The ubiquity and significance of extensional grabens on Mercury's lobate scarps

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Abstract

Mercury's surface is dominated by tectonic landforms formed by compression. Other than within basins, extensional landforms are not well known and have been presumed to be much rarer, with only a handful reported [1]. To date, two types of extensional grabens associated with lobate scarps have been described in literature: pristine back-scarp grabens associated with small lobate scarps (10s of kms in length and 10s of metres in relief) [2] and crestal grabens found on Calypso Rupes (381km in length and ~1km in relief) [3], [4]. This study identifies that such extensional grabens found on lobate scarps are much more widespread than previously recognised. These form when thrusting produces a hanging wall anticline, and local tensional stresses along the anticlinal axis cause antithetic faults to form in the folded strata, parallel or sub-parallel along the hinge zone, producing a down-dropped fault block. These small-scale features (often less than 1km in width, 10s of kms in length and likely 10s to 100s of metres in depth) are not expected survive 100s of millions of years because of regolith formation and impact gardening masking their signature [1], [2]. Our discovery and documentation of more extensional grabens may indicate that significant movement on many of Mercury's large lobate scarps persisted until geologically recent times. [1] P. K. Byrne, C. Klimczak, and A. M. C. Sengör, "The Tectonic Character of Mercury," in Mercury : The View After MESSENGER, 1st Editio., S. C. Solomon, L. R. Nittler, and B. J. Anderson, Eds. Cambridge: Cambridge University Press, 2018, pp. 249–286. [2] T. R. Watters, K. Daud, M. E. Banks, M. M. Selvans, C. R. Chapman, and C. M. Ernst, "Recent tectonic activity on Mercury revealed by small thrust fault scarps," Nat. Geosci., vol. 9, no. 10, pp. 743–747, 2016. [3] C. Klimczak, P. K. Byrne, A. M. C. Şengör, and S. C. Solomon, "Principles of structural geology on rocky planets," Can. J. Earth Sci., vol. 56, no. 12, pp. 1437–1457, Dec. 2019. [4] M. E. Banks et al., "Duration of activity on lobate-scarp thrust faults on Mercury," J. Geophys. Res. E Planets, vol. 120, no. 11, pp. 1751–1762, 2015.

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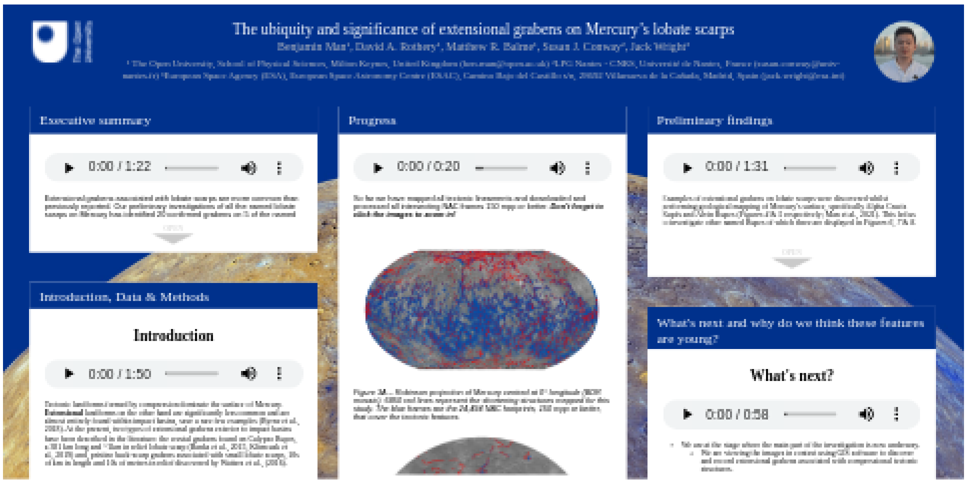

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EXECUTIVE SUMMARY

Extensional grabens associated with lobate scarps are more common than previously reported. Our preliminary investigations of all the named lobate scarps on Mercury has identified 20 confirmed grabens on 5 of the named structures with another 58 tentative grabens across 21 different structures. This has prompted our global survey of compressional tectonic structures in order to identify and record all associated extensional grabens. So far, all tectonic structures (6850 individual lines) have been mapped at a digitisation scale of 1:500,000 and all Narrow Angle Camera (NAC) frames (24,494 total) of 150 metres per pixel (mpp) or better that intersect the mapped tectonic structures have been downloaded and processed using the USGS's (United States Geological Survey) ISIS3 (Integrated Software for Imagers and Spectrometers version 3). The investigation is currently ongoing with the main bulk of NAC frames being analysed in context. Once the global survey is complete, we plan to discover as much as we can about the landforms, where they are forming and why, and what they can tell us with regard to Mercury's tectonic evolution.

If you'd like to keep up-to-date with the project on researchgate please scan the QR code.

INTRODUCTION, DATA & METHODS

Introduction

Tectonic landforms formed by compression dominate the surface of Mercury. **Extensional** landforms on the other hand are significantly less common and are almost entirely found within impact basins, save a rare few examples (Byrne et al., 2018). At the present, two types of extensional grabens exterior to impact basins have been described in the literature: the crestal grabens found on Calypso Rupes, a 381 km long and ~1km in relief lobate scarp (Banks et al., 2015, Klimczak et al., 2019) and, pristine back-scarp grabens associated with small lobate scarps, 10s of km in length and 10s of metres in relief discovered by Watters et al., (2016).

Formation

Extensional grabens associated with thrust structures form when thrusted strata produce a hanging wall anticline. Local tensional stresses along the anticlinal axis cause antithetic faults to form producing a down-dropped fault block; see *Figure 1* below.

