Structural control of scarps in the Rembrandt region of Mercury

Javier Ruiz [a,]*, Valle López [b], James M. Dohm [c], Carlos Fernández [d]

[a] Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, 28040 Madrid, Spain

[b] Escuela Técnica Superior de Ingenieros en Topografía, Geodesia y Cartografía, Universidad Politécnica de Madrid, Carretera de Valencia, km 7.5, 28031 Madrid, Spain

[c] Department of Hydrology and Water Resources, University of Arizona, Tucson 85721, AZ, USA.

[d] Departamento de Geodinámica y Paleontología, Universidad de Huelva, Campus de El Carmen, 21071 Huelva, Spain

* Corresponding author. E-mail: jaruiz@geo.ucm.es (J. Ruiz)

Abstract

Lobate scarps, thought to be the surface expression of large thrust faults, are the most spectacular contractional tectonic features visible on Mercury. Most lobate scarps follow a general and relatively simple pattern, with a roughly arcuate or linear form in plan view, and an asymmetric cross section characterized by a steeply rising scarp face and a gently declining back scarp. In this work, we study two peculiar and complex scarps in the Rembrandt region of Mercury through MESSENGER imagery. On the one hand, the formation of these scarps resulted in the deformation of features such as impact craters, fractures, extensional faults, and volcanic plains, while on the other hand, the deformed features partly influenced the formation of the scarps. Evidence for structural control on the formation of the scarps includes their orientation, segmentation, bifurcation, change in structural trend and dip orientation, and transition into high-relief ridges or wrinkle ridge morphologies in some cases. Thus, these two lobate scarps provide examples of complex geological relations among other features, expanding the recognized richness of mercurian geology. Also, the southern scarp records a complex history of contraction, suggesting that the development of some mercurian lobate scarps may be more complex than usually thought.

Key words: Mercury; Tectonics; Terrestrial planets

1. Introduction

Lobate scarps are the most spectacular contractional tectonic features visible on the surface of Mercury (e.g., Strom et al., 1975; Dzurisin, 1978; Watters et al., 2001, 2009a; Watters and Nimmo, 2010). Lobate scarps, which are thought to be the surface expression of large thrust faults resulting from contraction due to the cooling of the planet (e.g., Strom et al., 1975), deform the crust at depths ranging from 30 to 40 km (Watters et al., 2001; Egea-González et al., 2012). Their formation probably occurred during an important part of the mercurian geological history, with some being relatively young features (Watters et al., 2009a; Watters and Nimmo, 2010).

Most lobate scarps follow a general and relatively simple pattern, showing an approximately arcuate to linear form, and an asymmetric cross section characterized by a steeply rising scarp face and a gently declining back scarp (Watters et al., 1998, 2001). Other contractional features of Mercury are high-relief ridges and wrinkle ridges (for a review of the tectonics of Mercury see Watters and Nimmo, 2010); high-relief ridges are usually scarce, symmetric in cross section, and can transition into lobate scarps, suggesting a genetic relation, whereas wrinkle ridges are sinuous, morphologically complex, and generally located on volcanic plains.

Lobate-scarp development and plan-view morphology could have been influenced by pre-existing impact basins, which would have affected the mechanical behavior of the mercurian crust (Spudis and Guest, 1988). This is suggested by trends of some lobate scarp segments which parallel the rims of impact craters (e.g., Watters et al., 2001). On the other hand, structural control of lobate scarps by pre-existing tectonic structures has not yet been detailed in the literature on Mercury.

In this work, we study two peculiar and complex scarps imaged by the MESSENGER spacecraft in the Rembrandt region of Mercury (see Figure 1). These scarps show an amazing variety of evidence for structural control by pre-existing landforms, including impact craters, fractures, extensional faults, and volcanic plains. The evidence includes orientation, segmentation, bifurcation, abrupt change in structural trend, changes of dip orientation, and transition into high-relief and wrinkle ridge morphologies at or near impact crater margins and/or tectonic structures such as faults. Thus, these two scarps provide examples of tectonic complexity previously not reported for Mercury.

