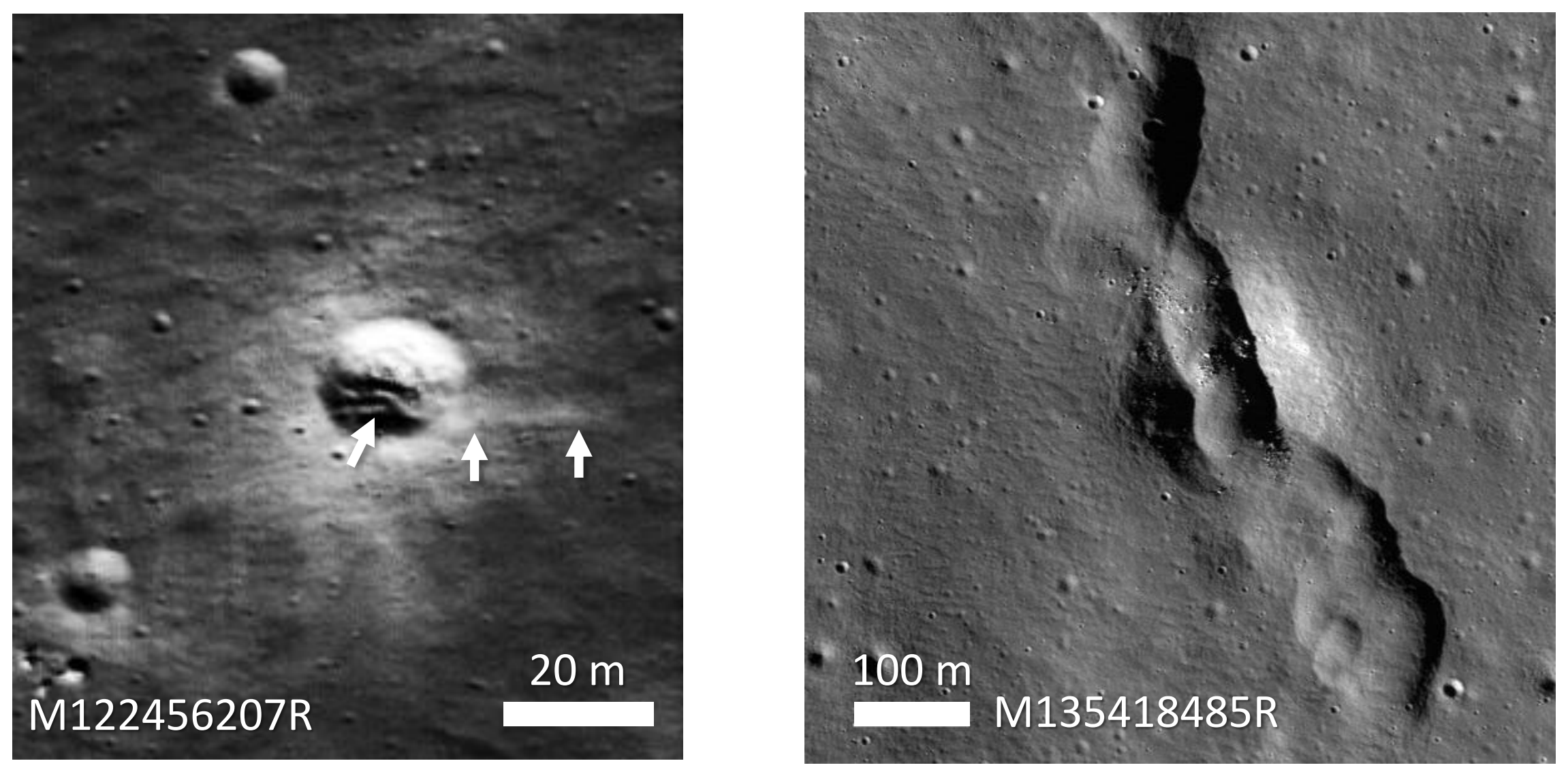

Fig. 4: LROC NAC images of small craters crosscut by wrinkle ridges

Constraints from Small Graben

- Meter-scale graben occur in back limbs of many morphologically crisp ridges/scarps, and usually either parallel or perpendicular to the associated ridge/scarp
- Parallel graben consistent with flexural bending in back limb[6,7,11]
- Perpendicular graben akin to tension gashes[11]
- A few have pit crater chains similar to Vitello graben[6]
- Based on regolith infill rates for shallow troughs, meter-scale graben estimated to be <50 Ma[6,25]
- Suggests associated ridges/scarps active within <50 Ma