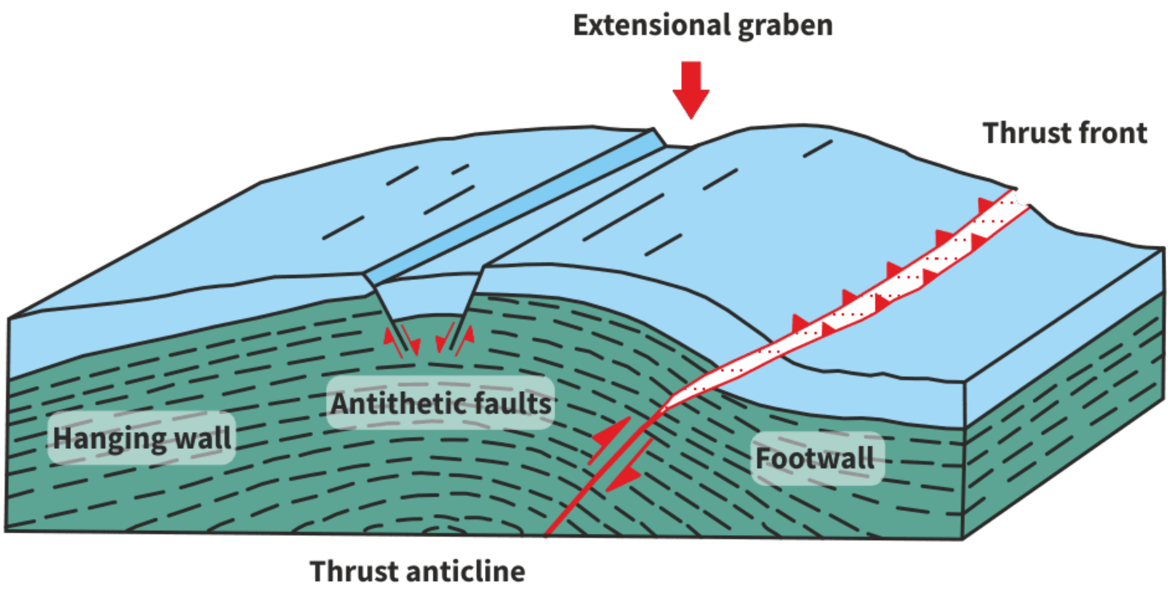


Figure 1 – Block diagram of extensional graben formation. Strata do not correspond to actual morphological units on Mercury. Notice the tension cracks along the crest of the anticline. Figure modified after Plescia and Golombek (1986).

Importance

1. Extensional grabens are small-scale shallow landforms, 10s to 100s of metres in depth, 10s of km in length and often less than 1 km in width. Such small-scale features are likely geologically young as they <u>are not expected to survive 100s of millions of years</u> due to impact gardening and regolith formation quickly masking their signatures (Byrne et al., 2018, Watters et al., 2016, Watters et al., 2012).
2. The presence of these landforms may indicate that movement on many of Mercury's compressional structures persisted until geologically recent times.
   - This therefore calls into question absolute age estimates of tectonic features' last movements using crater counting (Fegan et al., 2017, Galluzzi et al., 2019, Giacomini et al., 2015, Giacomini et al., 2020, Man et al., 2020), with all authors suggesting final movements took place billions of years ago.

Data

The data used for this project was collected by the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft's Mercury Dual Imaging System between 2011-2015.

For mapping of tectonic lineaments we used several datasets and examples of each for quadrangle H13 using a Lambert Conformal Conic projection are shown below in *Figure 2.* ***(Don't forget to click the images to zoom in!)***

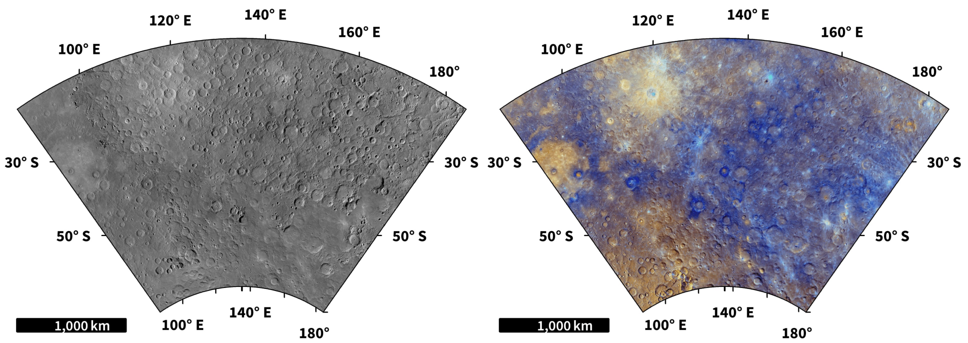


Figure 2A – Left = Basemap reduced data record (BDR) version 1.0 (166 mpp), Right = Enhanced Color (665 mpp).

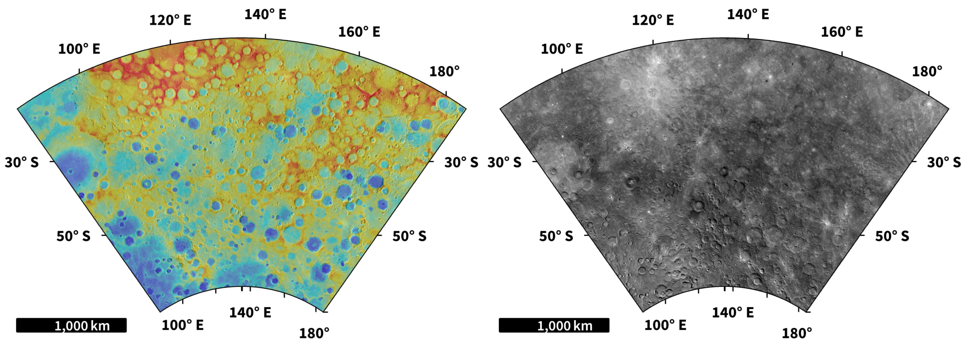


Figure 2B – Left Digital Elevation Model (665 mpp), Right = Low Incidence Angle mosaic (166 mpp).