2. The Rembrandt region

MESSENGER first imaged the Rembrandt region during its second and third flybys around Mercury (Figure 1). This region includes cratered terrains and intercrater plains. A complex geological history, including tectonism (contractional and extensional) and volcanism has been previously reported for the Rembrandt crater (Watters et al., 2009b), but detailed geological analysis has not been extended to the surroundings.

Figure 1 shows the two scarps studied in this work. Both scarps have a roughly ENE-WSW trend. The eastern part of the northern scarp (hereafter referred to as the RS1 scarp) deforms the heavily cratered terrain and the western margin of the Rembrandt crater, whereas its western part deforms intercrater plains. The southern scarp (hereafter referred to as the RS2 scarp) deforms the intercrater plains located to the southwest of the Rembrandt crater. In the next section, we describe both lobate scarps and their spatial association (and interaction) with other geological features.

3. The RS1 and RS2 scarps

The morphology of RS1 in plan view is relatively simple, though there appears to be fault segments. The east end of RS1 has a northeasterly trend, a prominent southeast-facing scarp, and disrupts and thrusts the Rembrandt impact basin as clearly visible on a shortened and thrusted small crater inside this basin (Watters et al., 2009b). This feature was interpreted by Watters et al. (2009b) as lobate scarp, but there is also a northwest-facing scarp associated to RS1, somewhat approximating their morphology to that of high relief ridges (see Dzurisin, 1978; Watters et al., 2009a). However, the northwest-facing scarp is less prominent, as evidenced through both preliminary stereo topographic models based on MESSENGER imagery (Preusker et al., 2011) and comparison with illumination and shadowing of both small ridges visible on the plains in the Rembrandt basin and nearby impact craters. Thus, whereas the southeast facing-scarp must be related to the main underlying thrust fault, the northwest-facing scarp can be interpreted as a secondary backthrust fault.

Coinciding with a change to a more east-west trend of RS1 and a structural discontinuity as it transects the Rembrandt rim to the west (Figure 2), the morphology in plan view becomes more complex. The change coincides with a small impact crater just inside the eastern rim of the Rembrandt basin (crater A of Figure 2). Inside crater A, the geometry of RS1 is obscured by the tectonic complexity of the Rembrandt rim, including a small and N-S oriented scarp (Figure 2) crossing crater A. The south-facing scarp of RS1 inside this small crater appears to be located close to the inner crater rim, and for this reason it is less visible than the north-facing scarp associated to the backthrust in the east part of RS1. Alternatively, the north-facing scarp inside crater A could be a fault segment boundary that separates individual thrust faults outside this crater.

West of Rembrandt rim, RS1 is nearly rectilinear, and has an appearance more similar to that observed in high-relief ridges (or linear ridges in the terminology of Dzurisin (1978)), although it is also reminiscent of some relatively linear wrinkle ridges on the martian surface (see Watters, 1993; Mueller and Golombek, 2004). Indeed, using MESSENGER image data, there are distinct north- and south-facing scarps which bound an elevated structure (i.e., an elongated scarp-bounded mesa). The western part of RS1 deforms both intercrater and heavily cratered plains materials (Pl2 and Pl1 of Figure 2, respectively). Although the scarp-bounded mesa is similarly wide on both terrains, it is more wrinkle ridge-like on the intercrater plains materials (see for example the crenulations on RS1 just east of crater B of Figure 2). The putative volcanic materials may provide a resistant layer overlying weak and brecciated and/or layered materials, which could favor a wrinkle ridge-like structure when thrust faults deform these materials (a wrinkle ridges is considered to be formed when a thrust fault, which remains blind, deforms near-surface layered materials; e.g., Schultz, 2000). In fact, wrinkle ridges are observable on mercurian (e.g., Caloris Planitia; Watters and Nimmo, 2010), venusian (Watters, 1988), lunar (Watters, 2010), and martian (e.g., Watters, 1993; Mueller and Golombek, 2004) volcanic plains. On the plains close to the west end of RS1, this scarp disrupts another impact crater (crater B, Figure 2), although in this case the trajectory of the scarp is modestly affected by the crater.

