

Geological Mapping and Structural Analysis of the Western Half of the Eminescu Quadrangle (H09), Mercury



Key Points:

- We present the first geological map of the western half of the Eminescu quadrangle (H09) on Mercury at a scale of 1:3,000,000
- Our results show that the surface geomorphology in the study area was mainly shaped by significant tectonic and cratering processes
- The map produced helped to identify key surface features as potential scientific targets to be imaged by the ESA–JAXA BepiColombo mission

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Citation:

El Yazidi, M., Sefton-Nash, E., Orgel, C., De Marchi, G., Filiberto, J., Bradák, B., et al. (2026). Geological mapping and structural analysis of the western half of the Eminescu Quadrangle (H09), Mercury. *Journal of Geophysical Research: Planets*, 131, e2024JE008785. <https://doi.org/10.1029/2024JE008785>

Received 22 OCT 2024

Accepted 29 MAY 2026

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Abstract We present the results of the first geological mapping of the western half of the Eminescu Quadrangle (H09) on Mercury. Multiple data sets from the NASA MESSENGER Mercury Dual Imaging System instrument were used to produce a geological map covering the area between 72°E and 108°E longitude and 22.5°N and 22.5°S latitude. The map was produced at an output scale of 1:3,000,000, with mapping and line digitizing performed at a scale of 1:400,000. We define three morphological plains units: smooth, intermediate, and intercrater plains. Impact craters larger than 5 km in diameter were mapped and classified using a three-class crater system (C1–C3) based on their degree of degradation. A large population of lobate scarps and wrinkle ridges was also mapped. Frequent surface interconnections are observed between craters and lobate scarps. Craters with diameters between 5 and 20 km are more widely distributed than craters larger than 20 km in diameter or buried and degraded craters. Our preliminary results indicate that compressional tectonic and impact cratering are the dominant processes shaping the surface geomorphology of the study area. The geological map produced in this work represents the first map of the western half of the Eminescu Quadrangle (H09) on Mercury at this output scale. This map will support further investigation of the geological context of the study area. Additionally, we propose a list of 38 geological sites as potential scientific targets to support the ESA–JAXA BepiColombo space mission's objectives to explore Mercury.

Plain Language Summary A detailed geological map was created for the western half of the Eminescu Quadrangle (H09) on Mercury using data sets from NASA's MESSENGER mission. This map was produced to support the goals of the ESA–JAXA BepiColombo space mission to explore Mercury. The mapping results reveal interesting surface geomorphology characterized by a widespread distribution of impact craters and lobate scarps. These features were formed by significant compressional tectonics and impact cratering processes. We distinguished three morphological plains units in the study area: smooth, intermediate, and intercrater plains. Surface deposits were also identified, including fields of hollows and regions of bright and dark material. We present the first geological map of the western half of the Eminescu Quadrangle (H09) on Mercury, compiled at a scale of 1:3,000,000. Further use of the map produced in this work will support detailed studies of the geological and tectonic context of the selected area, help determine the ages of geological units, and contribute to a more advanced understanding of Mercury's geology. We also defined a list of 38 geological sites as potential scientific targets to be imaged in support of the ESA–JAXA BepiColombo space mission's goals to explore Mercury.

1. Introduction

Details of Mercury's surface were recorded by two space missions: Mariner 10 (1973–1975) and the Mercury Surface, Space ENvironment, GEochemistry, and Ranging mission (2004–2015), known as MESSENGER. Mariner 10 provided the first major insights into the chemical and physical properties of Mercury, as well as extensive coverage of its surface geomorphology. More than 2,700 useful images were obtained during this mission, and nearly half of the planet's surface was imaged at resolutions of up to 100 m/pixel (Davies et al., 1978).

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NASA's MESSENGER mission subsequently mapped the entire surface of Mercury, producing a global panchromatic mosaic with an average resolution of 200 m/pixel, as well as high-resolution images of geologically significant regions at up to 20 m/pixel (Blewett et al., 2016). The Mercury Dual Imaging System (MDIS) onboard MESSENGER consists of a wide-angle camera (WAC) and a narrow-angle camera (NAC), both of which image Mercury's surface using 11 monochrome filters with high spatial resolution and a wide field of view (Hawkins et al., 2007). The MDIS imaging system covered approximately 62.5% of Mercury's surface at resolutions between 50 and 120 m/pixel and about 12% of the surface with three-color multispectral Reduced Data Records (RDRs) at a resolution of approximately 120 m/pixel.