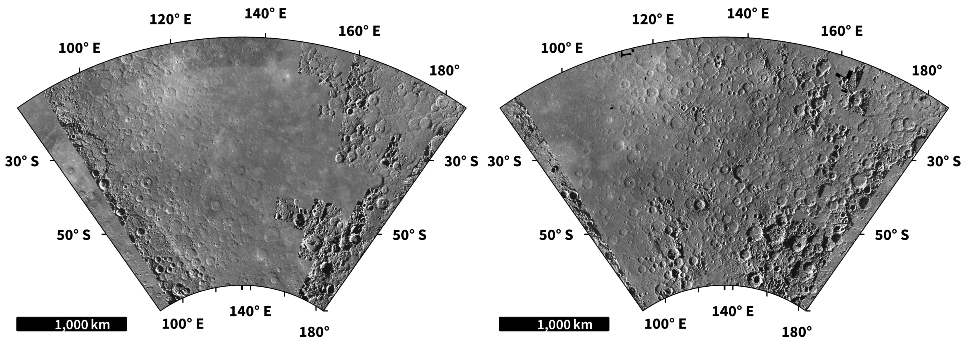


Figure 2C – Left = High Incidence East tiles (166 mpp), Right = High Incidence West tiles (166 mpp).

For the extensional graben survey, the aforementioned datasets plus individual NAC frames 150 mpp or better are to be used (NAC frame footprints are shown in blue in *Figure 3*).

All data was downloaded from the Planetary Data System curated by the National Aeronautics and Space Administration.

Methods

- All data has been processed using the USGS's ISIS3 so that image files can be viewed with the correct projection within a Geographical Information System (GIS) software.
- In this project we use ESRI's ArcGIS 10.5.1 and ArcGIS Pro 2.9.0. For selection of NAC frames, JMARS developed by Arizona State University's Mars Space Flight Facility was used (Christensen et al., 2009).
- Mapping of lineaments was undertaken on a quadrangle by quadrangle basis changing the conformal map projection to preserve the local shape of surface features. Digitisation scale was at a constant 1:500,000 with a streaming tolerance of one vertex every 2000 metres. See *Figure 3A*, tectonic lineaments are demarcated by the red linework.
- For the extensional grabens survey, a point is placed on each graben and is given either a "*confirmed*" or "*tentative*" designation based on my interpretation.

PROGRESS

So far we have mapped all tectonic lineaments and downloaded and processed all intersecting NAC frames 150 mpp or better. ***Don't forget to click the images to zoom in!***

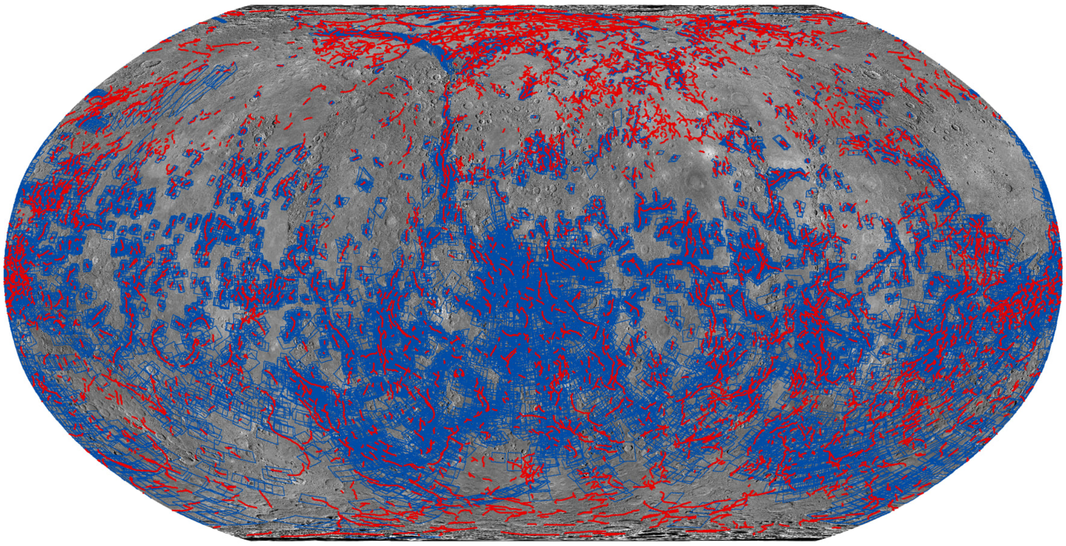


Figure 3A – Robinson projection of Mercury centred at 0° longitude (BDR mosaic). 6850 red lines represent the shortening structures mapped for this study. The blue frames are the 24,494 NAC footprints, 150 mpp or better, that cover the tectonic features.

