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GSA Data Repository Item 2019082

In-depth Analysis of Study Areas and Slip Distributions

Rima Ariadaeus

Rima Ariadaeus (Fig. 3A), a graben centered at 12°N, 007°E is part of the highlands bound by Mare Vaporum and Tranquillitatis. Rima Ariadaeus is a linear graben striking WNW/ESE and has a total length of 304 km with the average width ranging from 2 – 4 km. The graben crosses a near-perpendicular ridge at the near-center of the fault scarp. This graben system is composed of three fault segments on each graben-bounding side (Fig. 3B) with individual six fault segment lengths ranging from 29 km to 162 km. Two antithetic normal faults in the northwestern portion of Rima Ariadaeus are spaced slightly apart from the main fault segments (Fig. 3B). The antithetic faults to the southeast overlap in the center region of the graben.

The measured structural relief that informs our interpretation of slip distribution (Fig. 3C) reveals a clear displacement maximum of at the center of the slip distribution. This maximum fault displacement is 1021 m, located on the northern fault scarp (master fault). Graben-bounding faults in the northwest show low displacements, whereas the segments in the center and southeast of the structure show much higher slip distributions. Each segment is peaked towards the center of the fault segment, except when soft-linked faults interact, resulting in a skewed slip distribution. This slip distribution displays maximum displacement is at the center of the fault length and tapers towards the tip, and also highlights the interaction between soft-linked fault segments. The displacements for antithetic and master faults remain similar through the graben length indicating that this symmetric graben is mature.

Rima Cardanus

Rima Cardanus (Fig. S1), located on the western edge of Oceanus Procellarum is centered at 13°N, 069°W and is located at the transition between lunar highlands and the maria. This graben system is characterized by two near-perpendicular graben and was mapped as two separate graben systems, Rima Cardanus 1 and Rima Cardanus 2. Rima Cardanus 1 (Fig. S1B) strikes generally E/W and has a total length of 73 km with a graben width of 1 – 2 km.

Rima Cardanus 1 consists of two single oppositely dipping normal faults. The the southern fault scarp is crosscut by the main graben system from the south, whereas the northern scarps remains intact. The northern-dipping graben scarp was determined to be the master fault and the southern-dipping scarp its antithetic fault. Rima Cardanus 2 *(Fig. S1B)* strikes from a linear graben in the southwest to a semi-arcuate graben in the northeast and then is sharply truncated by the respectively much shorter and perpendicular Rima Cardanus 1. Generally striking SW/NE the graben-bounding faults change orientation to N/S towards the other graben system centered above it and terminates in the southern fault scarp. Rima Cardanus 2 is centered at 11°N 071°W and has a total length of 223 km. Each graben bounding side hosts a large subset faults segment. The average fault segment lengths range from 25 to 104 km. In this main graben system, the master fault is south-dipping and the antithetic counterpart is north-dipping.

The interpreted slip distributions for the two graben vary greatly (Fig. S1C-D). The slip distribution for Rima Cardanus 1 does not have a pronounced peak but a maximum displacement of 169 m on the southern fault scarp was measured (Fig. S1C). Master and antithetic displacements values are similar for this graben, displaying a symmetric graben profile. The slip distribution for the larger fault, Rima Cardanus 2 (Fig. S1D), indicates a much more complex picture. Generally, the slip distribution appears fairly flat, offset by a large peak near the

southwestern fault tip. The maximum displacement here is 303 m and only occurs along the northern fault. The remainder of the slip distribution shows several lower peaks. If individually interpreted nearly all fault segments display peaked profiles, where the longest fault in the center of the graben system has a maximum displacement of 246 m. The southwestern fault segments along Rima Cardanus 2, show an increase in displacement, indicating interaction and possible linkage with the previous fault. These slip distributions show evidence of linkage as well as flattened shapes and symmetric graben-bounding indicating a mature graben. Master and antithetic values in Rima Cardanus 2 are similar, indicating symmetry between both graben-bounding faults.

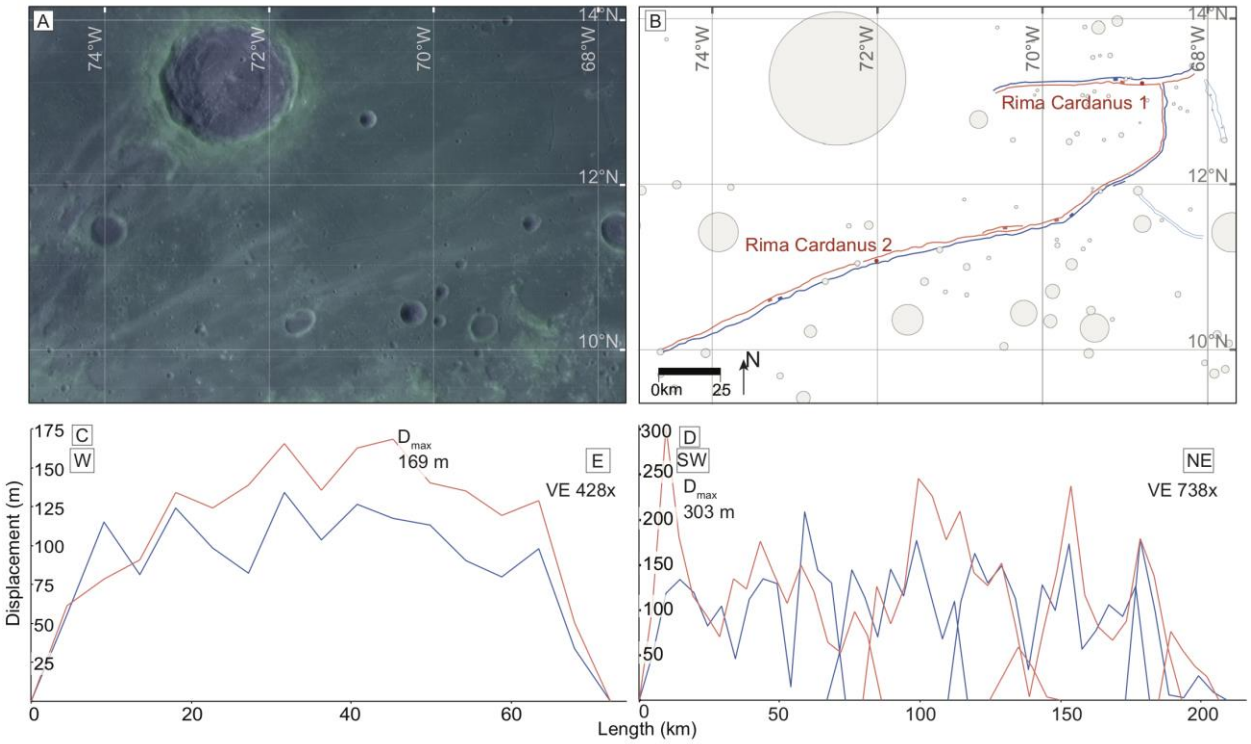


Figure S1. *Structural analysis of Rima Cardanus centered at 69°N, 013°W. (a) A LOLA DEM draped over LROC global image mosaic shows the study area in equirectangular projection. (b) Structural map of region shown in (a). This map reveals two major graben systems, Rima Cardanus 1 and Rima Cardanus 2. (c) The slip distribution for Rima Cardanus 1 shows a displacement with a plateaued shape. (d) Rima Cardanus 2 has a slip distribution with a maximum peak at the southwestern fault tip. The legend presented in Figure 3 applies to all figures in the Supplementary Material.*

Rima Cauchy

Rima Cauchy (Fig. S2), located within the eastern margin of Mare Tranquillitatis, is centered at 10°N, 038°E and generally strikes NW/SE. Rima Cauchy has a total length of 204 km and an average width of 2 km. Few small craters cut across graben segments but further leave the structure undisturbed. Rima Cauchy consists of 10 fault segments on each graben-bounding side (Fig. S2B). The center of the graben system shows several en echelon soft-linked fault segments, as well as one hard-linked segment on the northern fault scarp. Fault segment lengths range from 9 to 44 km in length and are highly variable across the graben. The graben is linear in the southeast and curvilinear in the northwest. Throughout the entire graben system, the master fault is north-dipping and the antithetic fault is south-dipping.

