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Recent extensional tectonics on the Moon revealed by the Lunar Reconnaissance Orbiter Camera

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Large-scale expressions of lunar tectonics—contractional wrinkle ridges and extensional rilles or graben—are directly related to stresses induced by mare basalt-filled basins[1,2]. Basin-related extensional tectonic activity ceased about 3.6 Gyr ago, whereas contractional tectonics continued until about 1.2 Gyr ago[2]. In the lunar highlands, relatively young contractional lobate scarps, less than 1 Gyr in age, were first identified in Apollo-era photographs[3]. However, no evidence of extensional landforms was found beyond the influence of mare basalt-filled basins and floor-fractured craters. Here we identify previously undetected small-scale graben in the farside highlands and in the mare basalts in images from the Lunar Reconnaissance Orbiter Camera. Crosscut impact craters with diameters as small as about 10 m, a lack of superposed craters, and graben depths as shallow as ∼1 m suggest these pristine-appearing graben are less than 50 Myr old. Thus, the young graben indicate recent extensional tectonic activity on the Moon where extensional stresses locally exceeded compressional stresses. We propose that these findings may be inconsistent with a totally molten early Moon, given that thermal history models for this scenario predict a high level of late-stage compressional stress[4–6] that might be expected to completely suppress the formation of graben.

Basin-localized lunar tectonics resulted in both basin-radial and basin-concentric graben and wrinkle ridges. Typically, basin-localized graben are found near basin margins and in the adjacent highlands whereas wrinkle ridges are restricted to the basin interior (ref. 2, plate 6) (Supplementary Note S1). The dominant contractional tectonic landform found outside of mare basins are lobate scarps[2,3]. These small-scale scarps are thought to be the surface expression of thrust faults[3]. Crosscutting relations with Copernican-age, small-diameter impact craters indicate the lobate scarps are relatively young, less than 1 Gyr old (ref. 3).

Small-scale graben revealed in 0.5–2.0 m/pixel Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images are often associated with lobate scarps (Supplementary Note S2). These graben were first found in the back-limb area of the Lee–Lincoln scarp[3,7] (∼20.3° N, 30.5° E) and are spatially correlated with a narrow rise along the crest of the scarp face and the elevated back-limb terrain[3]. Newly detected graben found in the back-limb terrain of the Madler scarp (∼10.8° S, 31.8° E; Supplementary Fig. S1) are located ∼2.5 km from the scarp face (Fig. 1a). The orientation of these graben is roughly perpendicular to the trend of the scarp. The dimensions of the graben vary, with the largest being ∼40 m wide and ∼500 m long. Graben in the back-limb area of the Pasteur scarp (∼8.6° S, 100.6° E; Supplementary Fig. S1) are ∼1.2 km from the scarp face (Fig. 1b). Unlike the Madler graben, the orientation of the Pasteur graben are subparallel to the scarp and extend for ∼1.5 km, with the largest ∼300 m in length and 20–30 m wide (Supplementary Note S3).

Lunar graben not located in the proximal back-limb terrain of lobate scarps have also been revealed in LROC NAC images. Graben found in the floor of Seares crater (∼74.7° N, 148.0° E; Supplementary Fig. S1) occur in the inter-scarp area of a cluster of seven lobate scarps (Fig. 1c). These graben are found over an area $<1\ \text{km}^2$ and have dimensions comparable to those in back-scarp terrain, ∼150–250 m in length and with maximum widths of ∼10–30 m. A NAC stereo-derived digital terrain model[8] reveals that the Seares graben occur in a relatively low-lying inter-scarp area.