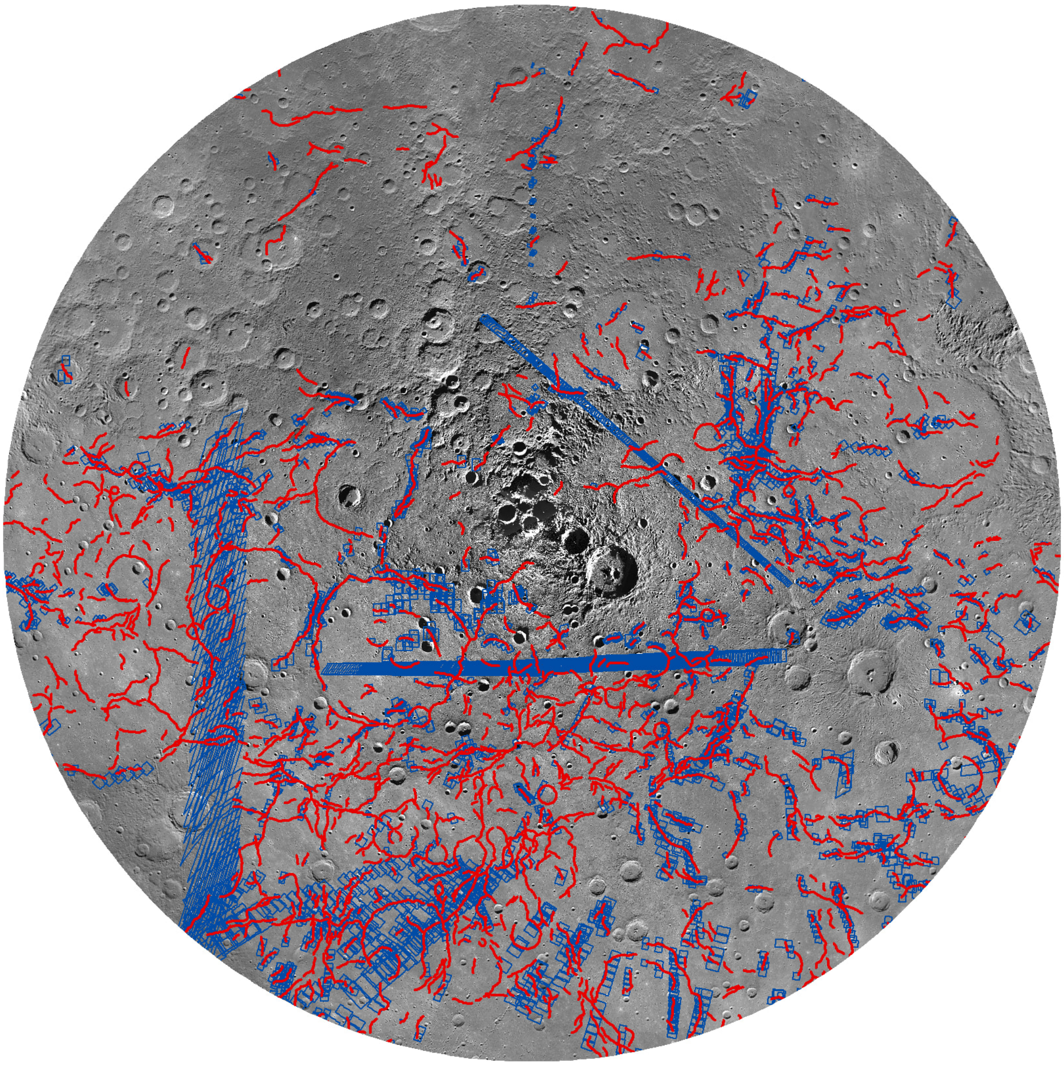


Figure 3B – North Pole "quadrangle" of Mercury (H01 Borealis) at in a Polar Stereographic projection from 65-90° N, top of figure = 180° longitude (BDR mosaic). Red lines and blue frames as in 3A.