The interpreted slip distribution for Rima Cauchy (Fig. S2C) shows a maximum displacement of 200 m along the southern fault scarp (master fault). Displacement clearly tapers towards the fault tip and peaks towards the fault trace center. The fault segment to the west of the peak also shows a relatively high displacement and represents an en echelon, interacting fault. Each of the individual profiles peak near the center of the fault segment length. Between fault length 100 to 130 km the displacement at individual fault tips is high (Fig. S2C) and skewed towards en echelon faults, suggesting soft-linkage between faults. Master and antithetic faults are predominantly asymmetric in the northwest and symmetric in the southeastern portion.

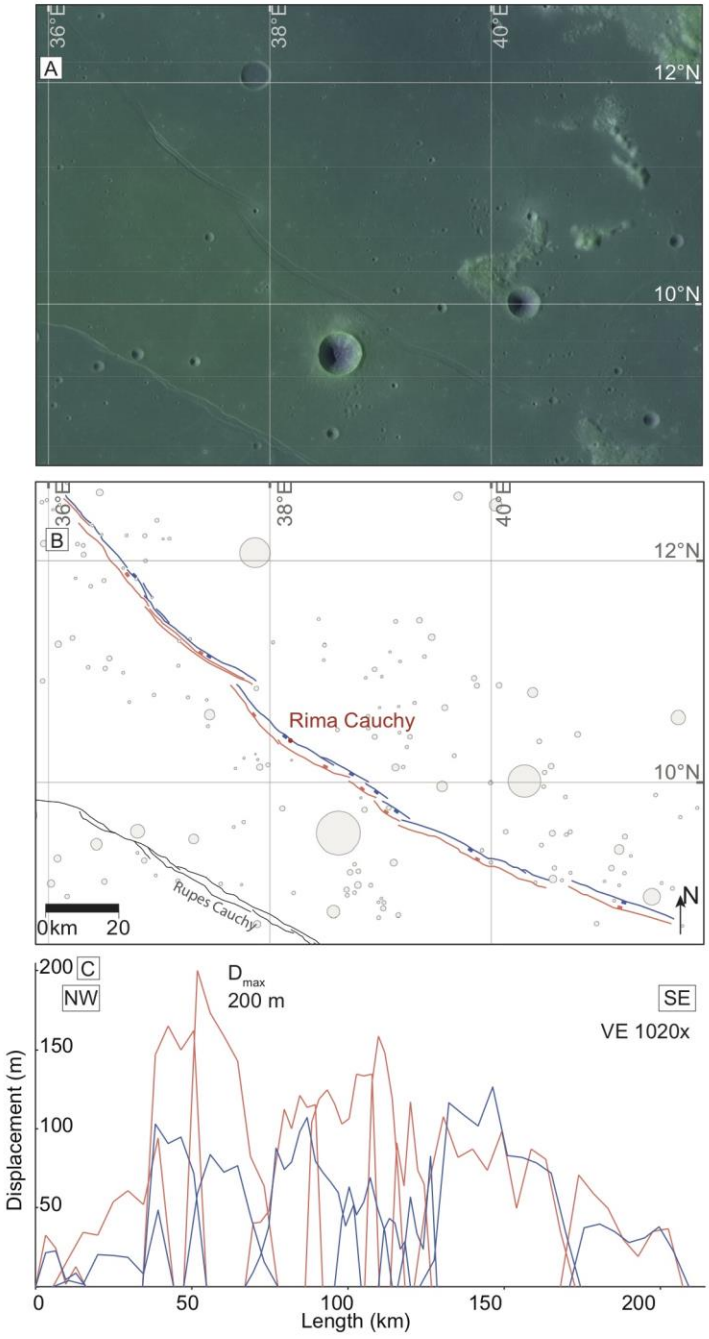


Figure S2. *Structural analysis of Rima Cauchy centered at 10°N, 038°E. (A) An equirectangular projection of a LOLA DEM draped over LROC global image mosaic shows the fault scarps of Rima Cauchy. (B) The corresponding structural map shows abundant, interacting fault segments. (C) The slip distribution for Rima Cauchy shows several high displacement peaks.*

Rimæ Daniell

Rimæ Daniell is a large graben system in the transitional terrain between Lacus Somniorum and Mare Serentatis (Fig. S3A). The subset of graben selected for this study system strikes linear in the southeast and northwest and is joined in the center by a slightly curved graben. Generally, Rimæ Daniell (Fig. S3B), strikes NW/SE and has a total length of 264 km with a range in width of 2 to 3 km. The north-dipping scarp is host to 18 individual fault segments and the south-dipping scarp consists of 14 fault segments. The graben turns into a single normal fault towards the southeast (Fig. S3B). The center of the graben is host to abundant soft-linked en echelon faults.

The interpreted slip distribution for Rimæ Daniell shows high displacement peaks near the graben fault tips and respectively lower displacement along the center of the fault trace (Fig. S3C). The maximum displacement, found along the western segment is along the scarp is 272 m, whereas the smoother, mare terrain generally exhibits lower displacements. Areas with increased fault segment soft-linkage show increases in displacement at the fault tips near the fault overlap and are evident in the slip distribution at length positions 100, 130, 160 and 200 km. A total of 22 individual fault segments display a symmetric peaked shape. The very southeastern fault has also a high displacement, similar to the first fault segment in this graben system.

The master fault is south-dipping along the analyzed graben. The antithetic fault scarp distribution is asymmetric, and the peak skewed towards the southeast. The master fault is also asymmetric, and its peak is skewed towards the northwest. This relationship results in a highly asymmetric slip distribution. Both graben-bounding faults also show large discrepancies in their relative offset, when the master fault displacement is high, the corresponding antithetic fault has a much lower displacement and vice versa. The southeastern fault represents the only half-graben

in this study.