A series of graben deform mare basalts that occupy a valley ∼20 km wide (∼33.1° S, 323° E; Supplementary Fig. S1) south of Mare Humorum and the Vitello impact crater (Fig. 2a,b). Here the graben flank a wrinkle ridge that is part of a ridge–lobate scarp transition (Fig. 2a), a structure in which the highland lobate scarp transitions into a wrinkle ridge where it crosses the contact with the mare basalts (see ref. 2). The Vitello graben are E–W to NE–SW oriented and extend over ∼3.5 km (Fig. 2b). These graben exhibit en echelon steps, indicating that faults most probably grew by segment linkage (see ref. 9). Lengths of the Vitello graben vary from tens of metres up to ∼600 m, with a maximum width of ∼15 m. Unlike the graben associated with lobate scarps, these graben occur over a larger area, and many are regularly spaced, separated by ∼100–200 m. Pit chains occur within some of the Vitello graben (Fig. 2c). These pits are circular to elliptical in shape and are up to ∼15 m in diameter, spanning the full width of the graben. Such depressions are commonly associated with extensional landforms on solid bodies in the Solar System and are thought to be the results of collapse of material into subsurface voids from dilation accompanying faulting or explosive outgassing following magma emplacement at shallow depth[10,11]. Lunar Orbiter Laser Altimeter (LOLA) profiles across the graben show their location is spatially correlated with a topographic rise that has a maximum relief of ∼16 m (Fig. 2b). Although many of the Vitello graben are <1 km from the wrinkle ridge, the topographic rise is not directly associated with the structural relief of the wrinkle ridge.

Of the newly detected graben, the largest are located in the farside highlands (∼17.8° N, 180.8° E; Supplementary Fig. S1), about 130 km northeast of the Virtanen impact crater. The NW-SE orientated Virtanen graben extend over an area ∼11 km long

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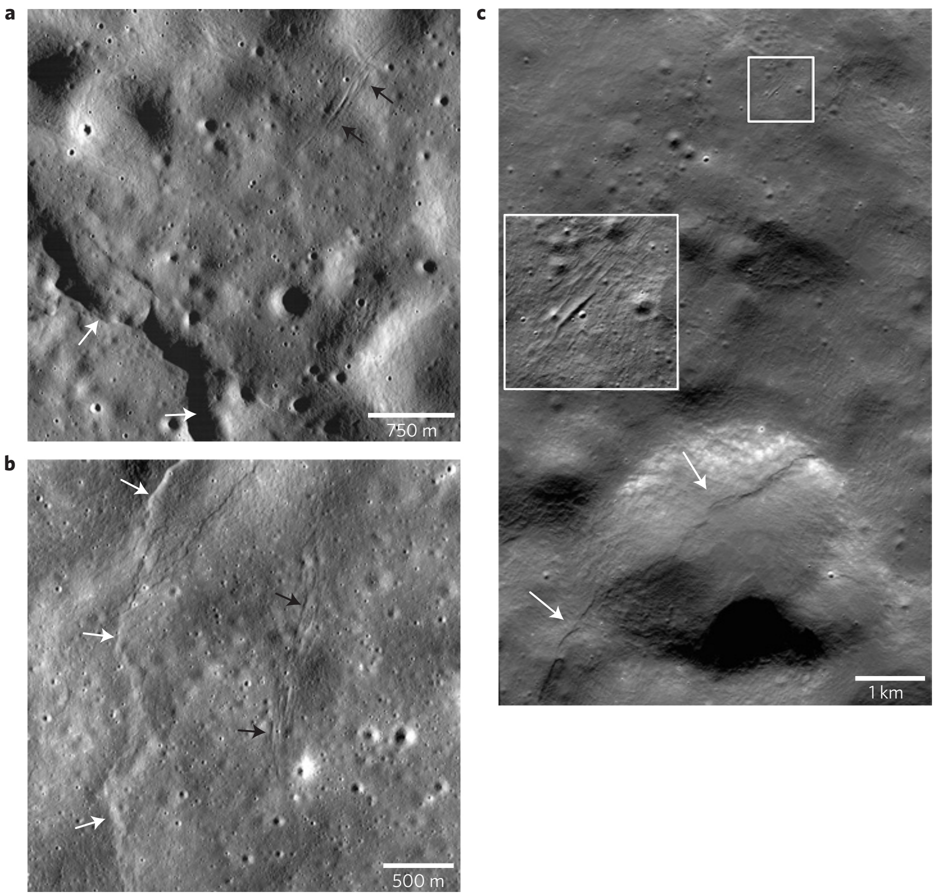