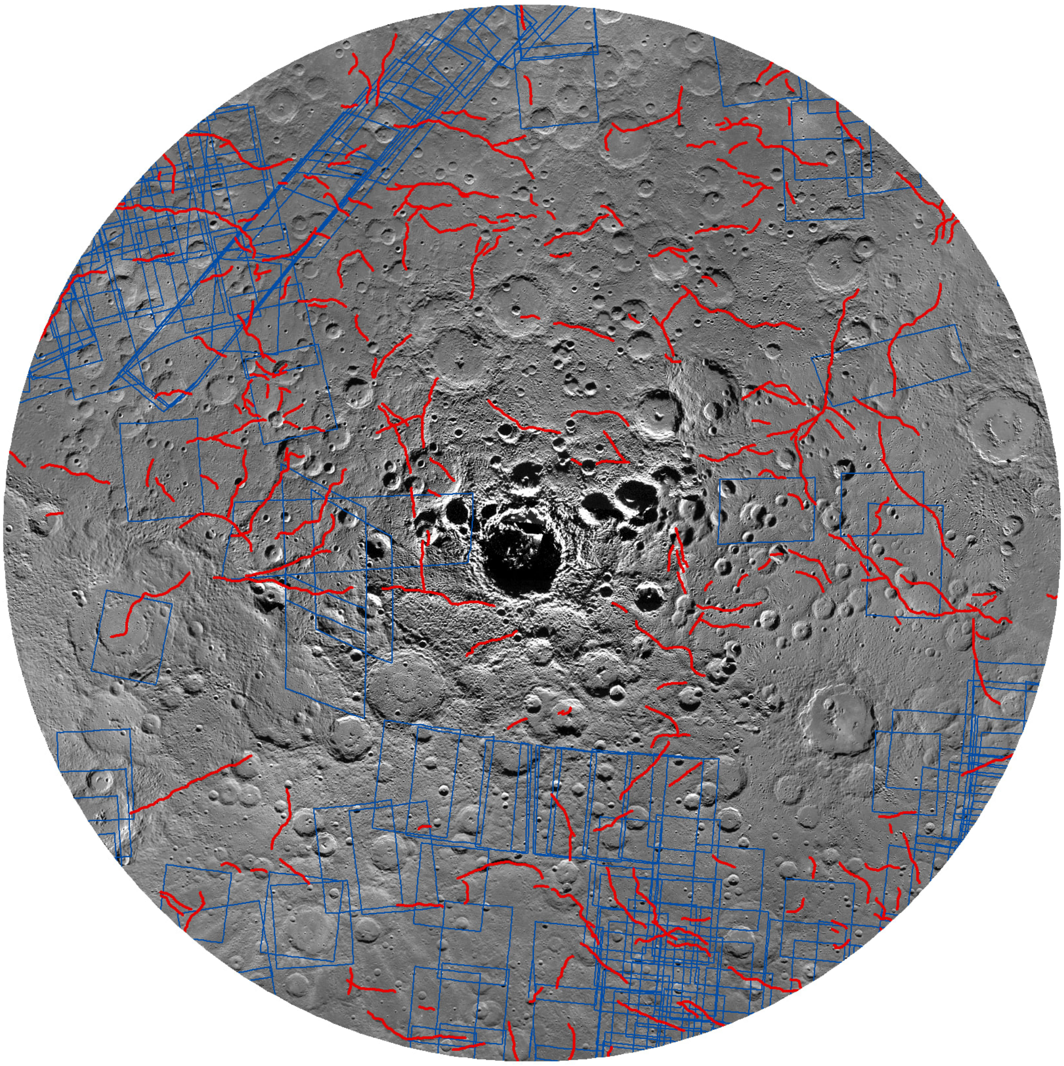


Figure 3C – South Pole "quadrangle" of Mercury (H15 Bach) in a Polar Stereographic projection from 65-90° S, top of figure = 0° longitude (BDR mosaic). Red lines and blue frames as in 3A.

PRELIMINARY FINDINGS

Examples of extensional grabens on lobate scarps were discovered whilst performing geological mapping of Mercury's surface, specifically Alpha Crucis Rupēs and Alvin Rupes (*Figures 4* & *5* respectively; Man et al., 2021). This led us to investigate other named Rupes of which three are displayed in *Figures 6*, *7* & *8*.

Alpha Crucis Rupes

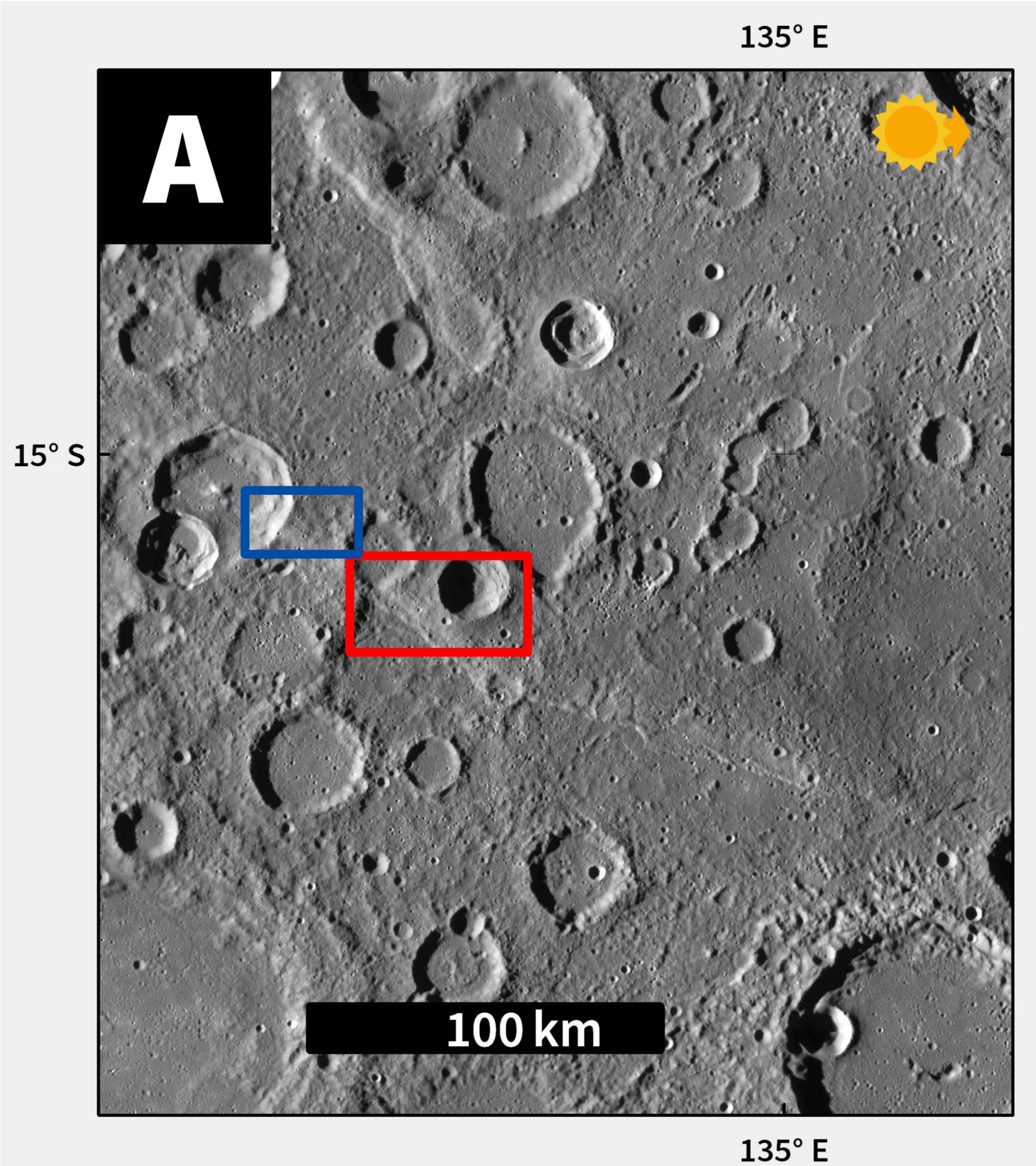


Figure 4A – Overview image of Alpha Crucis Rupēs with red box indiciating extent of 4B and blue box indicating extent of 4C.