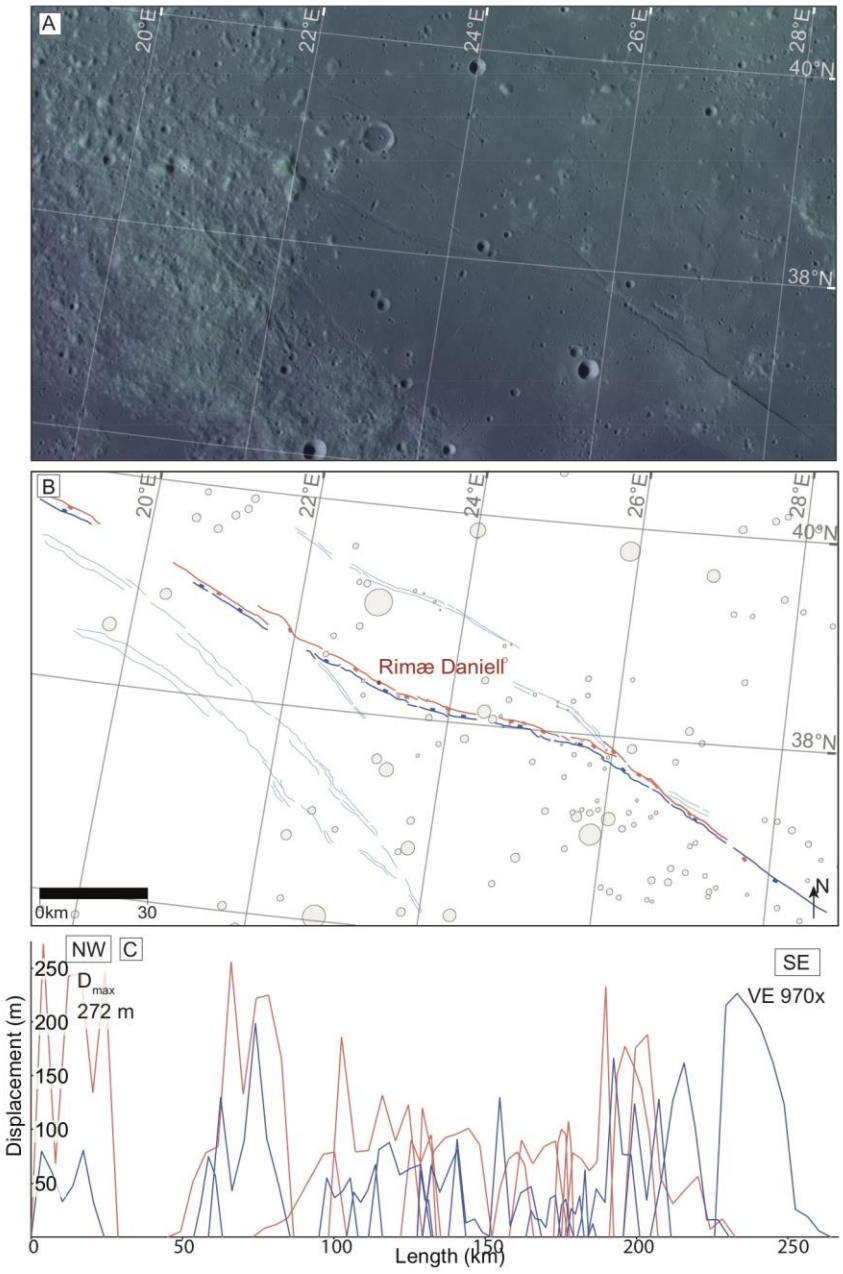


Figure S3. *Structural analysis of Rimæ Daniell centered at 38°N, 045°E. (A) LOLA DEM draped over LROC global image mosaic in north polar orthographic projection. (B) The corresponding structural map of the region reveals the specific graben examined in this study where the master fault is the south-dipping scarp. (C) Slip distributions for this graben show high displacement along rough terrain (west) and in locations where fault interactions have*

occurred (east).

Rima Flammarion and Rima Oppolzer

The next graben study site is composed of two different graben systems, Rima Flammarion in the west and Rima Oppolzer in the east (Fig. S4A). This study site is located in the highlands at the base of Sinus Medii and generally strikes WSW/ENE. These two graben have been previously interpreted as two individual graben (Arthur et al., 1963) but our mapping with LRO data indicates that they are part of one continuous graben which is spatially separated by rugged terrain and a crater. This higher resolution imagery revealed a fault traces that could be traced throughout the rugged terrain and clearly linked both individual faults. The entire length of both graben combined is 283 km.

Rima Oppolzer, which is truncated in the west by the 6.3 km diameter crater, Flammarion W, has a total length of 230 km. Each graben-bounding segment has 5 fault scarps ranging in length from 10 to 166 km in length. Generally, fault segments underlap along Rima Oppolzer, while a hard-linked segment is visible in the south-dipping Rima Flammarion. Rima Flammarion, which is truncated in the east by rough terrain, has a total length of 42 km. This graben consists of three individual fault segments with lengths ranging from 10 – 42 km. Rima Flammarion additionally shows a small overlap in fault segments along the north-dipping scarps. The master fault for these two graben is north-dipping, while the antithetic fault is south-dipping.

The interpreted slip distribution for Rima Flammarion and Rima Oppolzer has multiple peaks at ~ 200 m (Fig. S4B). The maximum displacement of 314 m in this graben system lies along a small ridge, which could account for the slightly higher displacement. The average displacement ranges from 100 to 200 m. Rima Flammarion has a slip distribution that has its highest displacement in the center of the fault trace, but also shows enlarged displacement

towards the next fault scarp segment. Rima Oppolzer shows two soft-linked overlaps along the southwest and four instances of underlap along the northeastern graben section. Both graben show increased displacement in soft-linked fault segments near graben length position 50 km. The shape of this graben is symmetric, as evinced by the similar displacements of master and antithetic faults.

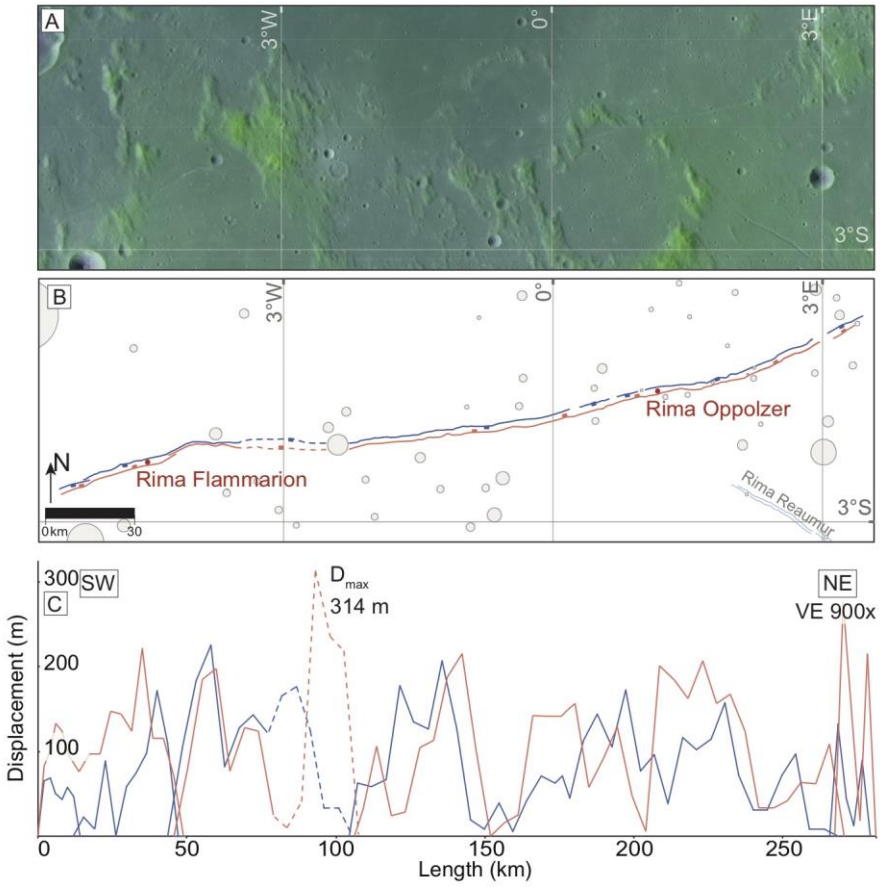


Figure S4. *Structural analysis of Rimæ Flammarion and Oppolzer . (A) LOLA DEM draped over LROC global mosaic image (equirectangualr position) here shows highland terrain with rough terrain and cratering. (B) Structural map of region shown in (A).The structural map of Rima Flammarion and Rima Oppolzer, together centered at 02°S, 001°W. Rima Flammarion fault segments show two overlaps whereas Rima Oppolzer has four underlapped fault segments. (D) The slip distribution of both graben show a nearly continous average displacement with only one*

large peak.

