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Small-scale lunar graben: Distribution, dimensions, and formation processes

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ABSTRACT

The Lunar Reconnaissance Orbiter Camera (LROC) is the first instrument to provide widespread coverage with a range of incidence angles at the resolution required to detect small-scale landforms. A sample ($n = 238$) of globally distributed, small-scale graben average 26 m wide and 179 m long. When dividing the population into those located within mare and highland regions, we observe that graben located within mare tend to be narrower, shorter, and more irregularly spaced than those in highland terrane. For graben associated with contractional landforms, those in mare are smaller in width and length than those in highlands; the same is true for graben independent of contractional landforms. Assuming a simple geometry, widths of mare graben associated with scarps or ridges are used to estimate the minimum depth range to a mechanical discontinuity (e.g., base of the regolith) resulting in values of ~4–48 m. These values are similar to the ranges estimated for regolith thickness from previous workers using Apollo 14 seismic data (3.9–8.5 m), crater counting techniques (8–33 m), crater morphology techniques (2.5–9 m), and crater blockiness (8–31 m). Widths of highland graben yield minimum depths of faulting of 209–296 m. While this range agrees well with models for regolith production (an older surface will have thicker regolith), this estimate likely does not represent the thickness of a mechanical unit due to the fragmented nature of the highland crust (it does not provide a defining boundary between bedrock and regolith). Spacing of mare graben not associated with contractional landforms is used to estimate maximum local mare unit thickness for two graben groups: 190 m for Posidonius and 296 m for Vitello. Maximum graben ages range from late Eratosthenian to early Copernican based on superposed and crosscut crater ages with a group of graben deforming ejecta from Copernicus crater. Data presented here provide further evidence of a globally distributed, young, small-scale graben population that has formed as a result of localized extension either from flexural bending or dilation due to contractional faulting or volcanic uplift, indicating a significant level of recent geologic activity.

1. Introduction

Large-scale linear and arcuate rilles or graben and contractional wrinkle ridges on the Moon were first reported within and around mare basins (Gilbert, 1893; Arthur, 1962). The formation and spatial distribution of these tectonic features is attributed to basin-localized stresses related to load-induced flexure and subsidence (Maxwell et al., 1975; Wilhelms, 1987). Presently, the Lunar Reconnaissance Orbiter Camera (LROC) is providing unprecedented coverage of the lunar surface, with Narrow Angle Camera (NAC) image pixel scales of 0.5–2 m, and Wide Angle Camera (WAC) image pixel scales of 100–400 m (Robinson et al., 2010). The meter-scale pixels and range of incidence angles (~30–80°) are necessary to identify and characterize small tectonic features. Such features include lobate scarps, defined as linear to arcuate surface expressions of low-angle thrust faults (Howard and Muehlberger, 1973; Binder and Gunga, 1985; Watters and Johnson, 2010; Watters et al., 2010) with lengths of hundreds of meters to kilometers (Banks et al., 2012). Other such features are graben, characterized by narrow, flat-floored depressions with lengths that exceed widths and bounded by two steeply dipping antithetic normal faults (e.g., Golombek, 1979; McGill and Stromquist, 1979). Typical dimensions of small-scale graben range from tens to hundreds of meters wide and up to a couple kilometers in length, making these a distinct population from the basin-related graben.

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Small-scale graben were noted by Watters et al. (2010) in association with the Lee-Lincoln scarp and are oriented subparallel and perpendicular to the strike of the scarp. The formation of these graben was interpreted as a result of regolith and bedrock extension due to flexural bending during formation of the Lee-Lincoln scarp (Watters et al., 2012a). Additional small-scale graben have been discovered, with estimated ages on the order of 50 Ma (Watters et al., 2012a) based on crosscutting relationships with small-diameter impact craters, lack of superposed craters, and infilling rates of shallow depressions, indicating recent extension on a body that is globally contracting.

Lunar Orbiter Laser Altimeter (LOLA) profiles (Smith et al., 2010) of Vitello graben show that they occur along a topographic rise or ridge-crest on the flank of a wrinkle ridge, but it is questionable whether the formation of these graben is connected with tectonic activity related to the ridge (Watters et al., 2012a). If some small-scale graben are not a result of overall contraction and are unrelated to scarp or ridge formation, an alternative hypothesis that involves uplift and flexural bending due to a subsurface laccolith was suggested by Watters et al. (2012a). If this is true, then the apparent young age of the graben would require Copernican-aged intrusive volcanism on the Moon, but previous workers have suggested this activity ceased much earlier (see review by Shearer et al., 2006). However, localized Copernican-aged extrusive volcanism, such as the Ina-D feature, has been discovered (Schultz et al., 2006; Braden et al., 2014). Crater counts on a newly identified population ($n = 75$) of Ina-style features indicate absolute model ages between 20 and 60 Ma, and equilibrium crater populations suggest ages less than 100 Ma (Braden et al., 2014).