Data derived from the MESSENGER MDIS instrument have promoted a global collaborative mapping initiative of Mercury's surface using the MDIS data set (Galluzzi, 2019). Mercury's surface is characterized by a high abundance of impact craters and large impact basins (Rothery et al., 2014). Rapid cooling, planetary contraction, and tidal despinning resulted in a significant number of tectonic scarps observed on the surface. These structural lineaments suggest that Mercury has undergone a unique thermal evolution, making it a subject of considerable scientific interest.

A series of detailed geological maps of Mercury's quadrangles were produced at a scale of 1:3,000,000 to support the ESA–JAXA BepiColombo space mission to explore Mercury (Benkhoff et al., 2021; Cremonese et al., 2020). As part of this global mapping collaboration (Galluzzi, 2019), we selected the western half of the Eminescu Quadrangle (H09) on Mercury (El Yazidi, 2023; El Yazidi et al., 2021, 2023). The selection of this area was based on its abundance of scientifically interesting surface features, such as Beagle Rupes, hollow deposits, prominent impact craters, and pyroclastic deposits, as well as color variations observed between plains units (De Toffoli et al., 2024; Thomas et al., 2014a, 2014b).

In addition, this quadrangle is one of the six regions of Mercury that were not imaged by the Mariner 10 spacecraft. As a result, geological maps have not yet been produced for this region, making it one of the highest-priority areas for geological mapping on Mercury. Due to funding availability and project deadline constraints, we decided to map only the western half of the Eminescu Quadrangle (H09) rather than the entire quadrangle.

The name of this quadrangle was suggested after the prominent impact crater Eminescu, which is located at 10.79°N, 245.87°W. The geology of the western half of the Eminescu Quadrangle (H09) remains largely unknown, justifying the need for a geological map to improve our understanding of the geodynamic processes that led to the formation of this region and to expand our knowledge of the formation and evolution of Mercury's geology.

The aim of this paper is to present the first geological map of the western half of the Eminescu Quadrangle (H09), to describe the regional geological and tectonic context, and to support the ESA–JAXA BepiColombo space mission by proposing a list of potential scientific targets to be imaged and studied in the near future. The paper also highlights open scientific questions to be addressed by instruments onboard the ESA–JAXA BepiColombo mission to Mercury, such as those related to hollows, pyroclastic deposits, and Mercury's magnetic field.

2. Data

To produce the geological map of the western half (Figure 1a) of the Eminescu Quadrangle (H09), we used the following remotely sensed and topographic data sets acquired at different incidence angles. These data were produced by the MESSENGER team (Denevi et al., 2018; Hawkins et al., 2007) and were used to map, analyze, and interpret surface features on Mercury:

Mercury MESSENGER MDIS BDR global mosaic (166 m/pixel): The Reduced Data Record (RDR), known as the Basemap RDR (BDR), consists of a monochrome reflectance image (Figure 1b) generated using MDIS NAC and WAC data acquired at low emission angles and an incidence angle of approximately 74° (Denevi et al., 2018; Hawkins et al., 2007). We used the BDR as the primary basemap and as the background for the final map.

Mercury MESSENGER MDIS LOI global mosaic (166 m/pixel): The low-incidence-angle (LOI) monochrome basemap (Figure 1c) was produced using NAC and WAC images at 750 nm, acquired at low emission angles and incidence angles of approximately 45° (Hawkins et al., 2007; Murchie et al., 2017). The LOI basemap was used to analyze reflectance variations among the plains units in the study area.