Rimæ Gerard

Rimæ Gerard consist of multiple graben near Gerard crater (Fig. S5A). Rimæ Gerard considered in this study is centered 46°N, 080°W and lies on the border between highlands and Oceanus Procellarum. Striking NW/SE, this graben has a total length of 115 km. The graben width varies; its widest extent of 2.2 km is in the center of the graben and the narrowest width of less than 1 km in the far southeastern portion. Rimæ Gerard cuts across two highly degraded craters and is cross cut by three small craters in the northwestern portion of the graben (Fig. S5B). It consists of two fault segments on each graben side with lengths ranging from 18 to 97 km.

The interpreted slip distribution for Rimæ Gerard has one dominant peak (Fig. S5C). The remainder of the slip distribution has a much lower displacement and tapers towards the fault tips. The maximum displacement for this graben is 538 m and lies substantially above the average displacement of 94 m for all fault scarps. The peak location coincides with one of the degraded crater rims, which could explain the unusually large divergence between average displacement and maximum displacement. All other segments in this system are plateaued but do not show evidence of interaction or fault linkage. The master fault in Rimæ Gerard is the north-dipping fault scarp. Along Rimæ Gerard, the graben profiles of master and antithetic faults are similar and symmetric displaying a mature graben.

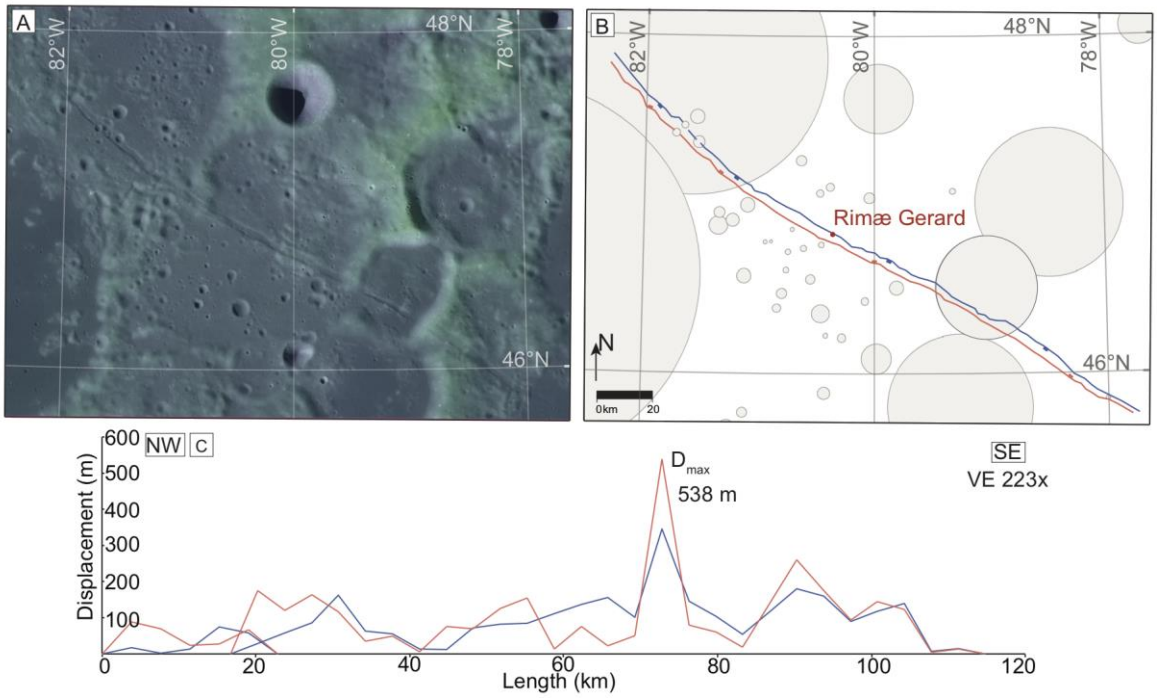


Figure. S5*. Structural analysis of Rimæ Gerard. (A) The LOLA DEM and LROC global image mosaic show the general rough topography around Rimæ Gerard in a north pole orthographic projection. (B) Structural map of region shown in (A). The structural map of the area reveals a north-dipping master and south-dipping antithetic faults cutting across several degraded craters. (C) Rimæ Gerard's slip distribution shows a flat slip distribution with a large peak in the proximity to the fault length center.*

Rimæ Goclenius

Rimæ Goclenius, centered at 08°S, 043°E, are a system of graben bounded by Mare Nectaris to the southwest and Mare Fecunditatis to the northeast (Fig. S6A). Both graben studied here are predominantly linear and strike NW/SE. Rimæ Goclenius 1 has a total length of 180 km and an average width of 1 to 2 km. The graben is crosscut by the nearby Gutenberg E crater in its center. The southern graben-bounding fault consists of 12 segments, while the northern fault is comprised of 10 individual fault segments (Fig. S6B) ranging in length from 4 to 43 km. The northwestern portion of Rimæ Goclenius 1 shows fault interaction and soft-linkage between graben segments, in contrast to the southeastern graben in which fault segments tend to underlap.

Rimæ Goclenius 2 has a strike parallel to Rima Goclenius 1 but is much shorter, with a total length of 43 km and a maximum width of 2 km. Two south-dipping faults scarps are opposed to 4 north-dipping fault scarps along Rimæ Goclenius 2. This graben shows a higher degree of fault segmentation and linkage, displaying two clearly overlapping fault segments along the graben length.

The interpreted slip distribution for Rimæ Goclenius 1 (Fig. S6C) has its maximum displacement skewed towards the southeastern fault tip with a maximum displacement of 291 m. Rimæ Goclenius 1 is right-skewed due to a high amount of fault linkage in that portion of the graben. When individually analyzed, the northwestern portion of this graben is peaked towards the its center. The southeastern region shows five soft-linked en echelon faults, resulting in several large peaks in the slip distribution displaying the result of interacting stress fields.

Rimæ Goclenius 2 shows a similar interpreted slip distribution with a maximum displacement of 128 m (Fig. S6D). This graben has several en echelon, soft-linked fault

segments resulting in a clear displacement peak at the center of the fault. When analyzed as individual fault segments, interacting faults show higher displacement in regions where faults overlap. Overall both slip distributions are excellent examples of increased displacement in soft-linked, en echelon fault scarps. Both graben have their master fault dipping to the north and antithetic fault scarps dipping to the south. The symmetry for Rimæ Goclenius 1 is not easily assessed but due to the abundant spikes in displacement it is interpreted as variable. Displacement along master and antithetic faults in Rimæ Goclenius 2 clearly reflects an asymmetric cross-section.

