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Morphostructural mapping of Borealis Planitia, Mercury

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ABSTRACT

Orbital data from the MESSENGER spacecraft show that a significant portion of Mercury's northern hemisphere is covered by smooth plains, which are interpreted to be flood volcanic material and/or impact melt. The smooth plains show pervasive tectonic structures and encompass a broad raised bulge of uncertain geophysical interpretation. In this work, we focus on the mapping of all the morphostructures within the northern smooth plains, aiming at providing a useful dataset for further studies about the mapped area. The structural map is obtained through a twofold process: first with an automatic mapping, using an algorithm to identify all the lineaments from a DEM; and second with a visual inspection and classification of the results of the algorithm in a GIS environment. The final maps are drafted at two different scales, 1:300,000 and 1:600,000. With this approach, we mapped and characterized more than fifty thousand lines marking scarps on the surface, creating a database with several morphometric attributes for each of the identified scarps (e.g. length, azimuth, and height), which can be used for geostatistical study of smooth plains tectonics. Our structural map reveals that: (i) the area is broadly dominated by wrinkle ridges, ghost crater assemblages of lineaments, and scarps related to impact crater processes (e.g. radial faults, secondary crater chains, ejecta emplacement) and that (ii) the amount of strain was not evenly accommodated throughout the northern smooth plains.

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Mercury; wrinkle ridges; ghost craters; automatic mapping; tectonic processes

1. Introduction

Orbital data acquired by the Mercury Dual Imaging System (MDIS) instrument onboard the NASA MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging) mission (Solomon Sean, et al., 2001, 2008) enabled the completion of the first mapping of Mercury's north polar region (50–90° of latitude). Previously, Mariner 10 and MESSENGER flyby image coverage (Danielson et al., 1975; Solomon et al., 2008; Trask & Guest, 1975) showed large regions of smooth plains surrounded by cratered terrains (Denevi et al., 2009; Head et al., 2011; Spudis & Guest, 1988; Strom et al., 2008). New orbital data acquired by MDIS (Hawkins et al., 2007) provided full coverage of the northern region of Mercury at high resolution, allowing a better understanding of the geomorphology of the area.

Two main geological terrains characterize the Mercury's north polar region: the northern heavily cratered terrain (NHCT) and the northern smooth plains (NSP) (Ostrach et al., 2015). The first unit is characterized by densely cratered areas (Fassett et al., 2011; Trask & Guest, 1975). The northern smooth plains are instead uniform with far fewer craters than the cratered terrain (Guest & Gault, 1976; Strom et al., 1975) and geomorphological features similar to the lunar maria (Head et al., 2008, p. 2011; Strom et al., 1975), though with different composition (e.g. Nittler et al., 2011; Vander Kaaden et al., 2017). Mariner 10 imagery showed that the NSP have a lower density of impact craters and are younger than the NHCT (Denevi et al., 2009; Head et al., 2011; Strom et al., 1975, p. 1975). The limited spatial resolution of the Mariner 10 dataset (Malin, 1978; Milkovich et al., 2002) did not permit the identification of volcanic features, but a volcanic origin of the NSP was hypothesized due to their distribution, young age, visible color properties, and overlapping relationships with tectonic structures (Murray, 1975; Robinson & Lucey, 1997; Robinson & Taylor, 2001; Spudis & Guest, 1988). It is also possible that the NSP are widely distributed due to effusive volcanism (Byrne et al., 2013; Denevi et al., 2009, 2013; Fassett et al., 2009; Freed et al., 2012; Goudge et al., 2014; Head et al., 2008, 2009, p. 2011; Hurwitz et al., 2013; Kerber et al., 2009, 2011; Klimczak et al., 2012; Murchie et al., 2008; Robinson

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et al., 2008; Solomon et al., 2008). Furthermore, volcanic activity in the NSP could be related to phenomena of partial flooding of the crater floors (Head et al., 2009) or to the record of volcanically resurfaced impact crater regions (Ostrach et al., 2015). Finally, the NSP area is characterized by the widespread occurrence of morphologic scarps as investigated in previous studies about the tectonics of the region based on digital mapping (e.g. Crane & Klimczak, 2019).

