EVIDENCE FOR ACTIVE TECTONISM AT THE LUNAR SURFACE.

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Introduction: Nearside basin-related extensional tectonism on the Moon was thought to have ended by about 3.6 billion years ago and mare basin-localized contractional deformation ended by about 1.2 billion years ago [1]. Lunar Reconnaissance Orbiter Camera (LROC) high-resolution images show the Moon's surface in unprecedented detail and have enabled us to find many previously unidentified tectonic landforms, forcing a re-assessment of our views of lunar tectonic history. The morphology and stratigraphic relationships of these newly identified populations of curvilinear tectonic landforms – contractional complex wrinkle ridges and simple lobate scarps, and extensional graben – imply a more intricate and longer-lasting history of deformation. Ongoing global image searches have shown a globally widespread population of young (<1 billion years old) lobate scarps [2,3] and clusters of small graben with widths of a few meters [4,5].

To complement these global image searches with sparser image coverage, we conducted a systematic high-resolution survey with nearly complete (>99%) areal coverage and mapped all types of lunar tectonic landforms (scarps, graben, and ridges). We selected Mare Frigoris as a type area – an ideal location due to its ~60° latitude enabling excellent imaging conditions and abundant, diverse tectonic landforms.

Data and Methods: Two LROC Narrow Angle Cameras (NACs) [6] acquire images with pixel scales ranging from 50 cm to 200 cm across a combined 5 km to 20 km wide swath. We calibrated and map-projected over 12,000 NAC images to form a nearly continuous mosaic over the basin [7]. Wrinkle ridges, lobate scarps, and graben were digitized as line segments in a GIS database. Small (<100 m diameter) craters crosscut by wrinkle ridges were also recorded as points.

Results: In addition to numerous relatively old wrinkle ridges and large (kilometer-width) graben with degraded morphologies superposed by numerous impact craters, we also identified several examples of wrinkle ridges, lobate scarps, and small graben with crisp morphologies and crosscutting relationships that imply young ages (<1 Ga) [2,4]. Particularly in western Mare Frigoris, we identified distinct groups of wrinkle ridges with crisp morphologies that were previously not well resolved. These wrinkle ridges have relatively steep slopes (at least 15°, although measurements are limited by topographic resolution) with abrupt changes in slope. They are superimposed by few large (>400 m diameter) impact craters and crosscut ~70 small (≤100 m diameter) craters (Fig. 1). Several wrinkle ridges transition to lobate scarps across the mare-highland boundary. Additional lobate scarps independent from any wrinkle ridges also occur, including an *en echelon* series of scarps over 300 km in length just east of Mare Frigoris. We also found numerous small graben exclusively associated with crisp wrinkle ridges and lobate scarps that tend to occur either perpendicular or parallel to the nearest scarp or ridge.

Discussion: Lobate scarp ages have previously been constrained to within 1 billion years [2,8] or even 50 million years [3] based on morphologic crispness, lack of superposed craters >400 m in diameter, and crosscutting of craters <100 m in diameter. Small graben have also previously been constrained to having formed within the past few tens or hundreds of Ma due to their still unfilled shallow depths (many are probably only a few meters deep, although measurement is limited by topographic resolution) and regolith infilling rates of 2-8 cm/million years [4,9].

Similar to lobate scarps, the crosscutting of numerous craters ≤100 m in diameter by wrinkle ridges indicates that those ridges have been active within the past 1 billion years (Fig 1) – contrary to previous studies which inferred wrinkle ridges formed shortly after mare basalt emplacement billions of years ago. The smallest crater crosscut by a wrinkle ridge is 21 m in diameter and retains bright ejecta, producing a model age of ~40 million years based on crater size and degradation [10] (Fig. 1A). The small graben, which are exclusively associated with crisp wrinkle ridges and lobate scarps, are interpreted to be secondary flexural effects and imply the host ridges and scarps have been active over the short lifetime of the graben (Fig. 1C) – within tens to hundreds of millions of years. The transition of many wrinkle ridges to lobate scarps at the mare-highland boundary further implies that both landforms were deforming concurrently over the same thrust fault, only with different surface expressions due to a contrast in mechanical properties.

The young age of some wrinkle ridges and the occurrence of ridge-scarp transitions implies that the population of young, crisp wrinkle ridges likely formed through the same mechanism as other young lobate scarps. The global population of lobate scarps implies the surface is under a state of net compression, likely from late-stage global thermal contraction [2,8,11].