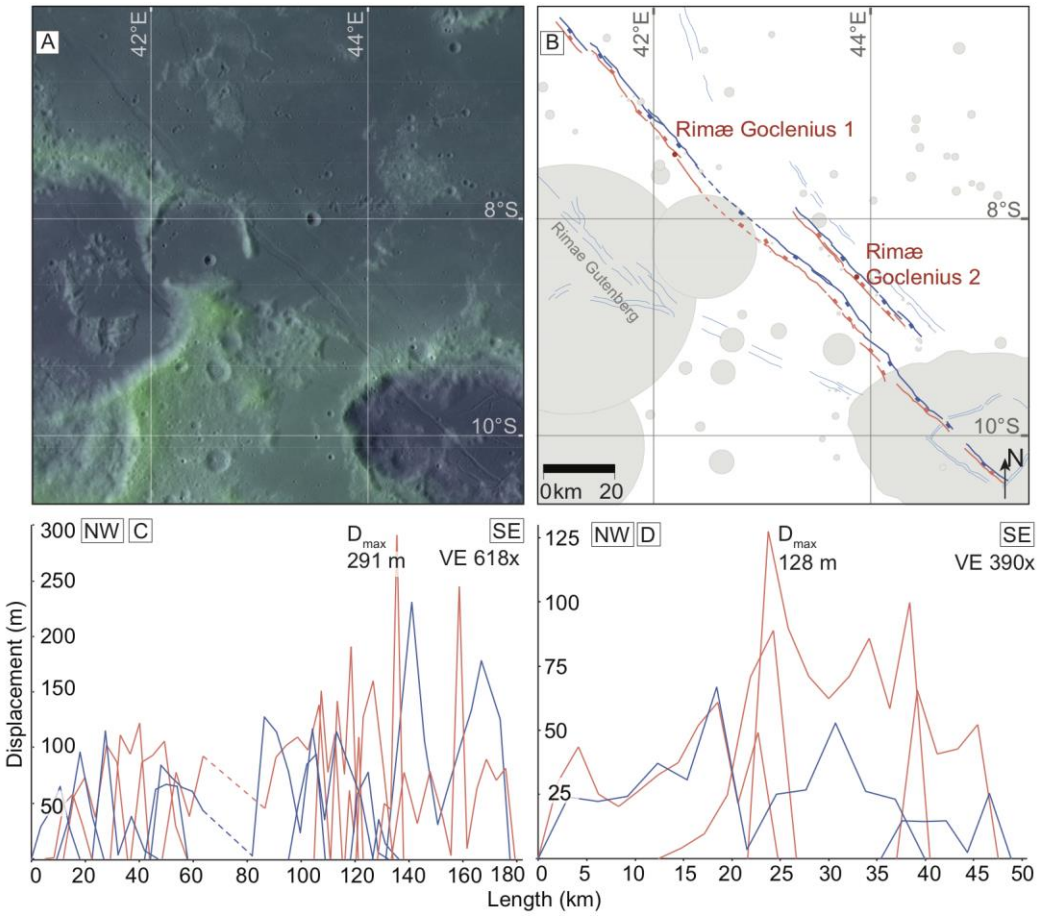


Figure S6. *Structural analysis of Rimæ Goclenius. (A) The LOLA DEM over LROC global image mosaic in equirectangular projection here shows the general area of a Rimæ Goclenius graben cutting across degraded craters and rough lunar terrain. (B) Structural map of region shown in (A). The structural map reveals two specific graben systems selected for detailed study. (C) The slip distribution for Rimæ Goclenius 1 displays large displacement in the southeastern portion of the graben. (D) The slip distritbution for Rimæ Goclenius 2 has peak near the center of the total fault length.*

Rima Hesiodus

Rima Hesiodus, centered at 31°S, 022°W, is located in the mare/highland transition zone south of Mare Nubium. The structure strikes NE/SW and has a total length of 304 km with widths ranging between 2 and 4 km (Fig. S7A). The graben mainly deforms mare units, but in its center portion, it cuts through rough terrain (marked in Fig. S7 by dashed lines). Its linear map pattern remains unaltered by the terrain change. The faults forming this graben are heavily segmented and display multiple fault overlaps, jogs, and underlaps in fault segment interaction. Each graben-bounding fault scarp consists of 15 fault segments, with fault segment lengths ranging from 4 to 91 km. The master fault is north-dipping throughout the graben system.

Our interpreted slip distribution of Rima Hesiodus shows a generally flat profile but contains a pronounced maximum of 381 m just southwest of the center of the graben. This displacement maximum is only observed on the south-dipping (antithetic) fault and is located near the topographic rise crossing the graben which, indicating the influence of rugged terrain on the slip distribution. The southern and northern scarps have average displacement of 138 and 112 m, respectively.

The observed fault segmentation in the southwestern part of the structure is also evident in its slip distribution in abundant peaked and overlapping fault profiles. Further northeast along the fault trace the interaction decreases and the slip distribution reflects less fault interaction. The lack of jogs or overlaps in the transition between symmetric and asymmetric slip distribution suggests that the more mature southwestern portion developed before the northeastern graben section. The majority of Rima Hesiodus is symmetric as evinced by the similar displacements along master and antithetic faults; the only sight deviation occurs in the northeastern portion.