Significant improvements in digital mapping procedures and new photo interpretation techniques along with the availability of high-resolution datasets have greatly improved the analysis of planetary surfaces. Several automatic mapping methods have been applied in planetary sciences to characterize geomorphologic features such as aeolian bedforms at different scales (Borraccini et al., 2007; Cardinale et al., 2020; Foroutan & Zimbelman, 2017; Vaz and Silvestro, 2014; Vaz et al., 2015); crater counting (Bandeira et al., 2007; Bue & Stepinski, 2006); and drainage networks (Stepinski & Collier, 2004). Here, we use the mapping technique introduced by Vaz (2011): a method aimed at extracting lineaments that represent topographic discontinuities from digital elevation models (DEM), which can be used to characterize tectonic structures in planetary surfaces (Vaz et al., 2014) without being affected by possible bias due to the illumination conditions of imagery.

In this work we apply this semi-automatic approach described in Vaz et al. (2014) to Mercury for the first time, producing a detailed morphotectonic map of the Borealis Planitia region. We defined our mapping area following the boundaries of the northern smooth deposits (NSP) as in Denevi et al. (2009 and 2013). Substantial parts of NSP are included in Mercury quadrangles H02 (Victoria) and H05 (Hokusai) both of which have been geologically mapped at 1:3M (Galluzzi et al., 2016; Wright et al., 2019) We adopt a semi-automatic procedure based on a digital elevation model (DEM) rather than imagery, resulting in the identification of tens of thousands of structures within the NSP (Figure 1), which represents a significantly wider geodatabase with respect to the previous maps obtained using traditional mapping techniques (e.g. Crane & Klimczak, 2019). The numeric attributes of each of the mapped lineaments can be used for quantitative studies to better characterize the density and spatial distribution of tectonic features and improve our understanding of the tectonic evolution of the NSP. Finally, Mercury's structural maps derived from imagery photogeologic interpretation might often be biased by the variable resolution and illumination conditions of the used basemaps. Indeed, more recent investigations based on MESSENGER data (Solomon et al., 2008), led to the revision of previous results based on Mariner imagery (e.g. Di Achille et al., 2012; Watters & Nimmo, 2010; Watters et al., 1998, 2004, 2009). In contrast, our mapping approach is unaffected by the imagery illumination conditions and variable resolution, since it is based on the use of a fixed resolution datasets, such as a equally spaced DEM.

2. Data and methods

MESSENGER MDIS visible imagery (Denevi et al., 2016; Hawkins et al., 2007) with a resolution of 166 meters per pixel was used as a basemap. Topography was reprocessed using the raw Mercury Laser Altimeter (MLA) data (Denevi et al., 2016; Hawkins et al., 2007), creating a final DEM with 500 m/pix to better characterize the tectonic lineaments and measure morphometric parameters (e.g. length, azimuth, scarp height). Elevation points were integrated using a block median operator (Wessel & Smith, 1998), and a natural neighbor algorithm was used for the interpolation. The first iteration revealed that some of the orbits presented a noticeable vertical offset. Therefore, we identified and removed 128 orbits from the dataset, obtaining a more uniform DEM.

With these datasets, we implemented a Geographical Information System (GIS) project in stereographic projection (centered at the NSP, 70° N and 30° E) and created a geo-structural map of the surface (Figures 2 and 3). Our map is obtained through a twofold process: (1) automatic mapping using an algorithm to identify all the lineaments from a DEM (Vaz, 2011; Vaz et al., 2014), and (2) visual inspection and classification of the results in a GIS environment. The final maps were drafted at two different scales, 1:300,000 and 1:600,000. With this approach, we mapped and characterized more than fifty thousand lines marking tectonic features on the surface, creating a database with several morphometric attributes (e.g. length, azimuth, tectonic lineaments height – a list of all the derived parameters and their description is provided in the Supplementary materials) that can be used for the geostatistical study of the smooth plains' tectonics. With respect to traditional mapping based on visible interpretation of imagery and topography, the technique used in this work is a more robust and detailed approach since it recognizes and maps all scarps present in the DEM; however, this means that a scarp/lineament classification stage is needed in order to study a specific set/type of structure. This is achieved through the second mapping step (the visual inspection of the results of the automatic procedure) by overlaying the mapped lineaments onto the image mosaics in a GIS interface, allowing a user to interpret the geomorphological meaning/origin of the automatically mapped features. In this classification stage, we recognized the tectonic structures and excluded other features that were not relevant for the structural analysis, some of which were not recognizable in the imagery or were clearly associated with DEM

