Origin of Neotectonics on the Lunar Nearside

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ABSTRACT

New observations of wrinkle ridges on the nearside maria of the Moon display signs of ongoing ridge modification. In association with the wrinkle ridges we observe an absence of superposed craters, narrow (<30 m) lobate scarps and graben, and thermal anomalies related to exposures of meter-size blocks. Many of these active wrinkle-ridge systems are well beyond the influence of mascon basins and unrelated to any global tectonic pattern. Nevertheless, they spatially correlate with ancient deep-seated dike intrusions on the lunar nearside revealed by gravity data analysis. We propose that this Active Nearside Tectonic System (ANTS) reflects on-going reactivation of an ancient system related to offset antipodal effects from the South-Pole-Aitken Basin.

INTRODUCTION

Tectonic stresses surrounding lunar mare basins have been associated with either extensional graben or contractional wrinkle-ridges. Graben are known to have formed ~3.6 Ga ago (Lucchitta and Watkins, 1978), while wrinkle ridges remained active due to mass loading after the bulk of basaltic lava emplacement within mare-filled impact basins ~3 Ga ago (Solomon and Head, 1979). Other studies, using Lunar Orbiter images documented examples of narrow wrinkle ridges and lobate scarps in the highlands (away from the maria) that cross cut small (<250 m) craters well outside the influence of mass loading (Schultz, 1976; Binder and Gunga, 1985). They concluded that combined with the existence of narrow (<15 m) grabens, much more recent (<~0.1 Ga) contractional and extensional tectonics must be ongoing. The distinction between a narrow lobate scarp and wrinkle ridge is primarily found in the lithology and layering (Howard and Muehlberger, 1973; Schultz, 1976).

High-resolution global coverage by the Lunar Reconnaissance Orbiter Camera (LROC) now establishes that some lobate scarps and wrinkle ridges indicate activity as recently as ~1 Ga ago (Watters et al., 2010; Yue et al., 2017; Williams et al., 2019). Even younger ages have been inferred based on multiple approaches including cross-cutting relations, crater counts and exposed boulders (Schultz, 1976; Clark et al., 2017; van der Bogert et al., 2018; Valantinas et al., 2018, Valantinas and Schultz, 2018; French et al., 2019). Recently, Watters et al. (2019) proposed that the Moon is currently tectonically active, the expression of which lies in young highland thrust faults that would have formed in response to tidal stresses superimposed on global contraction and correlated with seismic activity based on their distribution beyond the maria. Here, we document active tectonic regions of wrinkle ridge assemblages on the lunar nearside maria using LRO (Lunar Reconnaissance Orbiter) global data sets (high-resolution imaging, topography, and thermal infrared) and propose one possible origin for their activity. Most of the wrinkle ridge systems are beyond the influence of mascon loading, and are unrelated to what would be expected solely from global contraction or tidal interactions. Because of their recent formation, we argue that these young ridges are part of an Active Nearside Tectonic System (ANTS).

OBSERVATIONS

The LRO Diviner radiometer data and high-resolution LRO Narrow Angle Camera (NAC) images allow the mapping of over 500 individual wrinkle ridge segments across the lunar nearside (see **Fig. 1a**) with varying degrees of rockiness. The majority of them correlate with deep seated intrusions discovered by the Gravity Recovery and Interior Laboratory (GRAIL) (**Fig. 1b**) (Andrews-Hanna, 2014). The widespread abundance of boulders on wrinkle ridges can be clearly observed in Diviner rock abundance maps (Bandfield et al., 2011). The fractional area covered by lunar boulders is illustrated in **Fig. 2a** for southern Oceanus Procellarum (for the whole nearside see **Fig. DR2**). These rock abundance maps allow characterization of rocky wrinkle ridges into three qualitative categories: low, medium and high (shown in white, orange and red in **Fig. 1a**). To quantify these categories, we select 12 representative wrinkle ridges (see Table 1) and use high-resolution NAC images to measure their boulder patch areal density (total area of the boulder patches along the wrinkle ridge divided by ridge length). The calculated values are: <0.05 for low, ~0.05 – 0.1 for medium and ~0.1 – 0.26 for high rock abundance. There is a bias against ridges exposing highland materials with fewer boulders as well as unresolved by the Diviner instrument (yet still active) smaller scale systems. Boulder-topped ridges do not only occur along the margins of mascon-loaded impact basins (e.g., Serenitatis, Imbrium, Humorum, Crisium), but also in regions with very thin mare fill and very small gravity anomalies (Procellarum, Frigoris). Conversely, boulder-topped ridges are poorly expressed in the mare-filled Nectaris and Imbrium basins that have large Bouguer gravity anomalies indicative of significant mascon loading.