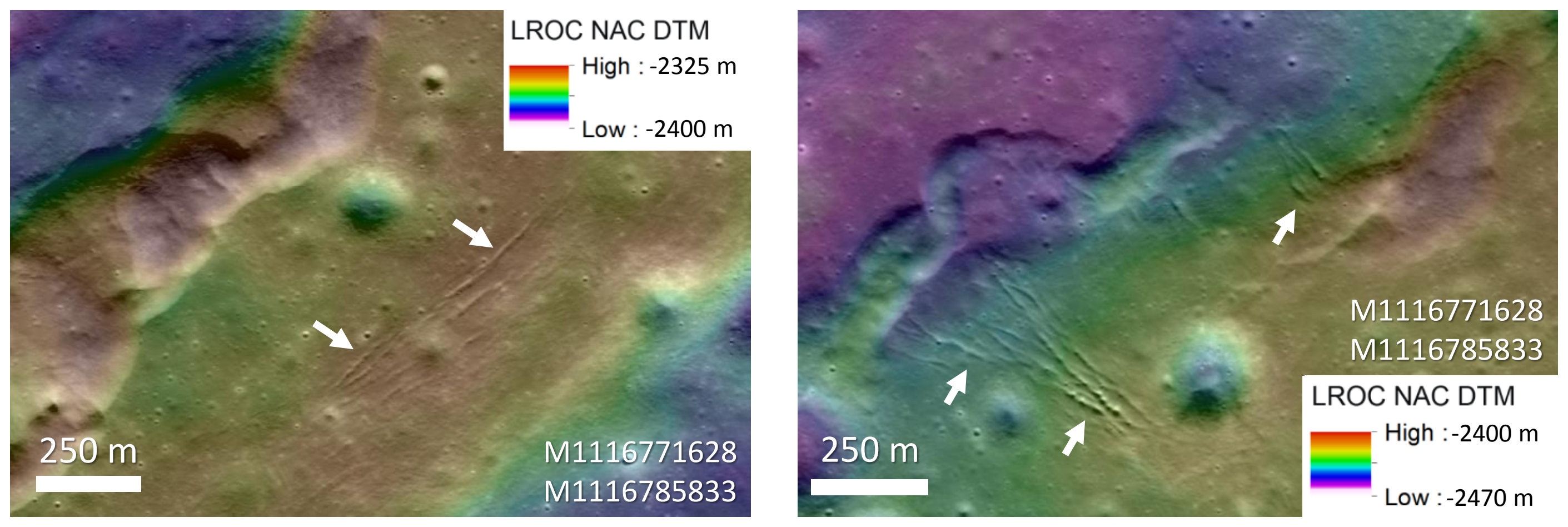

Fig. 5: LROC NAC digital terrain models of small graben (arrows), parallel (left) and perpendicular (right) to their associated wrinkle ridges

Conclusions

- Mare Frigoris is a tectonically diverse region with a complex deformational history
- Older wrinkle ridges and large graben in eastern Mare Frigoris likely formed due to mascon flexure and subsidence
- Older wrinkle ridges in western Mare Frigoris not consistent with mascon flexure and subsidence
- Lobate scarps and perhaps some wrinkle ridges may be due to global contractional stress, were active within the past 1.0 Ga, and might still be active today

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This work is supported by a NASA Earth and Space Science Fellowship, the LRO Project, ASU School of Earth and Space Exploration, and Smithsonian Institution National Air and Space Museum. We would also like to thank Joel Mueting, Megan Henriksen, the LROC team, and the GRAIL team.