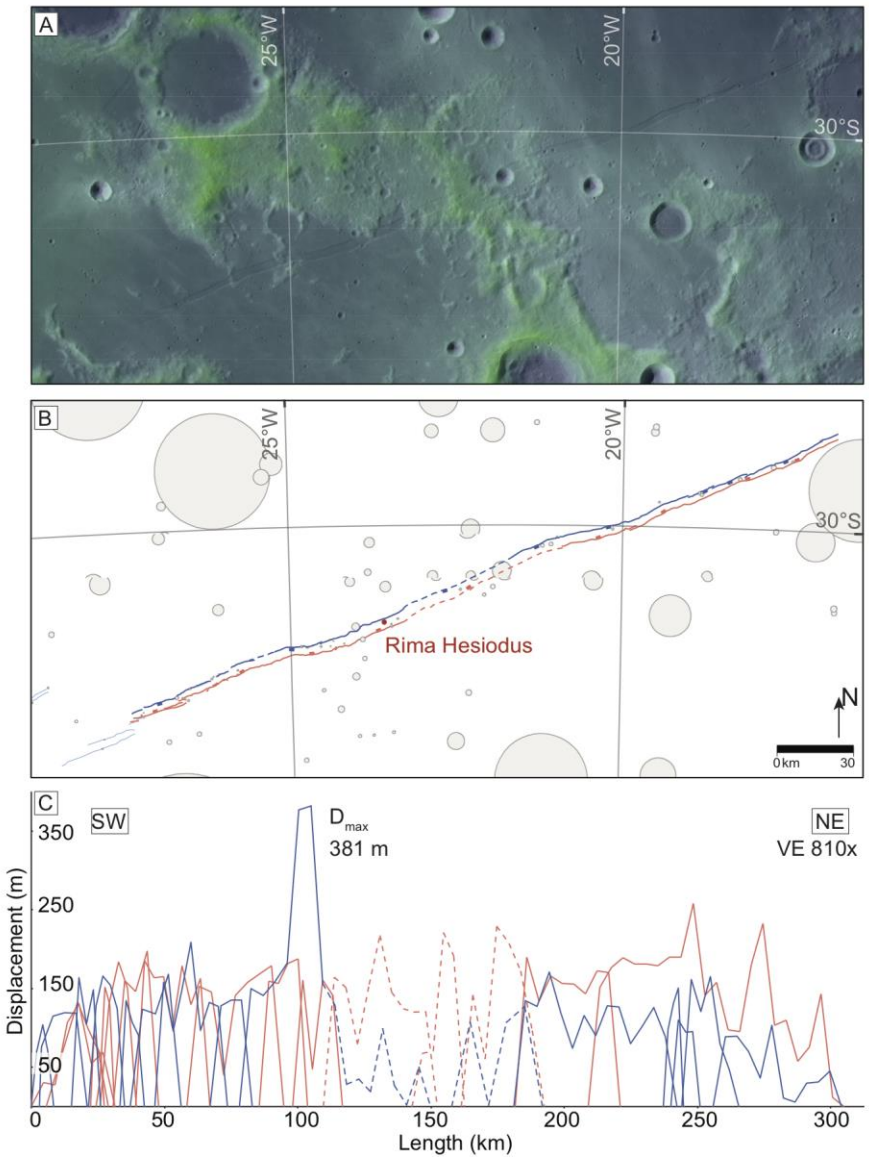


Figure S7. *Structural analysis of Rima Hesiodus. (A) A LOLA DEM over LROC global image mosaic in equirectangular projection shows the highland-mare transitional topography surrounding this graben. (B) Structural map of region shown in (A) reveals a north-dipping master and south-dipping antithetic fault. (C) The generally flat slip distribution of this Rima Hesiodus is interrupted by a large displacement peak near rough surface terrain.*

Rimæ Mersenius

The western edge of Mare Humorum is host to Rimæ Mersenius, where two well-defined NNE/SSW striking graben are bounded by craters on either graben side (Fig. S8A). The total length of this graben system is 173 km and ranges in graben width from 1 to 3 km. The graben cuts across a 14 km diameter crater near the its center and is cut by a 0.4 km diameter crater in the south. We grouped these two graben together into one system, which has two fault scarps on the western side and three segments on the eastern graben side. Individual fault segment lengths range from 27 km to 112 km. The largest overlap of fault segments occurs near the center of the graben and measures 13 km. This graben system has 14 jogs (hard-linked faults), four along the master fault (east-dipping) and 10 along the antithetic fault.

The interpreted slip distribution for Rimæ Mersenius is flat-topped, has a no pronounced displacements peaks, and an average displacement of 181 m (Fig. S8C). The maximum displacement of 349 m was measured along the east-dipping scarp is only slightly higher than surrounding peaks. Even though soft-linkage in the form of a large overlap is visible in map view near the center of the graben, this is not evident in the slip distribution. Larger displacement in the southern region can be attributed to higher regional topography. Displacement values for each graben-bounding fault scarps are not markedly different and lie very close. High symmetry between master and antithetic displacements indicate a well-developed, mature graben profile.

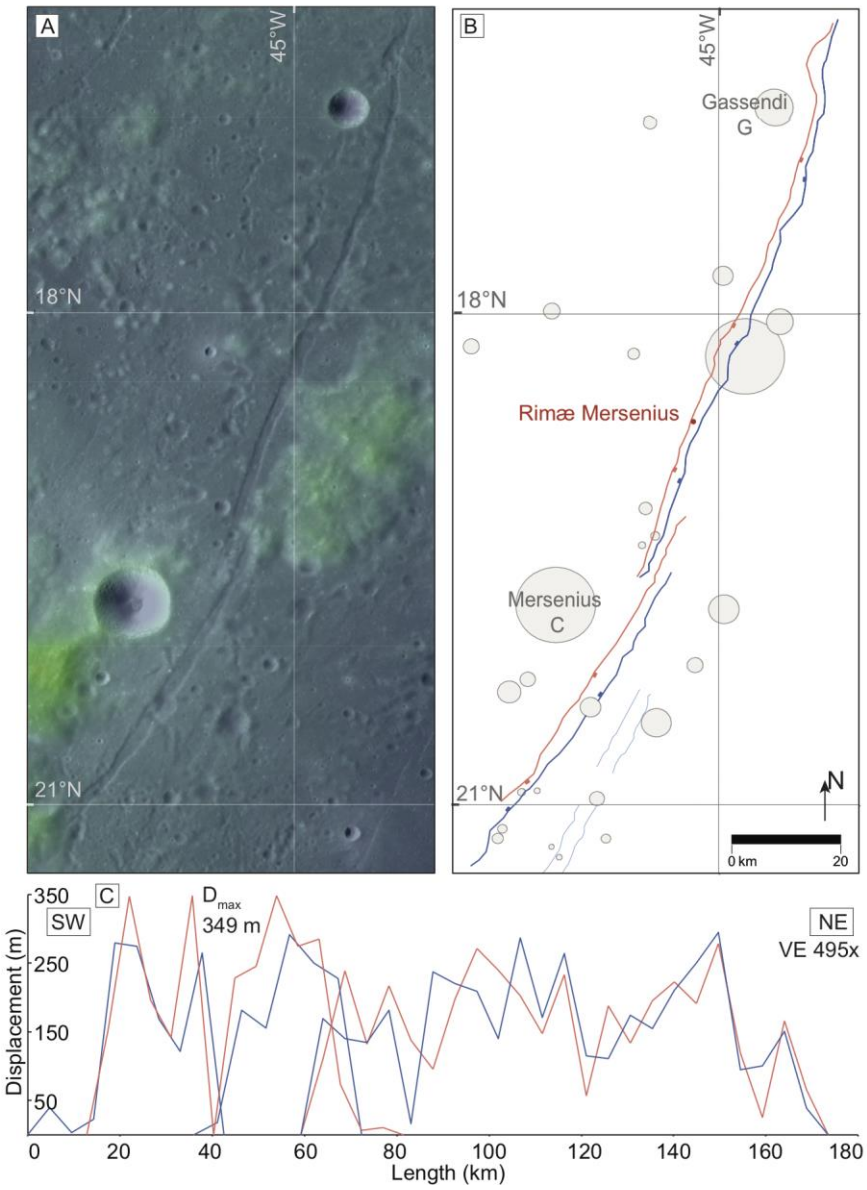


Figure S8*. Structural analysis of Rimæ Mersenius. (A) LOLA DEM over LROC global image mosaic in equirectangular projection shows the graben centered at 19°N, 045°W. (B) Structural map of region shown in (A) reveals two overlapping graben systems with a east-dipping master fault and a west-dipping antithetic fault. (C) The corresponding slip distribution is flat-topped and has three minor peaks between the southwestern tip and the center of the fault.*

Rimæ Plinius

Rimæ Plinius, centered at 17°N, 023°E, are several curvilinear to arcuate graben located along the southern border of Mare Serenitatis (Fig. S9A). We assessed the longest graben of this system, which is surrounded by smooth terrain and is located along a mare/highland transition. This graben strikes WSW/ENE and has a total length of 121 km and a maximum width of 3.4 km. Rimæ Plinius is superposed by a few small (less than 1.4 km diameter) craters. This graben is not segmented and is composed of two antithetic normal faults (Fig. S9B). In the southwestern graben region, the graben strike sharply changes to E/W indicating the possibility of previous fault linkage.

The interpreted slip distribution (Fig. S9C) for Rimæ Plinius shows several peaks distributed along the master fault. The maximum displacement for Rimæ Plinius is 389 m, located in the western portion of the north-dipping fault. The same region depicts a change in fault strike in map view, indicating that this may have been the location coalescence of graben. This inference is supported by an increase in displacement in both directions away from the change in fault strike. Master and antithetic slip distributions are predominantly asymmetric and only show symmetry between 20 and 50 km.