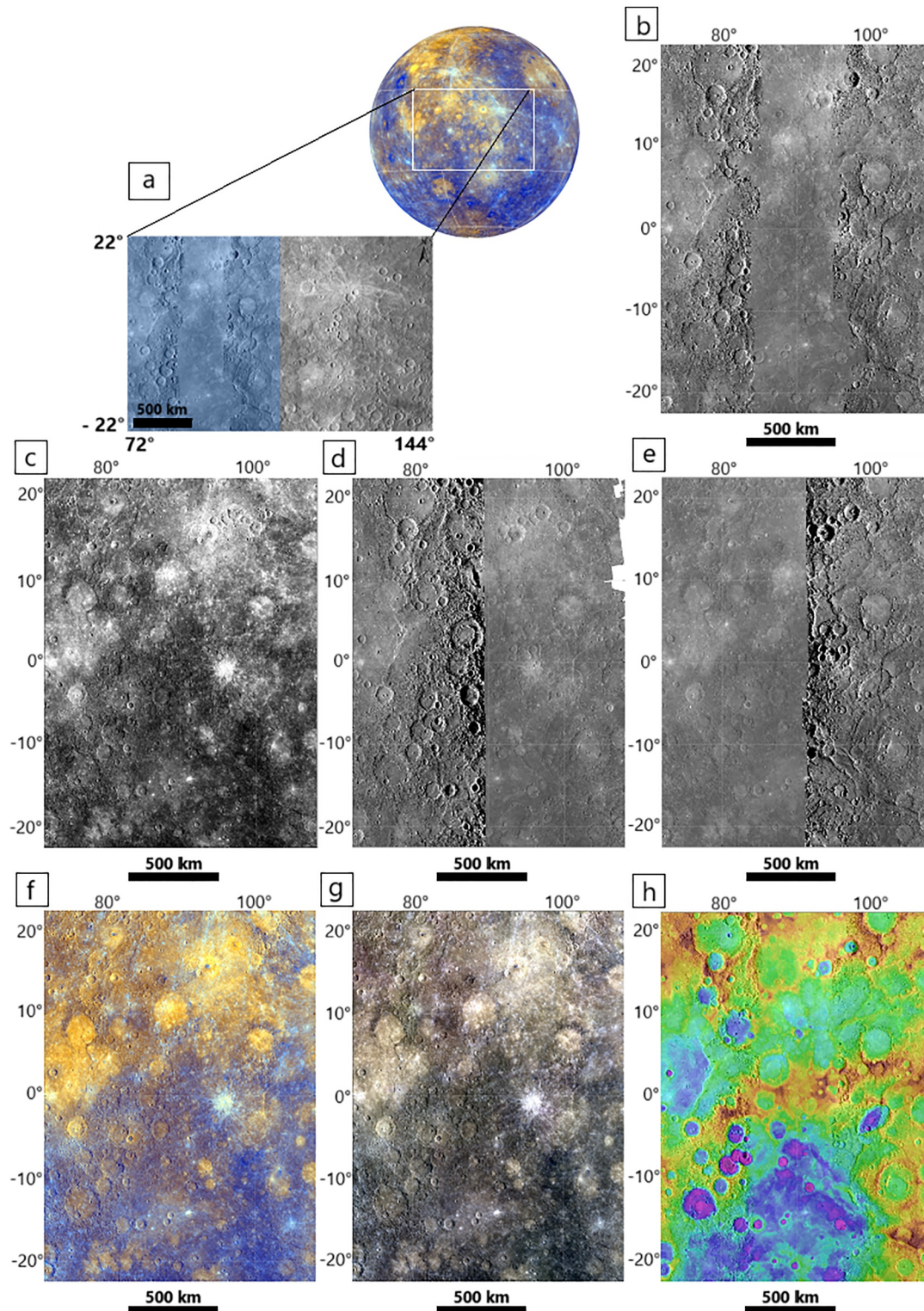


Figure 1. Context of the western half of the Eminescu Quadrangle (H09) and the basemaps used for geological mapping: (a) Location of the Eminescu Quadrangle (H09), with the study region shaded in blue. (b) BDR basemap. (c) LOI basemap. (d) High-Incidence West basemap. (e) High-Incidence East basemap. (f) Enhanced global color mosaic basemap. (g) MD3 global color mosaic. (h) Digital elevation model basemap.

Mercury MESSENGER MDIS High-Incidence West (HIW) global mosaic (166 m/pixel): The HIW illumination is a mosaic of NAC and WAC images acquired at 750 nm (Figure 1d) with low emission angles and an incidence angle of approximately 78° (Hawkins et al., 2007). This high-incidence illumination was used to accentuate the low-relief morphology, enhancing the visibility of asymmetric topography, with steeper slopes facing west than east.