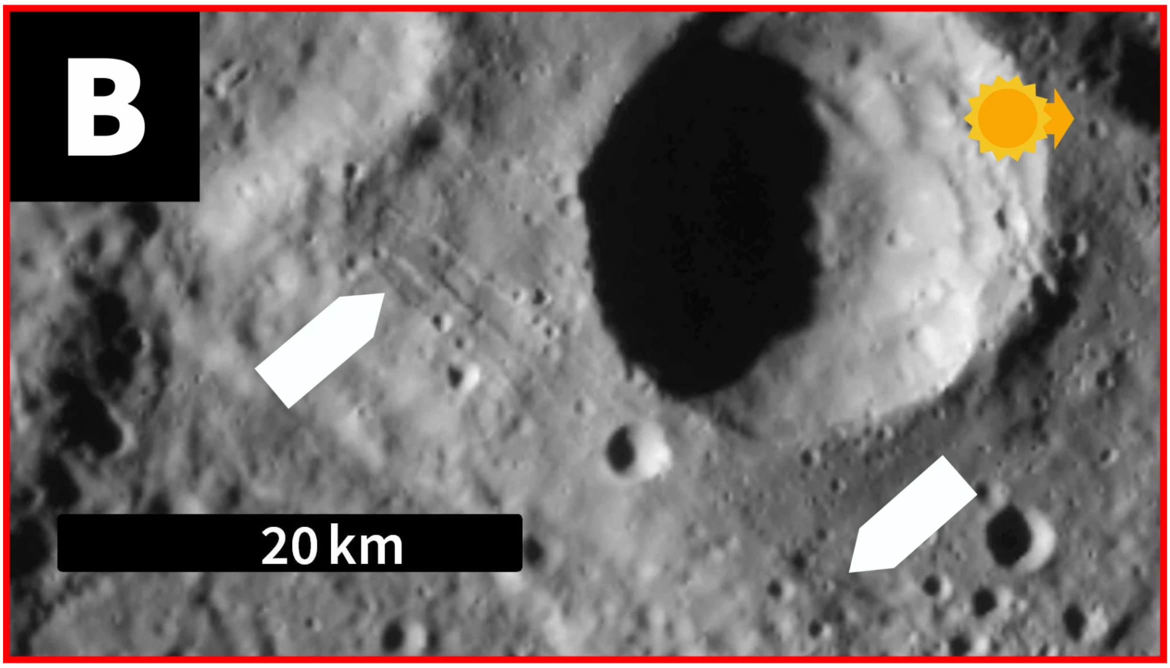


Figure 4B – Archetypical graben and horst structures found on top of the Alpha Crucis Rupēs thrust front. White arrows indicate the location of extensional grabens.

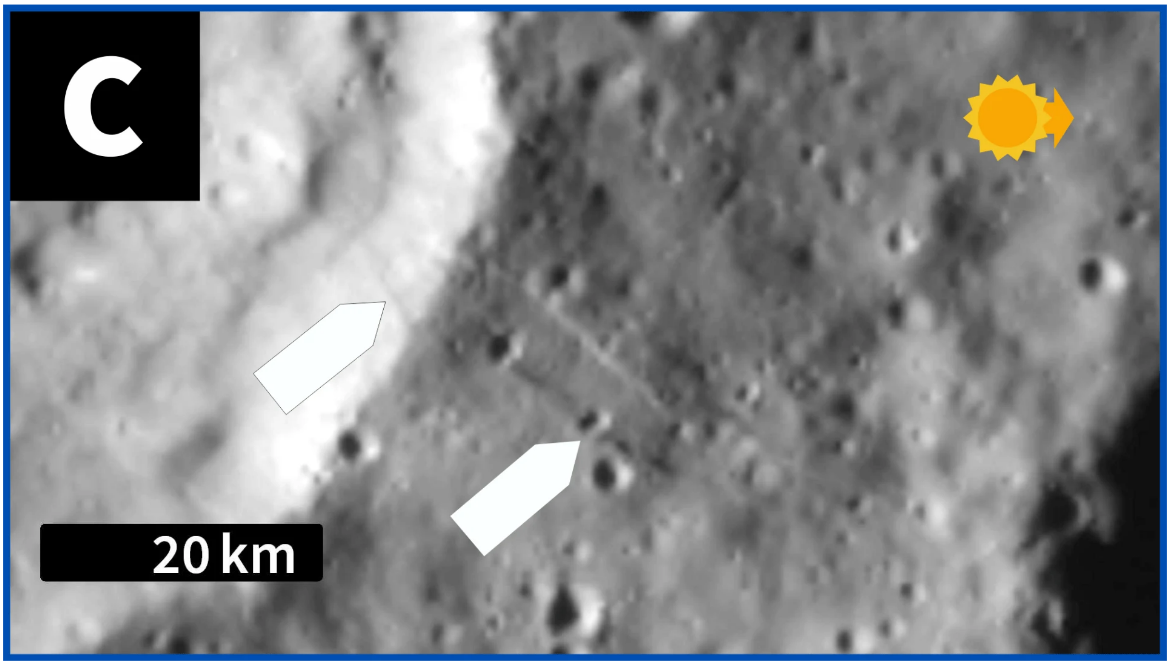


Figure 4C – Graben is observed cutting across the rim of the large crater (left white arrow). Right white arrow shows a small superposing crater deformed by the graben. This indicates that graben movement postdates the small impact.