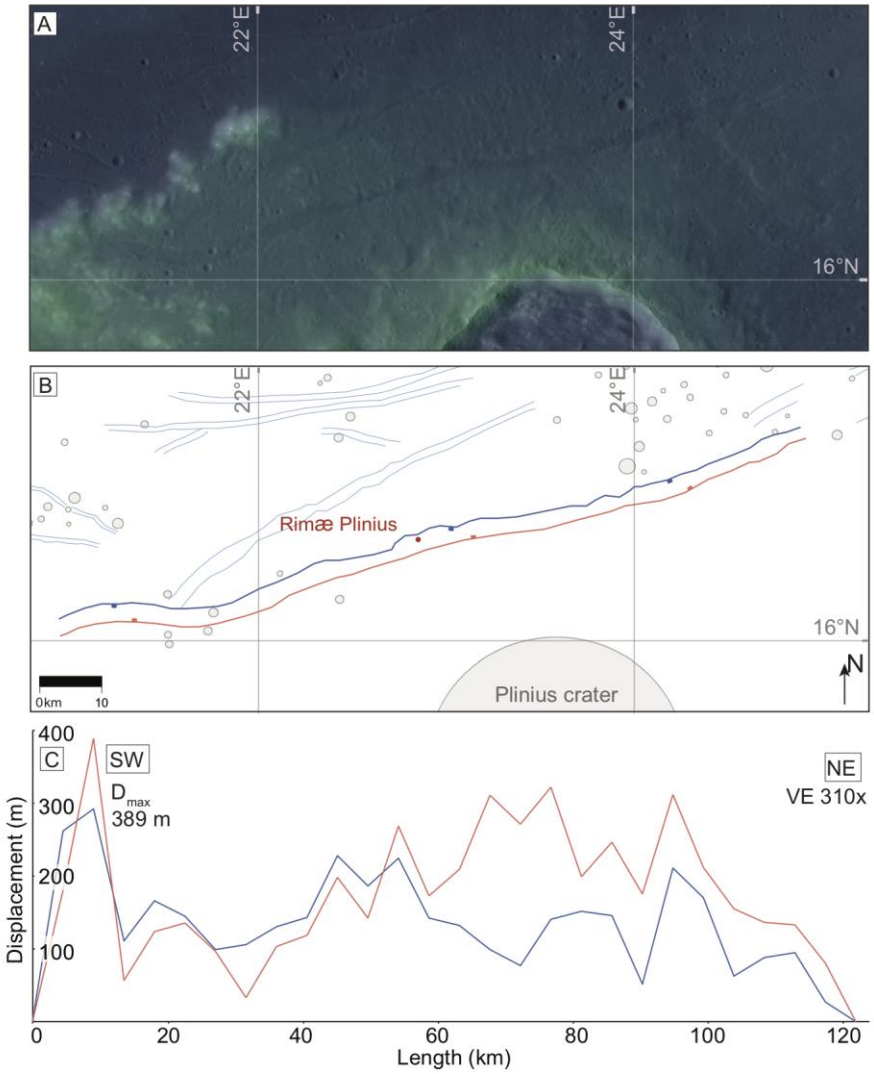


Figure S9. *Structural analysis of Rimæ Plinius. (A) A LOLA DEM over LROC global image mosaic in equirectangular projection shows a long graben along mare-highland transition zone. (B) The structural map of Rimæ Plinius shows the single master fault north-dipping towards Mare Serentatis. (C) The corresponding slip distributions shows to peaked regions with a local minium near 30 km.*

Schrödinger basin

The graben system in Schrödinger basin is located near the south pole on the far side of the Moon and includes the graben at the lowest elevation in this study (Fig. S10A). Graben in the basin are radial and concentric to the rim and we selected two NNW/SSE striking graben with semi-arcuate shape to be examined in this study. Parts of our analyzed graben cross through remnants of the central peak. The total length of this graben is 234 km and its width ranges from 1 to 4 km. Several small craters are superimposed on the graben scarps.

The northern graben is arcuate in map view with a total length of 79 km and is oriented circumferentially with respect to the center of Schrödinger basin. The northern graben is not segmented and is composed of two antithetic normal faults. The southern graben changes orientation at its northern tips and strikes linearly NW/SE. The southern graben has a length of 168 km and is composed of two western fault segments and two eastern fault segments.

The interpreted slip distributions for the two analyzed graben in Schrödinger basin displays three large peaks across the graben length (Fig. S10C). These peaks occur along the northern tip and surrounding the center of the graben on each side. The observed maximum of 1115 m and average displacement of 690 m are the highest across all our study sites. High displacement peaks coincide with the graben crossing topographically higher regions than its surroundings. The center of the graben system shows the maximum displacement. The master fault was found to be the east-dipping scarp. Displacements on the master and antithetic faults are highly variable and increasingly differ towards the north (Fig. S10C). This suggests that from north to south the graben becomes more symmetric and thus mature.