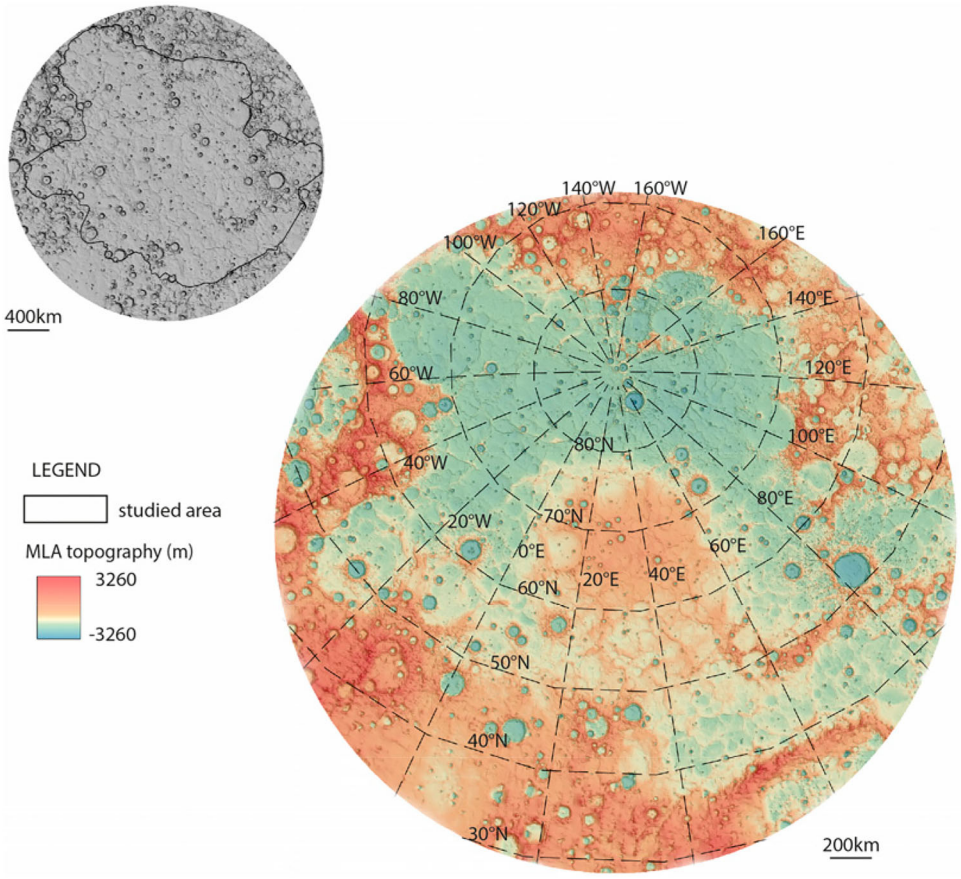

Figure 1. Northern hemisphere of Mercury: color coding from MLA topography. The investigated area is outlined by the black contour in the upper left inset.

artifacts. In this way, we extracted 45,012 lines from the DEM (Figure 2) and classified them as wrinkle ridges, lobate scarps, ghost craters, craters, and crater ejecta.

The same methods have previously been validated with MOLA (Mars Orbiter Laser Altimeter, 231 m/pixel) data and proved to be an effective way to map and analyze tectonic morphologies on other planets, producing tectono-structural maps that are comparable to photointerpretations (Vaz et al., 2012). We then investigated the regional stress fields using the orientation of the mapped tectonic lines, representing them in a rose diagram and computing circular statistics (Figure 4). Finally, we present line density maps weighted by the length and by the average height of the scarps computed on a circular kernel with 100 km radius (Figure 5). Particularly, we extracted a line density maps for the tectonic structures (Figure 5(a)) and a density map weighted for the product of line length by line height (Figure 5(b)).