Much of the trace of the southern scarp, RS2, is roughly parallel to that of RS1, including a somewhat similar northeasterly change in trend along its northeastern part. However, in certain aspects, RS2 is more complex than RS1 (Figure 2). RS2 starts inside the Rembrandt basin as wrinkle ridge(s) following a roughly N-S trace. Out of the Rembrandt basin RS2 progressively trends into a W-SW orientation, maintaining standard lobate scarp morphology, although as a low-relief feature (see also preliminary stereo topographic models of the eastern part of RS2 in Preusker et al., 2011) with a south-facing scarp.

Otherwise, the RS2 scarp is constituted by a complex system of structures in the intercrater plains just east of a deformed impact crater (crater C of Figure 2), including a northeastern branch bifurcation of RS2 (see Figures 2, where this feature is marked as RS2nb, and 3). Also, there is a nearly linear narrow trough-like feature (labeled T in Figures 2 and 3) cutting the main scarp. The northeastern branch of RS2 reaches trough T near 70ºE, and then follows, and even obscures, the trace of the northern part of this feature. Trough T therefore postdates the main development of RS2, but the north branch of RS2 postdates the trough, suggesting a complex geologic history for this lobate scarp. The north branch of RS2 was formed or reactivated subsequently to trough T formation; the trough, or more probably the associated weakness zone (since that the trough is a relatively minor feature), would have contributed to control the morphology of the northern branch of RS2. To the south of this zone, another lobate scarp, which has also been affected by the trough T, could have been partly thrusted by RS2 (see Figure 3); in fact, this area south of RS2 is tectonically complex, with several low scarps, oblique to RS2, whose relation with this scarp remains unclear.

Inside the crater C (Figures 2 and 3), RS2 has definite north- and south-facing scarps. Also, RS2 is crossed inside crater C by a narrow trough-like landform; RS2 seems slightly offset by this narrow feature, but we interpret this as an apparent impression, since no other features are similarly offset by the trough-like landform. West of crater C, RS2 is a single structure with a clearly north-facing scarp, suggesting an inversion of fault dip orientation; this north-facing scarp orientation of the western portion of RS2 is clearly evident in Figure 3, confirming the change of dip fault orientation. A possible interpretation of the structure of RS2 is shown in Figure 3b.

4. Discussion and conclusions

The two large lobate scarps in the Rembrandt region of this study show complex geological relations with other features, which expands the recorded richness of mercurian geology.

The RS1 scarp records lateral changes in morphology from an appearance similar to that of typical lobate scarps inside the Rembrandt basin (although including a probably backthrust scarp smaller than the main one) to a high-relief ridge appearance outside the crater, although somewhat resembling a wrinkle ridge-like morphology in the intercrater plains. In turn, RS2 transitions from wrinkle ridges in the plains inside the Rembrandt basin to lobate scarp outside the basin. Transitions from lobate scarps to high-relief ridges are known on Mercury (Watters et al., 2001; Watters and Nimmo, 2010): both types of features might be related to large reverse faults, which would have a higher dipping angle in the later case (Watters and Nimmo, 2010). Thus, the change in morphology of RS1 occurring in the Rembrandt basin rim could therefore be related to variations in fault dip angles inside and outside the basin. In this sense, Ferrari et al. (2011) have recently suggested that the presence of the Rembrandt basin might have affected the development of this scarp, maybe due to an inhomogeneous crustal layering.