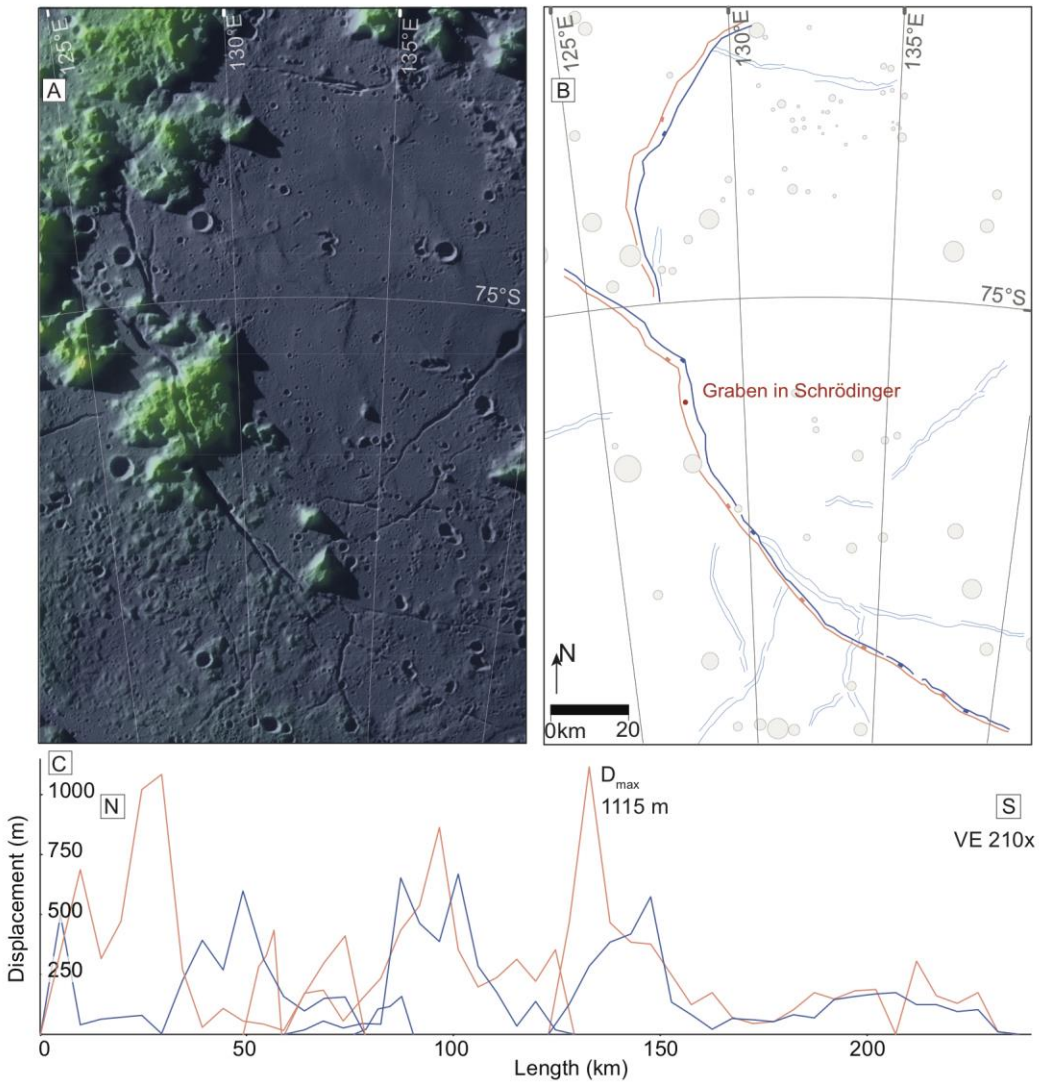
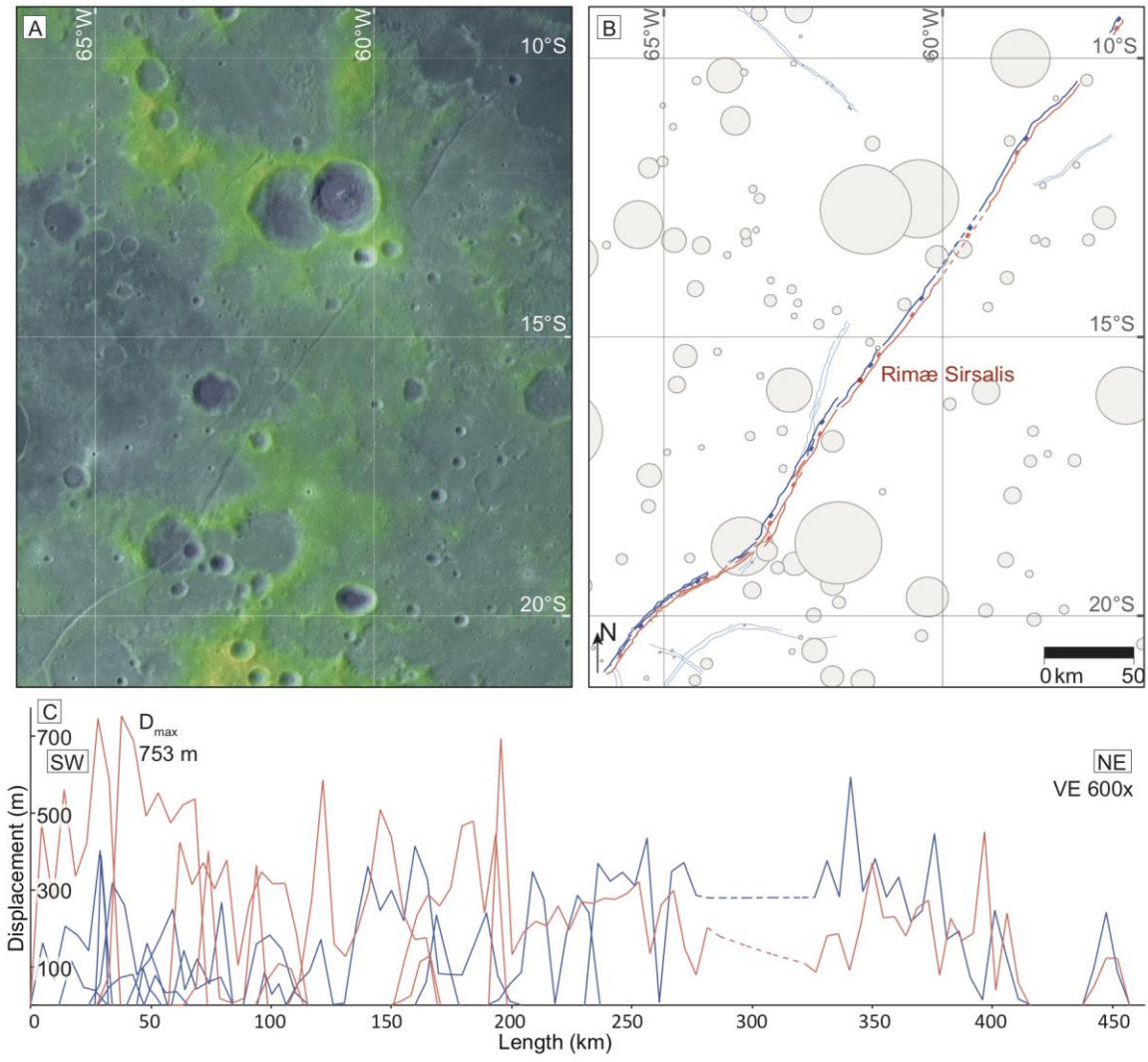


Figure S10. *Structural analysis of Schrödinger basin, centered at 75°S, 128°E. (A) A LOLA DEM over LROC global image mosaic in polar stereographic projection of the large impact basin Schroedinger shows central peaks and rough basin terrain. (B) The geologic map shows several arcute and long graben throughout the basin. Some graben cut across rougher terain. (C) The corresponding slip distribution for these graben displays a two high displacement peaks and an otherwhise genereally flattened profile.*

Rimæ Sirsalis

Rimæ Sirsalis are a set of graben that run radial to the southwestern portion of Oceanus Procellarum that straddles the highlands/mare transition (Fig. S11A). Rimæ Sirsalis is the longest graben system in this study with a total length of 453 km. The graben strikes SW/NE and displays width ranges of 2 km to 4 km. This graben is predominantly linear but shows a curved map pattern in its southern portion. The very northeastern tip of the graben system is separated from the main graben area by 32 km. The northeastern portion of the graben is partially covered by ejecta blankets from two large craters, and the same region is superposed by two smaller craters. Along the southern end of the graben system craters and further ejecta material are cut by the faults. This region also displays abundant fault segmentation with several faults scarps overlapping another over their entire lengths. Closer to the northeastern portion, and the mare, we find less fault segmentation and overlap. The individual fault scarp lengths in this graben are highly variable and range from 3 to 90 km.

The interpreted slip distribution for Rimæ Sirsalis shows a picture similar to the graben map trace; the southwestern portion is heavily segmented and shows abundant overlap, resulting in high displacement, especially along the master fault trace (Fig. S11C). The first few faults displacements are skewed towards each other indicating linkage between segments. Along this region of the slip distribution the antithetic fault shows a much lower displacement. The remainder of the graben less segmented. Rimæ Sirsalis's maximum displacement of 753 m is found along the west-dipping fault scarp and has the second highest maximum displacement of this study. Both graben-bounding sides are highly variable in their respective offsets across the graben. The southwestern extent is highly asymmetric and becomes increasingly more symmetric towards the northeast.



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344 ***Figure S11.*** *Structural analysis of Rimæ Sirsalis centered at 16°S, 059°W. (A) A LOLA DEM*
345 *over LROC global image mosaic in equirectangular projection depicts Rima Sirsalis progressing*
346 *further into the highland in a southwestern direction. (B) Abundant fault interaction is visible in*
347 *the geologic map of the area. (C) Rima Sirsalis's slip distribution is somewhat flattened higher*
348 *displacement on the southwestern side in comparison to the northeastern graben portion.*