The Apollo lunar seismic network recorded 28 shallow "moonquakes" [12]. One, a moment magnitude 2.7 [13] quake recorded on Dec. 6th, 1972, was located at 51°N, 45°E, by [12] with an assumed 100 km depth, although it could have been much closer to the surface. This places the quake to within 65 km (~2°) of the middle of the >300 km long series of lobate scarps to the east of Mare Frigoris. Spatial uncertainty on the reported epicenter is not precise to 1°, but should be accurate within a few degrees and suggests that thrust faults underlying this series of lobate scarps could have been the source of a recorded seismic event.

Energy release from recorded shallow seismic events and observed strain from lobate scarps can be compared to test if the observed young tectonic landforms could have produced the recorded level of shallow seismicity on the Moon. Strain and seismic energy release are empirically related by $M_0 = 2\mu dA\varepsilon$, where M_0 is the geodetic moment, μ is the shear modulus, d is fault depth, A is surface area, and ε is strain [14]. Lobate scarp faults are shallow with depths d of ~1 km [15]. We calculate A as the surface area of a sphere with a radius r of 1737.4 km. The strain ε observed from globally mapped lobate scarps is estimated to be between 0.01% [2] and 0.003% [3]. The shear modulus can be derived from the shear wave velocity and density by $\mu = V_s^2\rho$, where at 1 km depth, seismic shear wave velocity V_s is 2.8 km/s [16] and density ρ is 2550 kg/m^3 [17]. We divide the total geodetic moment by estimates for the lifetime of the lobate scarp population of 1 billion years to as little as 50 million years to obtain estimated annual seismic energy releases of $1.5*10^{14}$ N-m to $3*10^{15}$ N-m for 0.01% strain, and $4.5*10^{13}$ N-m to $9*10^{14}$ N-m for 0.003% strain. These estimated durations of strain release bound the average observed shallow seismic energy release of $6.6*10^{14}$ N-m recorded by Apollo [12,13]. We have not yet observed temporal changes in scarp relief or morphology, although changes due to ongoing activity along thrust faults would be difficult to detect due to the large number of scarps (>3000), relative infrequency of shallow seismic events (4-5/year), and demands on spacecraft resources that limit large-scale repeat image coverage. Nonetheless, strain from the mapped global population of young lobate scarps predicts a level of seismicity and energy release consistent with the shallow moonquakes recorded during Apollo.

Summary: The occurrence of numerous young lobate scarps, small shallow graben, and the new discovery of crisp young wrinkle ridges all indicate that the Moon has been active within the geologically recent past. The crisp morphologies of these landforms and their crosscutting relationships with small craters, coupled with the tantalizing records of shallow seismic sources, strongly suggest that the surface of the Moon is not static as we once thought and is likely still active today.

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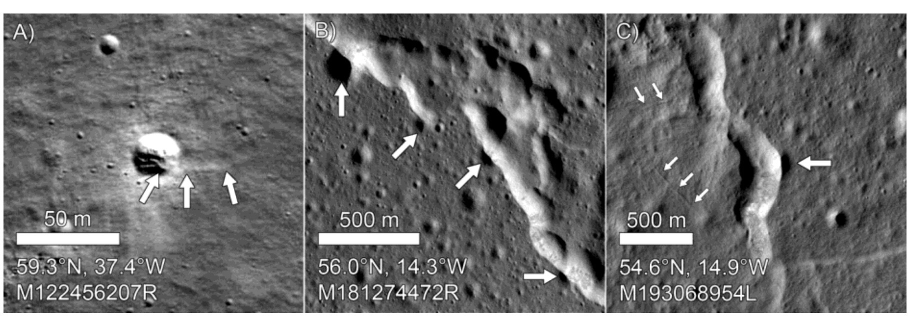

Fig. 1: LROC NAC images showing wrinkle ridges crosscutting small craters. A) A very small secondary wrinkle ridge (arrows) crosscuts a 21 meter diameter crater with bright ejecta. B) A larger wrinkle ridge crosscuts craters (arrows) with diameters of 190 m, 90 m, 100 m, and 80 m from left to right. C) A ~150 m diameter crater (large white arrow) with an indistinct rim almost completely thrust over by a wrinkle ridge with small shallow graben along the ridge flank (small white arrows).