Similarly, a transition from lobate scarps to wrinkle ridges has been reported for some lunar and martian structures (Lucchitta, 1976; Watters, 1993; Mangold et al., 1998; Anguita et al., 2006, Watters and Johnson, 2010), also associated with similar change in surface geology from cratered terrains to plains materials. This could be explained by more competent volcanic materials overlying unconsolidated (i.e., brecciated and/or layered) impact crater infill deposits, which would favor winkle ridge formation. Also, there is distinct structural control, as the eastern part of the RS1 scarp, near the western margin of Rembrandt basin (near impact crater A), abruptly changes trend and appears to be segmented, eventually transitioning into a narrow high-relief ridge.

Thus, lateral changes in the general morphology of RS1 and RS2 can be well correlated with local structural control, and the complexity of these changes is direct function of the complexity of the local geology.

Moreover, the RS2 scarp has experienced a complex and long history of contraction. A first phase of compression originated the main scarp and thrusted other pre-existing lobate scarps. Subsequently, two trough-like landforms cut the main scarp. Finally, new compression formed or reactivated a north branch of RS2, possibly following the structural control of the weakness zone associated to the trough-like feature T. This interpretation may be overly simplified, but our work confirms previous works suggesting that the development of at least some mercurian lobate scarps may be more complex than usually thought (Rothery and Massironi, 2010; Ferrari et al., 2011). The total amount of radius reduction deduced from shortening on lobate scars is 0.6-0.9 km (Watters et al., 2009), although this estimate is considered to be a lower limit due to lighting conditions. The actual global contraction could be even higher if thrusting of pre-existing lobate scarps is a common phenomenon. Moreover, reactivated faults might complicate the estimates of global contraction. Thus, the global tectonic evolution of Mercury could be more complex than a simple cooling-driven contraction.

High resolution images (and stereo topographic models that could potentially be produced from these images) obtained during the orbital phase of MESSENGER (with resolutions of ~200-300 m per pixel at the Rembrandt region) will serve to improve the tectonic description of the scarps analyzed in this study, as well as the derived geological history. For example, these images should help to determine the level of structural control on scarps development and appearance, confirm the wrinkle ridge-like characteristics of RS1 on intercrater plains materials, or determine the expression and significance of trough T.

The analysis of individual lobate scarps is useful to improve our knowledge of local tectonic and crustal mechanical properties (see also Rothery and Massironi, 2010), but we have shown that it also potentially has implications for the global geological history of Mercury.

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Figure caption

Figure 1. A MESSENGER-based mosaic with a resolution of 500 meters/pixel (~85.17 pixels/degree) showing the northern and southern lobate scarps analyzed in this investigation (RS1 and RS2, respectively), which are interpreted as thrust faults. Prepared with data obtained from the US Geological Survey web site (available on-line at http://astrogeology.usgs.gov/products/Mercury-Messenger-Global-Mosaic).

Figure 2. The same MESSENGER-based mosaic of Figure 1 detailing northern and southern scarps of this investigation (RS1 and RS2, respectively), interpreted to mark thrust faults, including other scarps (red lines), Rembrandt impact crater rim (blue lines), Rembrandt basin and a north-trending basin, both of which contain intercrater plains materials (Pl2) delineated by approximate geologic contacts (white lines), heavily cratered highland materials (Pl1), narrow ridges often wrinkle-ridge-like (pink lines), deformed impact craters of special interest as detailed in the text (craters A-D), trough-like landforms (tan lines), interpreted to be either extension features such as normal faults or lines of coalesced secondary craters associated with the Rembrandt impact event. RS2nb is a northeastern branch of RS2, and T is a narrow trough-like feature crossing the RS2 scarp; both features are discussed in the main text. Both RS1 and RS2 clearly show structural control in several places.

Figure 3. a) MESSENGER image showing RS2 in the area around crater C. **b)** The same MESSENGER image marking scarps (red lines) and a trough-like feature (labeled T), which crosses RS2.