Graben are observed on all of the terrestrial planets and many icy satellites (Schultz et al., 2010; Watters et al., 2010) and are generally larger (hundreds of meters up to tens of kilometers in width; Watters and Schultz, 2010) than the small-scale lunar graben. On Earth, studies have shown that graben form in both extensional and compressional tectonic environments (McGill and Stromquist, 1979; Gordon and Lewis, 1980; Campbell and Bentley, 1981; Philip and Meghraoui, 1983; Schlische et al., 1996) and in association with volcanism (Rubin and Pollard, 1988). On Mercury, graben are almost exclusively confined to the interiors of impact basins and volcanic smooth plains that have buried basins and craters (i.e., ghost craters) (Watters et al., 2009, 2012b; Prockter et al., 2010). Their formation is generally attributed to uplift due to load-induced stresses (basin exterior annular loading), lateral crustal flow, or thermal contraction of thick cooling units (Melosh and McKinnon, 1988; Watters et al., 2005, 2009, 2012b; Kennedy et al., 2008; Head et al., 2009; Freed et al., 2012). Venusian graben along fracture zones may be linked to mantle dynamics (Solomon et al., 1991) or gravitational spreading (Phillips and Hansen, 1994), while graben observed around coronae and chasmata are likely due to load-induced stresses (upwelling or loading of magmatic material) or as dilation over dike intrusions (Hansen and Phillips, 1993; Ernst et al., 2003; Krassilnikov and Head, 2003; Grindrod et al., 2005). Martian graben are thought to originate either as a consequence of tectonic rifting, dilation over dike intrusions, or from load-induced stresses (i.e., Tharsis) (Banerdt et al., 1992; Wilson and Head, 2002; Cailleau et al., 2003; Mège et al., 2003; Schultz et al., 2004; Golombek and Phillips, 2010).

This paper seeks to characterize the spatial distribution and dimensions of small-scale lunar graben. Graben dimensions and spacing are used to provide constraints on depth of faulting and faulted layer thickness. We make comparisons between mare and highlands graben, as well as graben associated and unassociated with lobate scarps or wrinkle ridges, in order to illuminate trends between different groups. Graben age is estimated using the principles of superposition and crosscutting relationships. Finally, we present a few examples of graben likely formed by different mechanisms and relate them to current understanding of recent surface activity on the Moon.

2. Data and methods

Graben were found by searching LROC NAC images, which have 100% coverage from ±60° to ±90° latitude and over 50% coverage from −45° to 45° latitude with incidence angles favorable for morphologic interpretations (45–80°). A random sample from the current population was selected for this study, while ensuring that the sample had a good spatial distribution.

Processing of LROC NAC images (radiometric calibration, map projection, mosaicking) was performed using the United States Geological Survey Integrated Software for Imagers and Spectrometers (ISIS) software package (Anderson et al., 2004). Graben length, maximum width, and spacing were measured directly from NAC images using ISIS. Measurement uncertainties are resolution dependent and vary with the scale of the graben but are conservatively on the order of two pixels, resulting in uncertainties less than 10% for graben lengths and less than 33% for graben widths. A Wide Angle Camera (WAC) 100 m global mosaic (Speyerer et al., 2011) was used for regional coverage.

Lengths and maximum widths of 238 individual graben are measured within 23 groups, where a group is defined as a geographically isolated system of graben. A set of graben represents those with similar orientation within a given group, and a group can have multiple sets of graben. The orientation for each graben is visually estimated with uncertainties of roughly ±5°. Fault segment lengths are measured for faults that grew by en echelon stepping. Only troughs with two observable bounded sides are measured and used for statistical analysis (half graben are not included). Although some graben are found within large impact basins dated Imbrian or older (Losiak et al., 2009), the graben are considered to have formed in the respective unit (mare or highlands) in which the crater is located. For the purposes of clarity and brevity, when we refer to 'graben width' later in the paper, we are describing the maximum graben width.

Topographic data for Posidonius are derived from WAC stereo models (GLD100) and have a mean vertical accuracy of better than 10 m for the nearside maria and better than 20 m over the entire dataset (Scholten et al., 2012). Topographic data for Copernicus were derived from NAC stereo pairs with a precision error of 1.86 m and a root mean square (RMS) error with LOLA elevations (nine different orbital tracks) of 1.35 m. Topography is used to determine if graben are related to the structural relief of the lobate scarp or wrinkle ridge. If topographic data are not available, scarp association is determined by relative location (i.e., in the backscarp terrain) and distance from the scarp face (up to several kilometers). Graben associated with wrinkle ridge formation may be located on the ridge (formed by flexural bending) or along its flanks (formed by dilation). Also, if graben are bounded by ridges and are located within the crossover area between ridge segments, they are considered related to the wrinkle ridge (formed by dilation).

3. Results

3.1. Spatial distribution and orientation

We find small-scale graben distributed globally (Fig. 1), consistently near lobate scarps (in the highlands) and wrinkle ridges (in the maria). However, a couple of groups – Copernicus and Posidonius – are not located within close proximity (∼few kilometers) to a scarp or ridge. The Vitello, Virtanen, and Posidonius graben occur along topographic rises that do not appear to be connected to any