Individual exposed boulder patches vary from a few meters to several hundreds of meters in size and form continuous regions or break into several segments along the wrinkle ridge (**Fig. 2b**). The boulders that comprise these outcrops range in size from just below the resolution limit of the NAC (~0.5 m/px) to ~10 m in diameter. Some patches are covered with a thin regolith layer, whereas others have little to no regolith cover, which seems to indicate ongoing exhumation at very small scales. In some cases, during exhumation the removed regolith accumulates at the bottom of the wrinkle ridge slopes and in between individual outcrops (**DR1**).

Boulder fields in the lunar maria are rare, except along steep walls of craters or rilles due to ongoing mass wasting. Recent impacts also can excavate competent bedrock from beneath the regolith and distribute boulders across the surface (Ghent et al, 2014). In both cases, the continuous impact bombardment gradually breaks down the boulders or buries them beneath mobilized regolith (ejecta or talus). This means that the transition from steep blocky crater walls to relatively smooth gradual slopes is a proxy for relative age. Preservation of blocky crater ejecta, whether recognized in high-resolution images or expressed as nighttime thermal anomalies, can also be used to establish a relative age (e.g., Ghent et al., 2014). Similarly, the occurrence of boulders associated with wrinkle ridges, and the boulder field area along a ridge can be related to recent activity.

We observe boulder patches on both high (20° – 30°) and low-slope (<10°) topography close to the ridges (e.g. **Fig. 2b & 2c**). In some cases, boulder fields occur on top of wrinkle ridges with slopes as low as 2° slopes, rather than as a talus along an abrupt break in slope (**Fig. 2d & 3a, b, c, d & DR3**). Because boulder tracks are uncommon on these regolith piles, most boulders along these ridges are immobile or the local slopes are too low for boulders to roll downhill in response to seismic activity. Small graben on top of some wrinkle ridges require a component of extensional flexure during the recent thrust faulting as the fault reaches the surface (**DR4**).

DISCUSSION

High rock abundances on wrinkle ridges, such as those seen in Diviner and NAC images, require recent tectonic activity. Boulder-size distributions in ejecta around young craters of known ages indicate complete rock destruction in 300 Ma (Basilevsky et al., 2013). This result qualitatively agrees with the general Diviner rock abundance dataset (Ghent et al., 2014). However, on many ridges, the cluster of numerous boulders with minimal accumulations of regolith implies an age < 26 Ma (Basilevsky et al., 2013). The absence of small craters on the boulder patches presented in our study further indicates that these features are geologically young and are forming faster than eroded via meteorite bombardment. Low small crater abundances on select wrinkle ridges with boulder-free ridge areas have been shown to imply surface ages of <10 Ma in Mare Humorum (Valantinas et al., 2018; see also Williams et al., 2019 for ridges in Frigoris).

The origin of boulder-topped ridges requires either that the rate of boulder exposure exceeds the rate of downslope movement and subsequent regolith development or that the regolith be removed by some process. As an example of the former, an elephant-hide texture (Gold, 1972; Schultz, 1976) has been attributed to downslope mass wasting and occurs on numerous ridges (even without exposed boulders). As for regolith removal, the presence of closely packed boulders on flat surfaces implies that the rate of boulder exposure must be high (and ongoing). Otherwise, meteoritic bombardment would have generated a narrow accumulation of debris around each boulder, and boulders would occur in isolation. Boulder fields on flat regions on top of a ridge may represent an exposed bedrock layer. When layered mare basalts buckled during sudden episodes of uplift (or after reaching a critical state), the regolith may have drained into small fractures and voids below. Layered basalts would then be expected since emplacement likely occurred in a succession of thin (~10 m) flows billions of years ago (Schaber et al., 1976). A broken layer from cooling or proto-regolith development likely forms in between basalt flows. The existence of blocky surfaces on low-slope surfaces requires ongoing processes that continuously expose the substrates (French et al., 2019).