3. Results

We divided the identified lineaments into the following units: tectonic lines (e.g. wrinkle ridges, lobate scarps), ghost craters (buried and/or subdued impact craters with circular outlines) still visible in the elevation data as annular ridges; Head et al., 2009), craters (rims and central peaks), and crater ejecta (materials excavated from a crater cavity during impact or erupted from a volcanic vent – Hargitai, 2021). The photo-interpretation and inspection of the automatically identified features resulted in the exclusion of about 5% of the original lineaments, reducing the final identified lineaments to about 45,000 (Figure 2). The excluded lineaments were mostly represented by small (few kilometer long) elements that could not be associated to any of the defined structural units based on visual inspection of images and topography and their geological context. These lineaments were most likely due to DEM artifacts at km-scale. Within the investigated area, 27.5% of the mapped features correspond to tectonic features (wrinkle ridges and lobate scarps), 4.3% to ghost craters, 24.7% to craters, and 43.5% to crater ejecta. Tectonic features are spread over the entire area (Figures 3(a)–(b)) with lengths ranging between 4 and 180 km. The mapped scarps form complex arrays of wrinkle ridges and lobate scarps with average height of 245 ± 131 m. We also mapped ghost craters (Figure 3(a)–(b)). These features are widespread throughout the NSP area and outline impact features with diameters ranging from a few to several hundreds of kilometers (Figure 3(a)). The largest basin (Figure 3(a)) within the studied area, near Borealis Planitia, has a diameter of about 200 km and may contain graben structures in the crater floor (Head et al., 2011). In this area, we also mapped craters with diameters ranging between