Mercury MESSENGER MDIS High-Incidence East (HIE) global mosaic (166 m/pixel): The HIE illumination follows the same concept as the HIW. These data were acquired at low emission angles and high solar incidence angles (~78°) from the east (Figure 1e). The HIE basemap consists of NAC and WAC mosaics with images obtained at 750 nm (Hawkins et al., 2007). Like the HIW, the HIE basemap is used to accentuate the low-relief morphology. HIE and HIW were used jointly to identify the surface structures.

Mercury MESSENGER MDIS enhanced color global mosaic (665 m/pixel): This basemap was created as a mosaic of images extracted at 430, 750, and 1,000 nm and assigns the second and the first principal component and the 430/1000 ratio to the red, green, and blue (RGB) channels, respectively (Denevi et al., 2009, 2018; Domingue et al., 2015; Hawkins et al., 2007). This color composite (Figure 1f) is used to identify plains units: Smooth plains (SP) typically appear yellow, pyroclastic deposits or faculae (Prockter et al., 2010) appear orange, intercrater plains appear blue or gray, and crater rays appear light cyan (Denevi et al., 2013; Murchie et al., 2015; Whitten et al., 2014).

Mercury MESSENGER MDIS MD3 color global mosaic (665 m/pixel): This basemap is a mosaicked 3-Color Map Projected Multispectral RDR (MD3), consisting of a global color map produced using narrow-band filters at 1000, 750, and 430 nm, assigned to the red, green, and blue spectral channels, respectively (Figure 1g). The MD3 basemap is used to highlight color variations within the plains unit (Hawkins et al., 2007).

Mercury MESSENGER Global digital elevation model (DEM) mosaic (665 m/pixel): This DEM consists of topographic data (Figure 1h) produced by the United States Geological Survey (USGS). The gridded MDIS DEM includes metadata with map projection information, allowing each pixel to be associated with latitude and longitude. This topographic product was derived from MESSENGER MDIS NAC and WAC images using stereo photogrammetry data sets (Becker et al., 2016) and the Integrated Software for Imagers and Spectrometers version 3 (ISIS3). We used the V2 version of the MDIS DEM, produced with a 1-sigma filter, in which topographic data are displayed as color-keyed elevations overlaid with hill-shaded relief. The DEM is used to determine the vertical displacement of linear structures such as lobate scarps and wrinkle ridges, to analyze crater characteristics and to measure the elevation of plains units.

We noted that the HIE and HIW illumination basemaps present issues related to the illumination angle (Figures 1d and 1e). In some areas, these basemaps show very intense illumination on one side and complete shadow on the opposite side. The HIW basemap also has a data gap in the northeastern part of the study area. As a result of these illumination issues, it was sometimes challenging to digitize the boundaries of certain linear features and to draw the linework of the geological units. A similar problem was observed with the LOI basemap (Figure 1c), where areas of very bright reflectance hindered the identification of small-scale surface materials, crater rims, and ejecta extensions.

Although the BDR is often used as the primary basemap, it has uneven illumination. To avoid overmapping surface features, we used all basemaps during the mapping process to compensate for data gaps and illumination issues. This combined use of multiple basemaps helped prevent both under- and overmapping of geological contacts, crater ejecta boundaries, and surface materials. Despite these limitations, the illumination conditions did not affect the identification or mapping of features. By combining views from the different basemaps, we were able to observe, delineate, and map the full extent of surface features. The basemaps complemented each other, allowing us to draw the linework accurately. Data, supplementary information files, shapefiles and the final map are deposited in a specific repository at El Yazidi et al. (2025).

3. Methods

The following methods were used to produce the geological map of the western half of the Eminescu Quadrangle (H09).

3.1. Projection

The study area is located along the equator and is centered at 90°E. The basemaps we used are georeferenced and projected in the equirectangular Mercury projection conventionally adopted for this region of Mercury (Hargitai et al., 2017; Longley et al., 2015; Snyder, 1987). This projection is essentially cylindrical and centered on the selected region along the equator. The horizontal coordinate represents longitude, while the vertical coordinate represents latitude. The standard parallel is taken as 0°, and the central meridian is 180°E.