Figure 1
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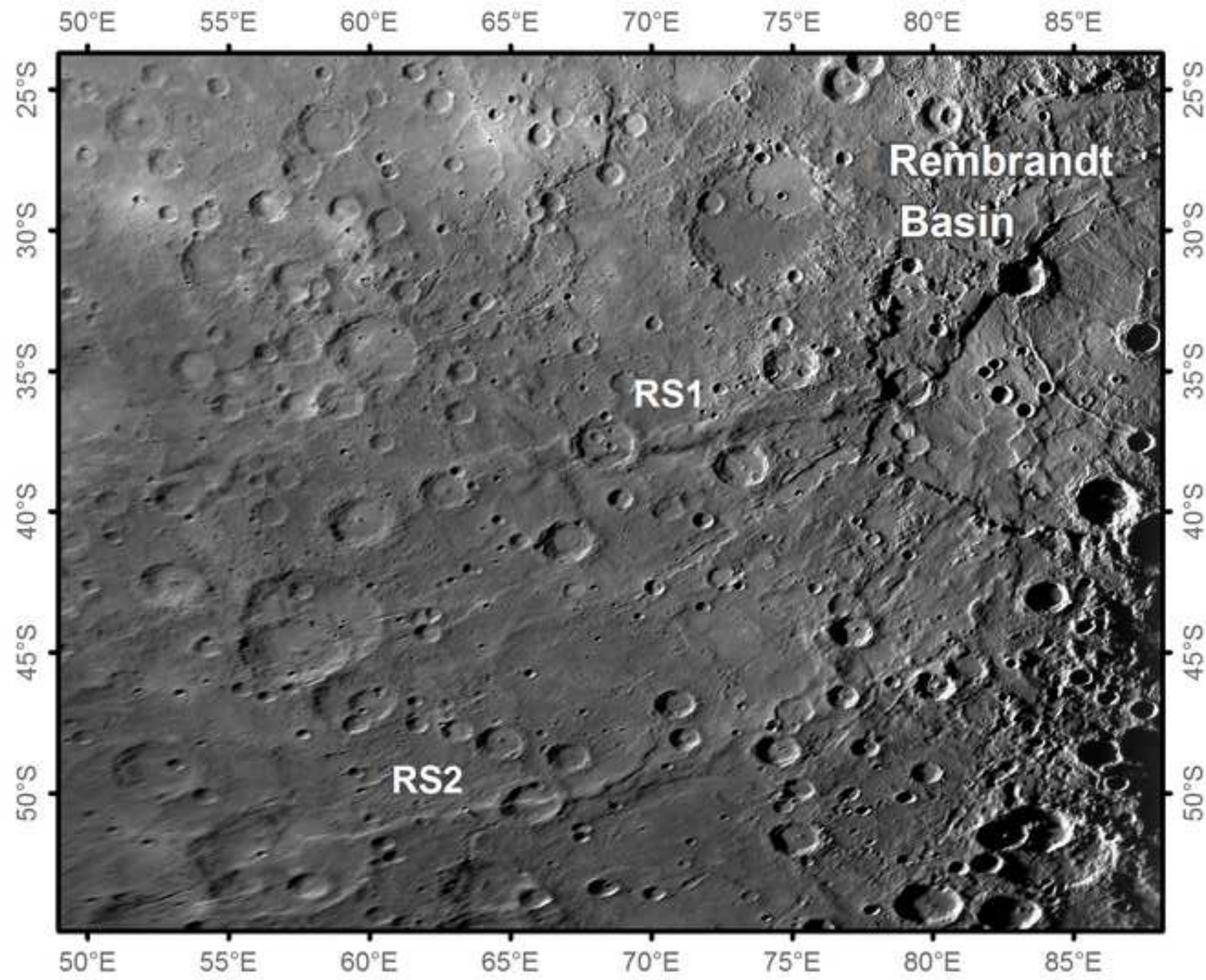