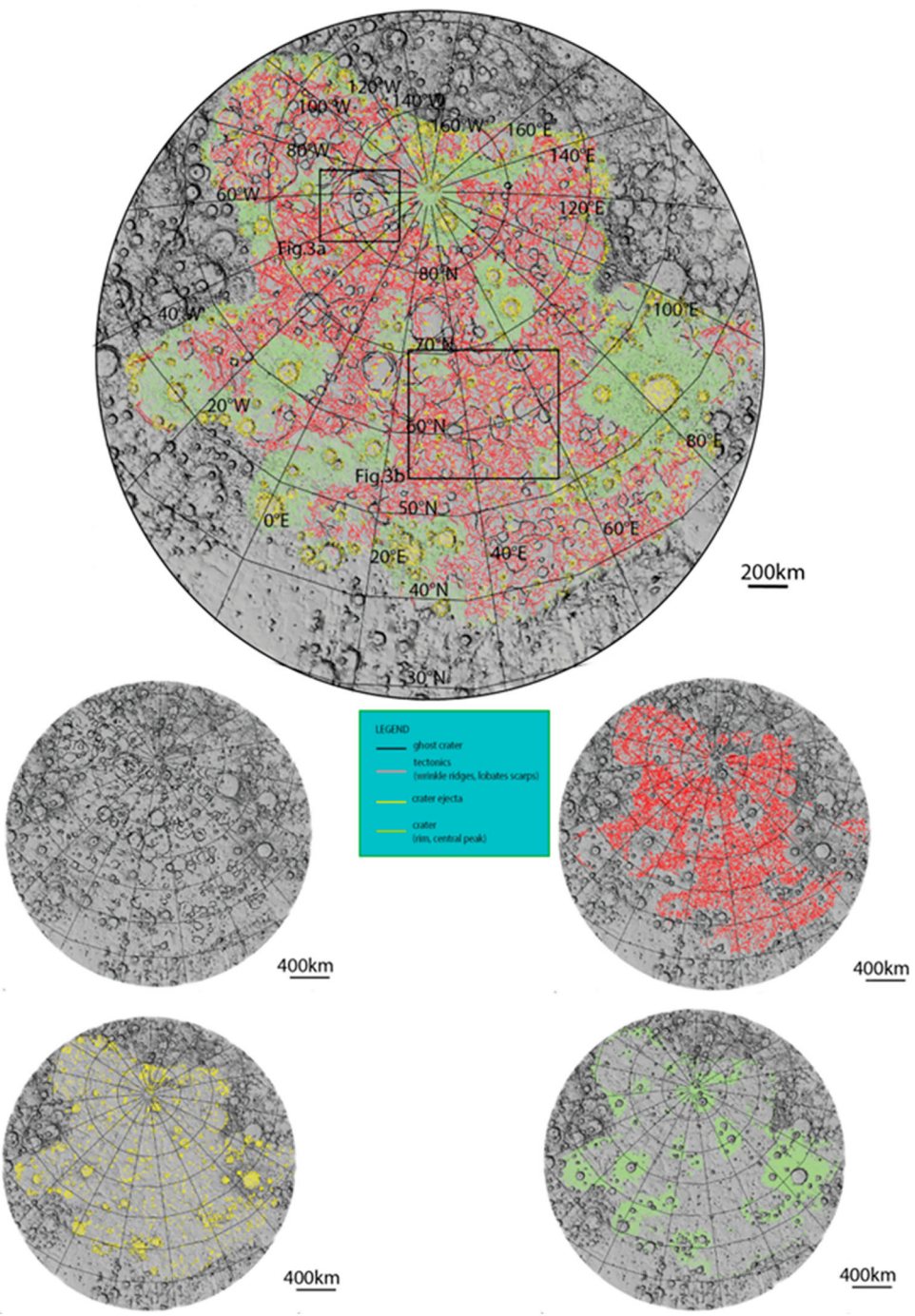

Figure 2. MLA shaded relief with superimposed geo-structural map. Lines were automatically extracted from the DTM and manually classified according to their geomorphologic significance using visible image mosaics for context.

80 and 200 km (Figure 3), including both rims and central peaks in the same class. A separate unit has been defined for the crater ejecta (Figure 3).

An overview of the lineament density map (Figure 5(a)) does not show clear tectonic clusters. The overall spatial anisotropy of the features shows a few gaps occurring in the central zone of the map. These gaps are related to the obliteration of features by impact crater structures since the gaps are associated with relatively young craters showing well-developed ejecta blankets (compare Figure 2 and Figure 5(a)). However, at the regional scale several high spatial density zones are localized in association with topographic rises and ghost craters. Contrary to the homogeneity of the spatial distribution of the lineaments, a plot of the Cartesian azimuth of the structural features shows a clear bimodal distribution at ~50° and ~135° (Figure 4). It is unclear whether the latter bimodal distribution might be related to a global stress field compatible with the overall geodynamic evolution of Mercury (e.g. Di Achille et al., 2012; Dombard, and Hauck, 2008; Melosh & Dzurisin, 1978). In addition, more detailed observations are needed to evaluate the different hypotheses to explain the tectonic evolution of Mercury's northern smooth plains. Standard line density (obtained by dividing the partial length of

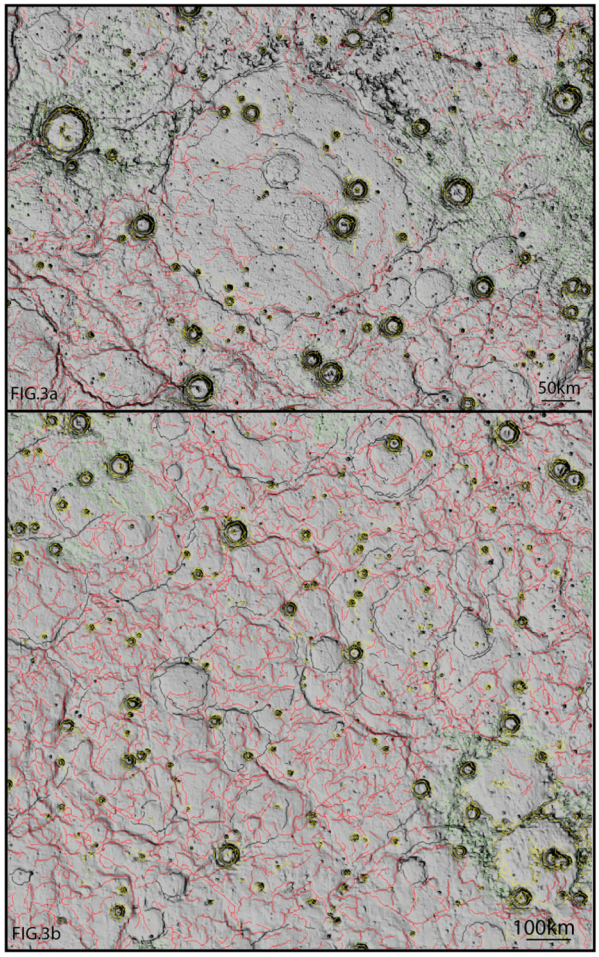

Figure 3. Close up of two regions (see Figure 2 for locations) within the studied area, showing the mapped features based on the photo-interpretation of DEM and visible data.

the lines that intersect the circular sampling neighborhood and its area) is nearly uniform, excluding the areas where craters and their ejecta obscure the tectonic features (Figure 5(a)). However, the line density weighted by the average height of the tectonic scarps; i.e. the density that is weighted by the length*height product and represents the vertical area deformed by the tectonic processes, suggests that strains are not uniform, with higher strains concentrated north-northwest of the bulge. Indeed, the latter weighting parameterization is a better proxy for the amount of cumulative strain since it integrates 3D information usually not considered in the classic 2D analysis of tectonic lineaments.