Four models have been proposed to account for lunar tectonics: 1) subsidence due to mascon loading within impact basins (Melosh, 1978; Solomon and Head, 1979), 2) orbital recession and despinning (Melosh, 1977; Melosh, 1980), 3) global contraction (Solomon and Chaiken, 1976), and 4) Earth-raised solid body tides (Watters et al., 2015). The first process cannot account for the distribution of active ridges well beyond impact basins and within relatively thin sequences of mare basalts, e.g., Oceanus Procellarum (**Fig. 1a**). In the second model, orbital recession and despinning of a synchronously rotating planet should create global stresses in the lithosphere. This model predicts a distinct fault pattern: contractional N-S striking thrust faults in an area of 30° latitude and longitude at the sub-Earth point and its antipode; a system of strike-slip faults outside of this area; and extensional E-W oriented normal faults at the polar regions. This pattern is inconsistent with the Procellarum system. While despinning alone might account for the global distribution of small lobate scarps in the lunar highlands (Watters et al., 2015), such a mechanism cannot explain the localization and the NW orientation of active wrinkle ridge systems in the SW Procellarum (e.g. Fig. 2). The third model states that global contraction due to cooling of the interior should result in horizontally isotropic compressional stress that produce uniformly distributed thrust faults with random orientations. This pattern is also inconsistent with the orientations of small lobate scarps (Watters et al., 2015) and the distribution of wrinkle ridges shown here. Finally, diurnal tidal stresses due to Earth-generated during lunar librations are too low (Weber et al., 2009). Watters et al. (2019) recently proposed that a mechanism combining orbital recession and de-spinning with Earth-generated tides could account for the distribution of shallow moonquakes. Nonetheless, this mechanism alone also cannot account for the ridge/graben system of Procellarum.

Active ridge formation beyond the effects of impact basin loading (see **DR5**) requires a mechanism other than mascon-controlled sagging. The Active Nearside Tectonic System, ANTS (**Fig. 1b)** could be the surface expression of ongoing reactivated faults, which spatially correlate with the deep seated ancient intrusions discovered by GRAIL (Andrews-Hanna et al., 2014). That study proposed that these intrusions could have been responsible for PKT volcanism ~3.51 Ga ago, but were closed off due to load-induced flexure and contraction of the upper lithosphere. According to the model, these intrusions formed long ago and are no longer active therefore it does not explain the origin of recent and ongoing deformation of wrinkle ridges following the ANTS. While those authors also suggested that wrinkle ridges may be surface manifestations of these ancient intrusions, there was no explanation for the disparity in ages. During a period of global extension (in response to increased radiogenic heating around 4 Ga), however, intrusions would have followed pre-existing structural weaknesses and would have controlled the conduits expressed by the source regions of sinuous rilles located on the crests of wrinkle ridges (e.g., Herigonius region in southern Procellarum), unrelated to basin loading by mascons. In fact, the level of ongoing tectonic activity along ridges expressed by blocky exposures within Procellarum and Frigoris, where mascon loading is absent, is comparable to mascon-loaded regions of Serenitatis and Humorum.