Figure 2
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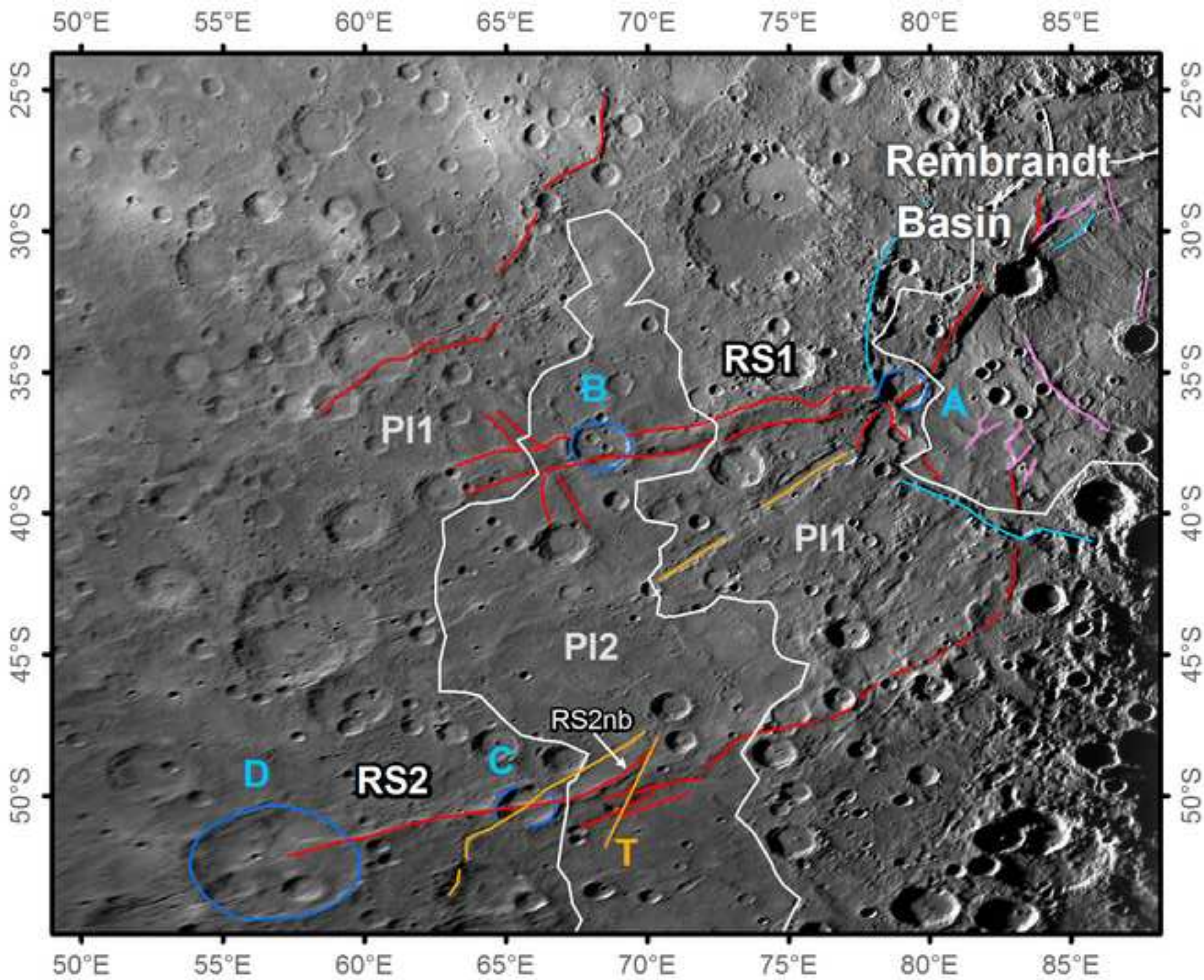