Figure 1 | Small-scale graben with lobate scarps. a, Madler scarp, in northern Mare Nectaris (∼10.8° S, 31.8° E), has graben (black arrows) oriented perpendicular to the scarp face (white arrows). LROC NAC frames M116107010L and M116107010R. **b**, Graben (black arrows) associated with the highland Pasteur scarp (∼8.6° S, 100.6° E) are oriented parallel to the scarp face (white arrows). LROC NAC frame M103854211L. **c**, Graben on the floor of Seares crater (∼74.7° N, 148.0° E). The graben (inset) are located in the inter-scarp area of a cluster of lobate scarps (one indicated by white arrows). Width of the inset box is ∼900 m. LROC NAC frames M156626383L and M156626383R.

(Fig. 3a) and up to ∼1.6 km wide. The largest graben has a maximum width of ∼500 m (Fig. 3b). The Vitello graben and those associated with lobate scarps can be described as simple graben, structures characterized by individual troughs with lengths that greatly exceed widths. The Virtanen graben are complex, consisting of closely spaced and overlapping segments that exhibit complex fault linkages. Bounding faults of the graben are often segmented, and in some cases individual fault segments are linked by relay ramps, downward-sloping landforms bounded by two adjacent, overlapping normal faults (Fig. 3c). This graben complex resembles those seen in larger-scale planetary rift systems[9] and is unlike any found previously on the Moon. NAC stereo-derived topography shows that the graben occur on the slopes, and along the crest, of a ridge-like rise with several hundred metres of relief (Supplementary Note S4). The depths of the graben vary from ∼17 m to ∼1 m (Supplementary Fig. S4). The graben and rise are located on the floor of a heavily degraded, pre-Nectarian basin ∼580 km in diameter (Supplementary Fig. S1). A lobate scarp, one of a cluster of scarps with orientations subparallel to the graben, occurs ∼8 km south of the Virtanen graben (Fig. 3a). LOLA profiles crossing the scarp show that it has ∼30 m of relief. However, the large distance (8 km) between the graben and the scarp makes a direct link problematic.

The overall crisp morphology and a lack of superposed, relatively large-diameter (>400 m) impact craters (see ref. 12) show that the newly discovered graben are young. The largest impact crater superimposed on the Virtanen graben is ∼180 m in diameter. Craters with diameters down to ∼10 m are deformed by graben (Fig. 4a). Similarly, the Vitello graben crosscut craters with diameters as large as ∼250 m and as small as ∼7 m (Fig. 4b). Lunar craters with diameters of 50–100 m or smaller, and fresh craters up to 400 m in diameter are Copernican in age[12], estimated to be ∼800 ± 15 Myr at most (defined by the age of Copernicus crater)[13]. Shallow depressions in the lunar regolith are estimated to fill in at a rate of 5 ± 3 cm Myr^{-1}, based on analysis of boulder tracks[14]. At this rate of in-filling, graben formed in regolith with depths of ∼1 m would be expected to disappear in ∼12.5–50 Myr. Thus, the small-scale graben probably formed less than 50 Myr ago. The presence of shallow, small-scale graben in the back-limbs of lobate scarps is consistent with the interpretation that lobate scarps are young tectonic landforms[3].

Crater density ages of the mare basalts indicate that no large-scale mare units younger than ∼3.6 ± 0.2 Gyr are crosscut by graben[15–18], suggesting that mare basin-related extension ceased not long after the end of the period of the late heavy bombardment (∼3.8 Gyr). The cessation of basin-related flexural extension due to loading by mare basalts may be the result of the superposition of compressional stresses from global contraction, marking a stage in the Moon's thermal history at which interior cooling resulted in a shift from net expansion to net contraction[19,20]. The level of compressional stresses from the observed population of young thrust faults is estimated to be ∼10 MPa (ref. 3). This estimate is consistent with thermal models for an early Moon with an initially hot exterior and magma ocean that predict a relatively