3.2. Scale

We followed the mapping rules defined by Tobler (1987) and the USGS recommendations for geological mapping (Skinner et al., 2019, 2022). We used a mapping scale of 2,000 × the basemap pixel size (Tobler, 1987). The linework was drawn at 1:400,000 for a basemap resolution of 166 m/pixel. For consistency, we used a vertex spacing of 1,000 m, which corresponds to approximately 0.6 mm at the mapping scale (Tanaka et al., 2011). This mapping scale allows for accurate digitization of surface features without producing a pixelated view or risking overmapping. The scale was chosen in accordance with the global mapping collaboration for Mercury's quadrangles, as described by Mancinelli et al. (2016), Galluzzi et al. (2016), Guzzetta et al. (2017), Wright et al. (2019), Pegg et al. (2021a, 2021b), Giacomini et al. (2022), Malliband et al. (2022), and Man et al. (2023). The map was prepared for publication at an output scale of 1:3,000,000 (Skinner et al., 2019, 2022).

3.3. Map Elements and Guidelines

We adopted the same symbology and guidelines used in Galluzzi et al. (2016), Wright et al. (2019), Malliband et al. (2022), and Man et al. (2023). The symbology is based on the mapping standards of the USGS (Skinner et al., 2019, 2022) and the Federal Geographic Data Committee, with appropriate modifications to maintain consistency with previous MESSENGER-era Mercury maps (Galluzzi et al., 2016; Giacomini et al., 2022; Guzzetta et al., 2017; Malliband et al., 2022; Man et al., 2023; Mancinelli et al., 2016; Pegg et al., 2021a, 2021b; Wright et al., 2019).

We digitized vector layers on the basemap raster layers, beginning with the creation of a project file containing a dedicated geodatabase for the feature classes. Surface features were classified into six map units according to their type. Each unit includes specific feature types that were mapped using different symbologies applied through polyline and polygon shapefiles. These shapefiles consist of geographically located vertices connected by vector line segments.

We define the following feature classes for the map elements, following the same approach and guidelines used in previous maps:

3.3.1. Linear Feature Structures

This category includes tectonic lineaments such as lobate scarps and wrinkle ridges. Lobate scarps were mapped using polyline shapefiles with solid lines for certain features and dashed lines for uncertain features, distinguishing the level of confidence and prominence of these linear structures. Thrust faults appear on the surface as asymmetric lobate scarps. The linework of these faults was drawn along the slope break on the steeper side of the tectonic structure. Thrust faults are represented by continuous lines with triangular teeth pointing toward the hanging wall (Examples shown in Figures 2a and 2b). Wrinkle ridges were mapped using continuous solid lines placed over their crests. These structures are typically identified by their symmetrical profiles and lower relief than lobate scarps (Watters & Nimmo, 2010).

3.3.2. Impact Crater Rims

This category represents crater outlines. We identified three classes of impact crater rims based on diameter (D) and the degree of rim degradation: Crater crests with $D > 20$ km, crater crests with $5 \text{ km} < D < 20$ km, and crests of degraded or buried craters with $D > 5$ km. Examples of these crater classes are shown in Figures 2c and 2d.

Craters with rims larger than 20 km are mapped with a solid continuous line with double inward ticks. Craters with rims between 5 and 20 km are mapped with a simple continuous solid line. Craters smaller than 5 km in diameter were not mapped due to their small size and to avoid overloading the final map. Buried or degraded