Finally, we could not quantitatively compare our results to previous mapping studies (e.g. Crane & Klimczak, 2019; Galluzzi et al., 2016; Wright et al., 2019) within the Borealis Planitia since none of the published maps were publicly released in GIS format. Moreover, Wright et al. (2019) and Galluzzi et al. (2016) focused their mapping mostly on geological units, classifying main tectonic structures at the mapped scale. While Crane and Klimczak (2019) focused their mapping on the tectonic structures of Borealis Planitia following standard mapping approaches based on visual inspection of datasets. They reported a main E-W trend for wrinkle ridges. Our results do not confirm the presence of such E-W preferential orientation for wrinkle ridges. This inconsistency might be explained considering the different mapping approaches and the

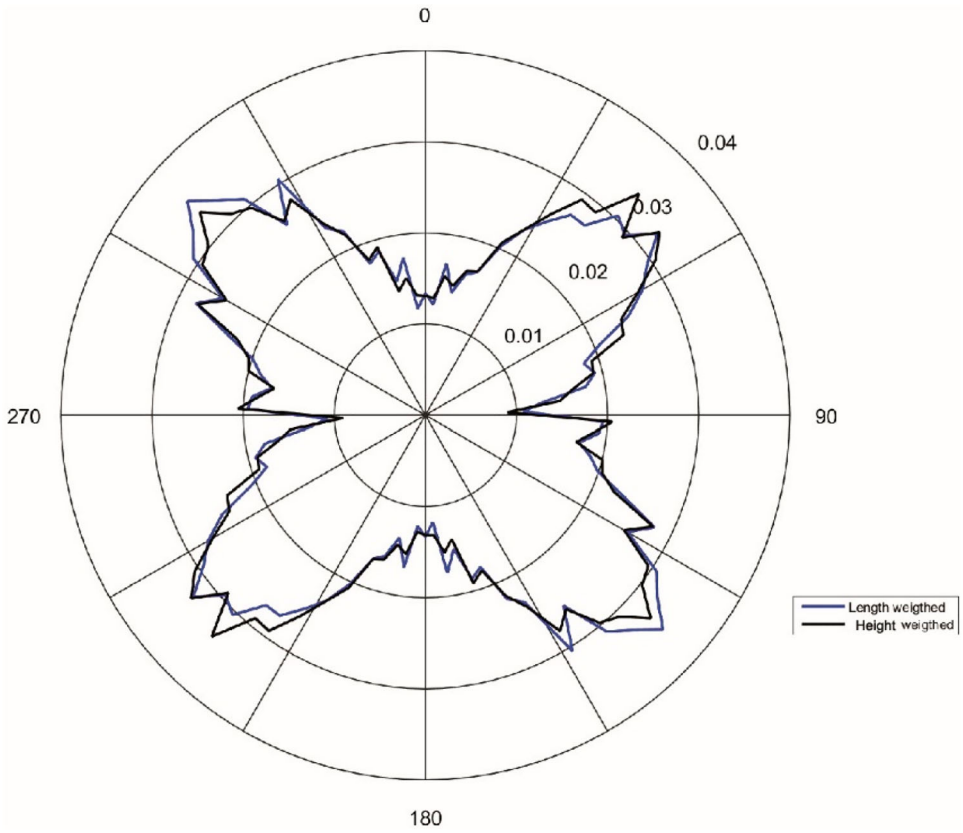

Figure 4. Scarps length- (blue) and height- (black) -weighted azimuth frequency distribution of the tectonic features.