Figure 3a
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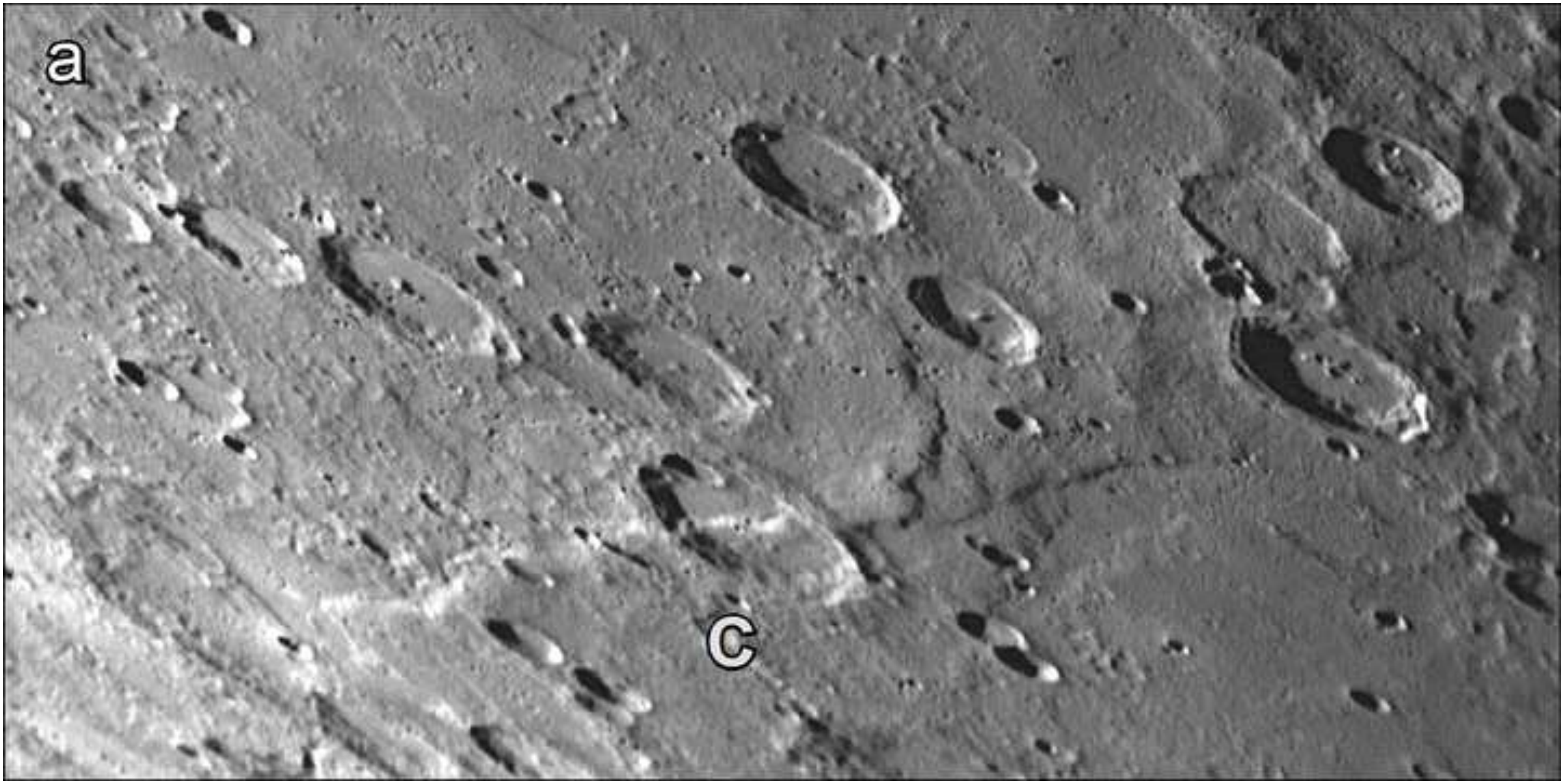

Figure 3b
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