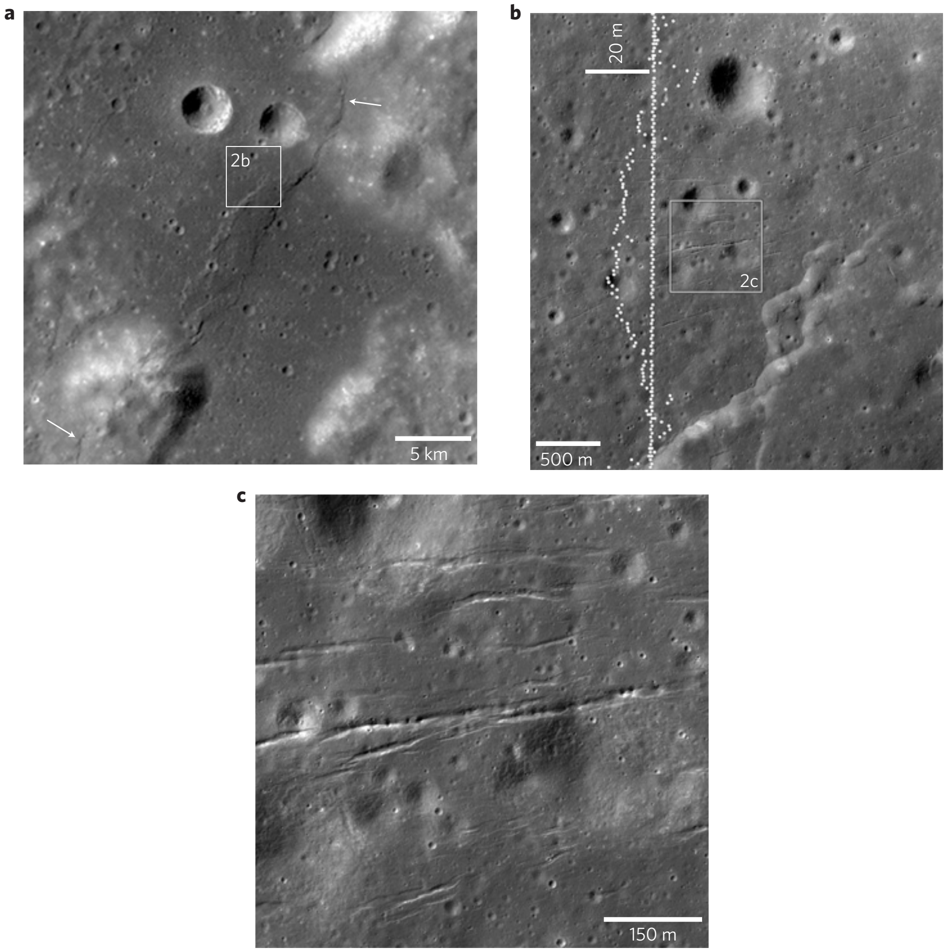

Figure 2 | Vitello graben in nearside mare basalts (∼33.1° S, 323° E). a, The graben occur in mare basalts south of Mare Humorum, near a wrinkle ridge that is part of a lobate scarp–wrinkle ridge transition (white arrows). LROC Wide Angle Camera (WAC) mosaic. **b**, The Vitello graben are regularly spaced and LOLA topography shows they formed on a low-relief, topographic rise (white dots are elevations plotted along the LOLA ground track, scale bar for elevation plot shown in upper left). LROC NAC image frame M104756463R, location is shown in **a**. **c**, Graben exhibit en echelon steps and pit crater chains. LROC NAC frame M104756463R, location is shown in **b**.

low level of global compressional stress, 100 MPa or less since the end of the late heavy bombardment[19–21]. The presence of relatively young graben on the Moon shows localized extension in a dominantly contractional regime. Because extensional stresses must locally exceed the compressional stresses for normal faults to form, these graben may have implications for the current state of stress if the near-surface crustal materials they deform were not isolated from the background stresses or the background stresses were not relaxed. The total extensional stress necessary to form shallow-depth normal faults (in the presence of a ∼10 MPa background compressional stress) is estimated to be on the order of 12 MPa (Supplementary Note S5). Thus, the localized formation of small-scale graben may be consistent with a recent low level of global compressional stress. Higher levels of late-stage compressional stress predicted in nearly, or totally molten, early-Moon thermal models (up to 350 MPa; refs 4–6) are expected to largely or completely suppress normal faulting. It has been suggested that the small-scale lunar thrust fault scarps could result from high levels of compressional stress if significant contractional strain is accommodated by the near-surface pervasively fractured crustal zone and regolith[6].