Alvin Rupes

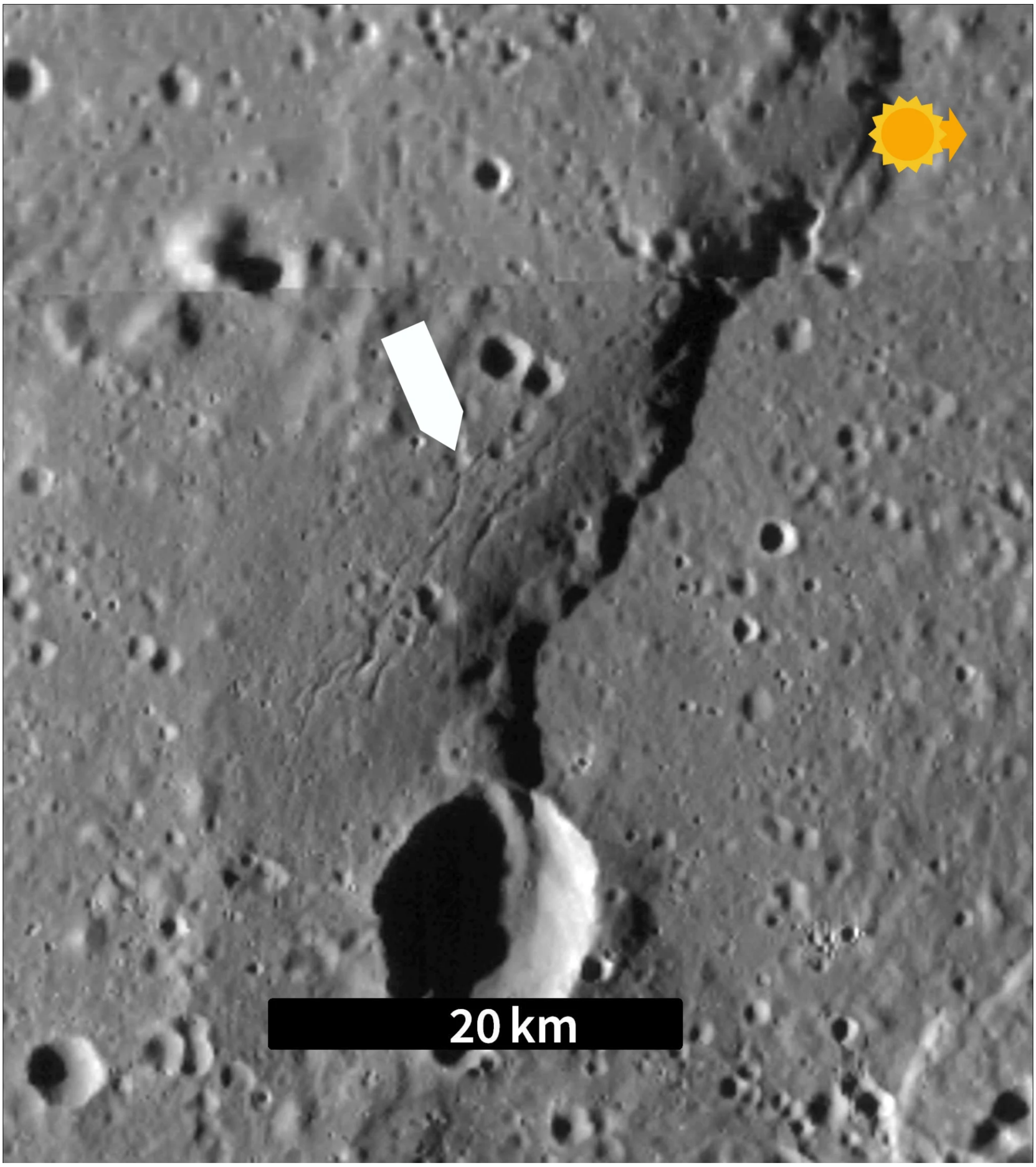


Figure 5 – Alvin Rupes, white arrow identifies a complex array of extensional grabens on the crest of the thrusted hanging wall anticline.

Adventure Rupes

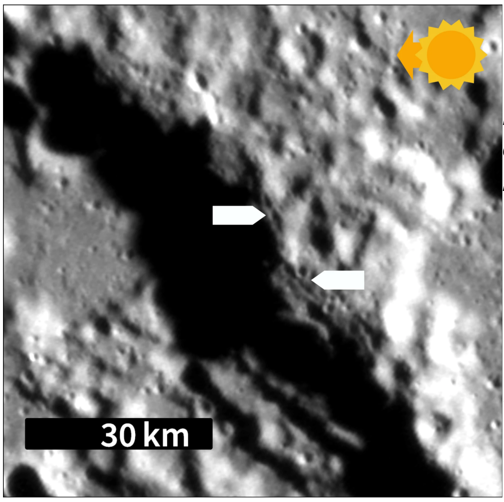
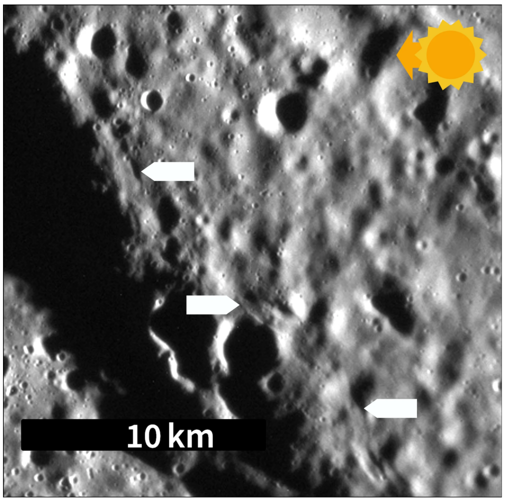


Figure 6 – Adventure Rupes, white arrows identify confirmed extensional grabens just above the thrust's break in slope.

Grifo Rupes

Figure 7 – Grifo Rupes, white arrows identify confirmed extensional grabens. Notice the centre white arrow points to a graben cutting the rim of a ~2km diameter crater.