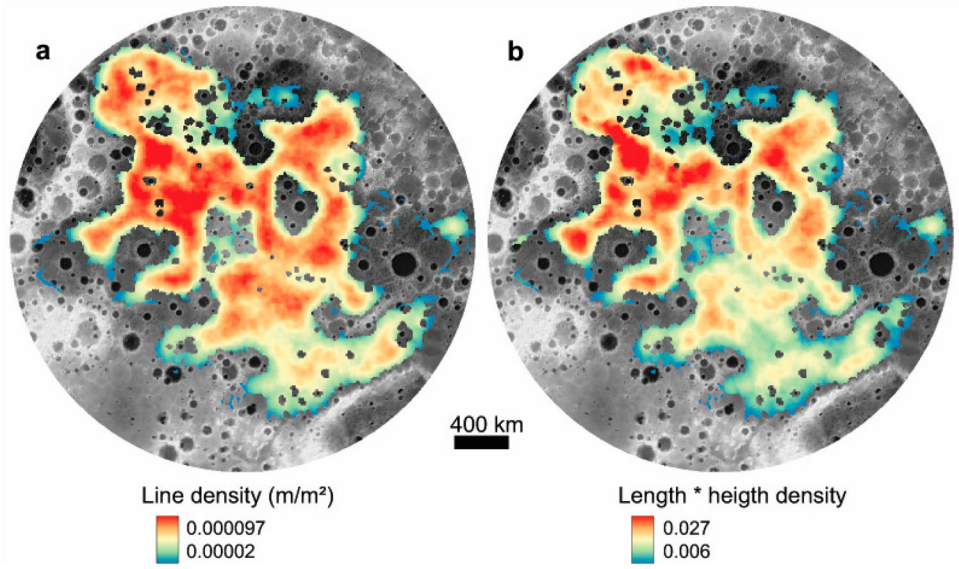

Figure 5. Line density of the mapped tectonic features computed on a circular kernel with 100 km radius. (a) standard line density (obtained by dividing the partial length of the lines that intersect the circular sampling neighborhood and its area); excluding the areas where craters and their ejecta obscure the tectonic features the density distribution is nearly uniform. (b) line density weighted by the average height of the tectonic scarps, i.e. the density is weighted by the length*height product, which represents the vertical area deformed by the tectonic processes; this parameterization is a better proxy for the amount of cumulative strain, since it integrates 3D information usually not considered in the classic 2D analysis of tectonic lineaments. Overall, the data suggests that strains are not uniform, with higher strains concentrated north-northwest of the bulge.

possibility that the E-W trend reported by Crane and Klimczak (2019) might have been biased by the imagery illumination conditions in relationship with the sub-vertical inclination of the Mercury's axis that would enhance the visibility of E-W oriented structures.

4. Summary

We present a high-resolution structural map of the Mercury's northern smooth plains produced using a semi-automatic mapping approach based on a tailored DEM. The new map revealed more than 45,000 morphotectonic lineaments over the northern smooth plains of Mercury. The identified lineaments have been archived into GIS vector shapefiles, including several numeric attributes (e.g. azimuth, length, height, slope, etc.) for each lineament. These morphometric attributes allowed us to characterize the spatial distribution of tectonic lineaments, which can be used to perform tectonic structural studies about the NSP. This map reveals that the area is broadly dominated by wrinkle ridges, ghost crater assemblages of lineaments, and scarps related to impact crater processes (e.g. radial faults, secondary crater chains, ejecta emplacement). Our structural regional analysis may be used as basemap for tectonic and geodynamic studies to understand the evolution of the northern smooth plains, as well as a target database for future missions to Mercury, starting with the joint ESA-JAXA BepiColombo mission.

Software

The tailored DEM used in this study was derived reprocessing MESSENGER Mercury Laser Altimeter (MLA) data (Denevi et al., 2016; Hawkins et al., 2007), by integrating the elevation points using the software Generic Mapping Tool (GMT, Wessel & Smith, 1998) and its block median operator. MESSENGER MDIS visible imagery (Denevi et al., 2016; Hawkins et al., 2007) were processed and mosaicked using the USGS Astrogeology Research Program Integrated Software for Imagers and Spectrometers (ISIS, http://isis.astrogeology.usgs.gov) software. Imagery and topography were subsequently used to implement a Geographical Information System (GIS) project using the QGIS software (http://www.qgis.org). The automatic mapping was realized with an algorithm to identify all the lineaments from a DEM (Vaz, 2011; Vaz et al., 2014) using the MATLAB software and exported as linear Shapefile. The final maps were drafted in QGIS using its Shapefile and layout editing tools.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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