The extensional stresses that formed the graben located in the back-limb areas of lobate scarps are probably due to uplift and flexural bending in response to slip on underlying scarp-related thrust faults, where bending stresses cause normal faulting of the near-surface crust and regolith (see ref. 3). In this case, compressional stresses may have been locally relaxed by the formation of the scarps and extension limited to back-limb, near-surface regolith layers. Thus, local extensional stresses need not exceed global compressional stresses for graben to form.

In contrast, late-stage compressional stresses in the near-surface materials deformed by the Seares, Virtanen, and Vitello graben may not have been relaxed by contractional tectonic features. The inter-scarp graben of the Seares cluster could have formed in response to extensional stresses induced by dilation from the development of the surrounding lobate scarps. With the available data, the Virtanen and Vitello graben cannot be directly connected to the structural relief of the nearby contractional tectonic landforms. Also, there are no nearby Copernican-age impact craters on the scale of Virtanen or Vitello graben that might have influenced their formation, ruling out impact-induced stresses. If the formation of these graben is not related to contraction, an alternate explanation for the topography and extensional stresses is localized uplift due to shallow volcanic intrusives in the form of laccoliths. Laccolith intrusions can result in uplift and flexural bending of the overlying material (Supplementary Note S6). This mechanism has been proposed to account for uplift and extension in lunar floor-fractured craters[22–25] (Supplementary Note S1). It must be noted, however, that there is currently no direct evidence of young (<100 Myr) extrusive volcanism on the