Two underlying processes could be controlling current wrinkle ridge activity. First, the nearside lunar lithosphere could still be adjusting to an ancient "Procellarum Basin" that shaped the lunar nearside and resulted in a radial/concentric tectonic pattern and nearside geochemical anomalies (Cadogan, 1974; Whitaker, 1981). However, Andrews-Hanna et al. (2014) argue that the GRAIL geophysical record is inconsistent with such a basin. Alternatively, Schultz and Crawford (2011) proposed that nearside tectonics reflect much later reactivation of faults related to deep transient stresses generated by the South-Pole-Aitken (SPA) basin about 4.3 Ga. In this model, the proposed trajectory of the SPA impactor is oblique, based on the shape of its relict rim massifs, asymmetric exposure of KREEP materials, and expected collapse during a large oblique impact. Both experiments and shock-physics models indicated antipodal failure occurs due to extension conditions deep within a spherical body. Introduction of thermal conditions and self-gravity into the model revealed that antipodal extensional failure extended nearly to the core/mantle interface, while deep-seated failure occurred within the mantle and crust. Rather than occurring directly opposite the center of the SPA, the predicted damage is expected to be opposite of the region of first contact by the SPA impactor. This region corresponds to a broad, low-relief dome southwest of the Imbrium basin that centers on a system of radial and concentric graben and wrinkle ridges (e.g. **DR6**). Schultz and Crawford (2011) postulate that the nearside concentration of mare basalts, geochemical anomalies and tectonic systems were all controlled by the offset-antipodal effects of SPA.

Boulder capped wrinkle ridge systems observed as thermal anomalies in Diviner data and as morphologic evidence in LROC NAC images (see also French et al., 2019) require a currently active tectonic process to explain their origin in the lunar nearside maria. Orientations and distributions of these active ridges do not match the ones predicted by other mechanisms (e.g. despinning, global contraction and Earth-raised solid body tides), but match with GRAIL intrusions and SPA-induced damage features. Activity could be sustained by continued fault adjustments over these deep-seated intrusions. The Apollo seismometers may have recorded signs of these adjustments within currently occurring moonquakes (Nakamura et al., 1982). While shallow moonquakes may correlate with the combined effects of Earth-generated tides and global contraction (Watters et al., 2019), deep moonquakes require a different origin. Zhao et al. (2012)

note that deep nearside moonquakes may reflect mantle heterogeneity, and Frolich and Nakamura (2009) argue that deep moonquakes occur in regions where brittle fracture is not possible. Hence, they may reflect movement of liquid phases or partial melts in the mantle that fill cracks or are tidally pumped into properly oriented shear zones. These deep moonquakes could be related to conditions initiated by the SPA collision.

Wrinkle ridges should thus be a target of interest for future exploration of lunar seismicity and sample collection. Exposed boulders on wrinkle ridges contain the original *in-situ* bedrock material of lunar basalts, which was not available for Apollo astronauts. The identification of young tectonic features indicative of ongoing moonquakes (Kumar et al., 2016; Watters et al., 2019) speak to the need for a global geophysical network (NRC, 2011). This would increase our understanding of the intensity, frequency and risks of the current seismic activity.

FIGURE CAPTIONS

Figure 1. A global map of lunar wrinkle ridge segments exhibiting boulder abundance distributions, which make up the Active Nearside Tectonic System (ANTS). (a) LRO Wide Angle Camera (WAC) mosaic. Circle denotes the location of Fig 2 and the square the location of Fig 3. Abundances are marked from red to white in decreasing concentration. (b) GRAIL gravity gradients (Andrews-Hanna et al., 2014) in units of Eötvös (1 E= $10^{-9}s^{-2}$) with wrinkle ridges from this study overlain as black lines.

Figure 2. (a) Wrinkle ridge with very high rock abundances in southern Oceanus Procellarum. (b) Close up of the same ridge. (c) Rocky area on top of the ridge. (d) Small boulder patches outside of the ridge (Coords: -11.27, -37.92). NAC frame M160200185RC.

Figure 3. (a) LRO NAC image showing a wrinkle ridge segment in Oceanus Procellarum. (b) LROC NAC Digital Terrain Model (DTM) of the same area. (c) Slope profile of a boulder field, denoted by the A' to B' transect in (a) and (b). (d) Elevation profile of a boulder field, denoted by the A' to B' transect in (a) and (b). Boulder fields are commonly observed on slopes of wrinkle ridges but also can form on relatively flat terrains (slopes <10 degrees). Note small boulder patches on the southeastern part of the image, which appear to be on very gentle slopes.

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