Calypso Rupes

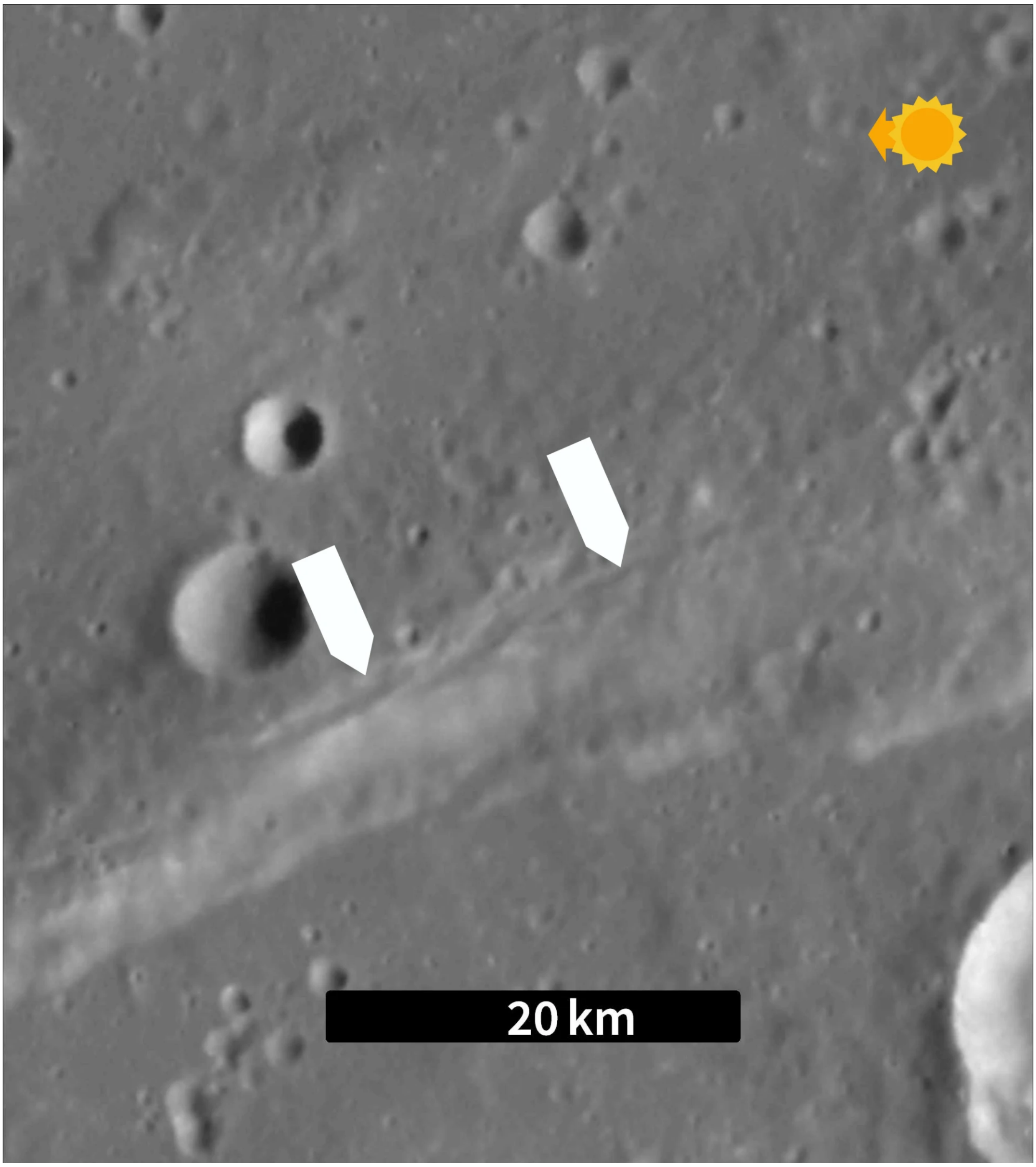


Figure 8 – Calypso Rupes, white arrows identify confirmed extensional grabens just above the break in slope. First observed by Banks et al., (2015) and then reported on by Klimczak et al., (2019).

WHAT'S NEXT AND WHY DO WE THINK THESE FEATURES ARE YOUNG?

What's next?

- We are at the stage where the main part of the investigation is now underway.
  - We are viewing the images in context using GIS software to discover and record extensional grabens associated with compressional tectonic structures.
- Once the extensional graben survey is complete, there are numerous avenues of analysis that we can pursue. For example:
  - Are there any patterns such as are they randomly distributed across the planet or clustered in certain areas?
  - Are they found on structures of varying relief or do they only form on structures with significant relief?
  - Are they more commonly found on structures cutting smooth plains or intercrater plains?
  - Is there a relationship between the presence of extensional grabens and the orientation of the parent compressional structure?
  - Is there evidence of recent movements with superposing craters being deformed by extensional graben?
  - Are the extensional grabens deep enough to perform shadow measurements to ascertain depth metrics?

Why we think these features are young

Mercury is often compared with the Moon as both are terrestrial airless bodies. Research regarding the differences between Mercury and the Moon's regolith, regolith production rate and micrometeoric flux suggests that Mercury's regolith layer is significantly thicker (Kreslavsky & Head 2015, Zharkova et al., 2020) and the production rate is greater due to a higher micrometeoric flux (Cintala 1992. Borin et al., 2009). In addition, abrasion by micrometeoric impacts on Mercury is considerably more efficient than on the Moon (Kreslavsky et al., 2021). Furthermore, the optical maturation rate of Mercury's regolith is up to 4 times faster than on the Moon (Braden and Robinson 2013), and work by Fassett et al., (2017) proposes that crater degradation on Mercury is twice as fast as on Moon.

With all this said, extensional grabens on Mercury are likely to be very young and may be evidence for ongoing tectonism.

Acknowledgements

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AUTHOR INFORMATION

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3rd year doctoral student at The Open University, United Kingdom.

For my doctoral studies I am mapping the Neruda quadrangle (H13) of Mercury and investigating extensional grabens, their ubiquity and signifiance in regard to Mercury's tectonic evolution.

Feel free to e-mail me at: ben.man@open.ac.uk or find me on twitter!

@AstroBenjamin

ABSTRACT

Mercury's surface is dominated by tectonic landforms formed by compression. Other than within basins, extensional landforms are not well known and have been presumed to be much rarer, with only a handful reported [1]. To date, two types of extensional grabens associated with lobate scarps have been described in literature: pristine back-scarp grabens associated with small lobate scarps (10s of kms in length and 10s of metres in relief) [2] and crestal grabens found on Calypso Rupes (381km in length and ~1km in relief) [3], [4].

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