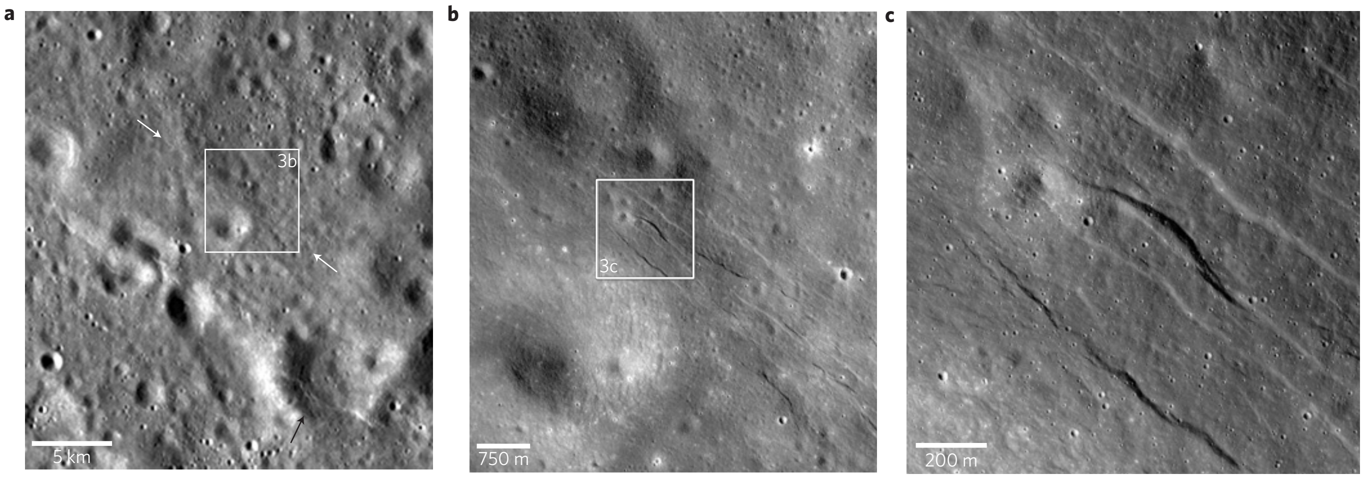

Figure 3 | Virtanen graben in the farside highlands (∼17.8 ° N, 180.8° E). a, The graben extend over 11 km (white arrows) and crosscut the northern rim of a heavily degraded ∼2.5 km diameter crater. A lobate scarp with a similar orientation to the graben is located to the southeast (black arrow). LROC WAC mosaic. **b**, These graben are the largest and most complex of the newly detected extensional features. LROC NAC frames M136362376L and M136362376R, location is shown in **a**. **c**, Graben are linked by relay ramps, downward-sloping landforms bounded by two adjacent, overlapping normal faults. Figure location is shown in **b**.

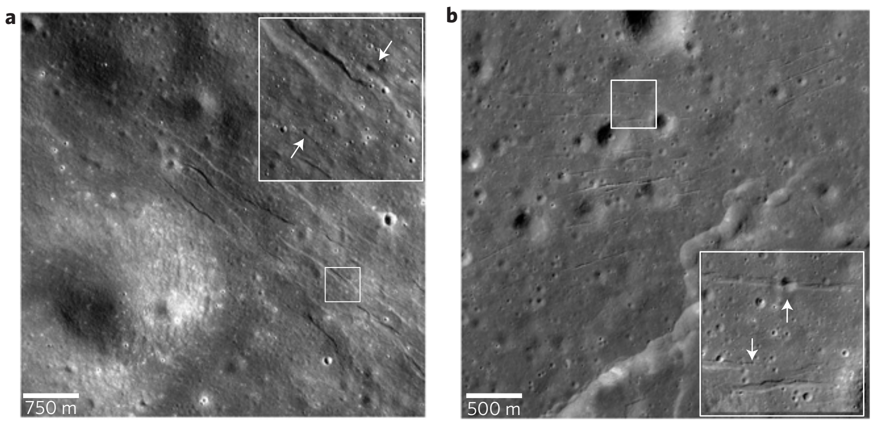

Figure 4 | Crosscutting relations between graben and impact craters. a, The Virtanen graben (∼17.8° N, 180.8° E) crosscut the rim of a degraded 2.5 km diameter impact crater and smaller craters with diameters down to ∼25 m (inset, upper white arrow) and ∼10 m (inset, lower white arrow). The width of the inset box is ∼430 m. LROC NAC image frames M136362376L and M136362376R. **b**, The Vitello graben crosscut a degraded ∼27 m diameter crater (inset, upper white arrow) and a ∼7 m diameter crater (inset, lower white arrow). The width of the inset box is ∼300 m. LROC NAC image frame M104756463R.

Moon[17,18,26] that would substantiate this mechanism. Regardless of the mechanism for generating the extensional stresses, if the background compressional stresses have not been locally relaxed or the deformed materials mechanically isolated, these young graben may provide evidence that the late-stage global compressional stress in the lunar crust was low.

The young age of the graben (perhaps $\ll$50 Myr) along with the contractional lobate scarps[3] show that significant recent tectonic activity has taken place on the Moon. Recent tectonic activity is consistent with Apollo seismic data[2,27]. Of the recorded moonquakes, 28 were shallow (<100 km depth; see refs 2,27) and some have best-fit depths in the crust and near the surface[28]. Although many shallow moonquakes seem to occur at the edges of mare basins, others are located in the nearside highlands[2,27]. Slip on faults associated with the young graben and lobate scarps may be possible sources of some of the shallow moonquakes. Reprocessing of deep seismic event records suggests the lunar outer core is fluid and surrounded by a partially molten boundary layer[29]. Thus, cooling of a still hot interior may have driven recent geologic activity on the Moon.

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Author contributions

T.R.W. drafted the manuscript. M.S.R. is the principal investigator of the LRO Cameras, was responsible for development and operation of the camera system, and contributed to scientific interpretations. M.E.B. assisted with NAC image processing and the identification of tectonic features. T.T. generated the NAC digital terrain models used in the investigation. B.W.D. assisted in the age estimates of the tectonic features. All of the authors contributed to interpretation and analysis of the data.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to T.R.W.