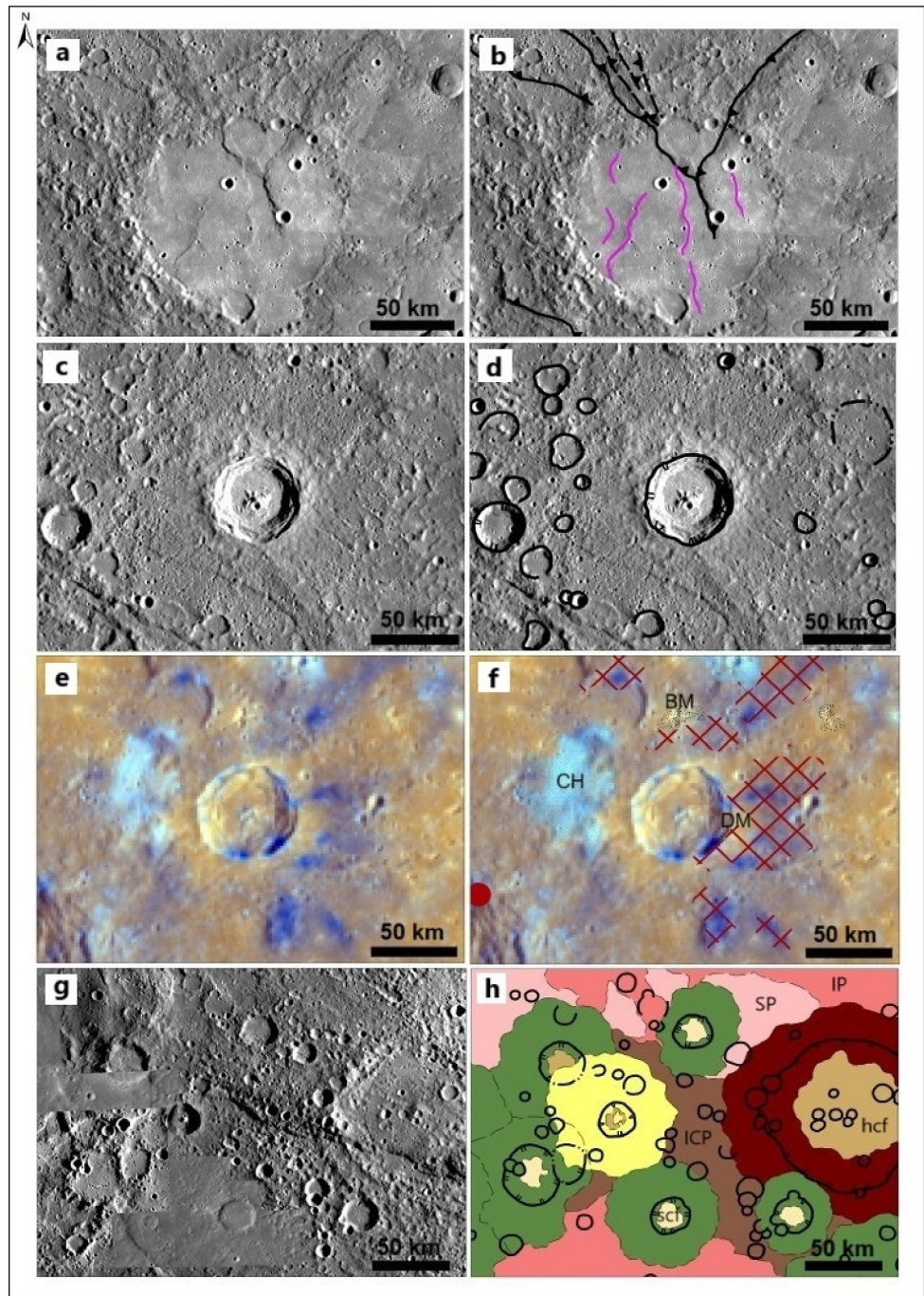


Figure 2. Map elements and three-class crater classification (C3–C1). Left: views over different basemaps (a, c, e, g). Right: interpreted background (b, d, f, h).

craters are mapped with a dot-dashed line, as their rims are often covered by ejecta from nearby fresh craters or younger plains units. The rims of distinctively irregular pits, interpreted as volcanic vents, are mapped with lines featuring single inward ticks.

3.3.3. Surface Features

This class of map elements includes: (a) Bright Material (BM), (b) Clusters of Hollows (CH), (c) Dark Material, (d) Rough Ejecta (RE), and (e) secondary crater chains or catenae (Examples shown in Figures 2e and 2f). These

features are identified as textures that allow one or more underlying units to remain partially visible. These textures do not entirely cover the underlying units and sometimes include faculae—bright surface material that is relatively red and thought to be pyroclastic deposits (Goudge et al., 2014; Head et al., 2008; Jozwiak et al., 2018; Kerber et al., 2009, 2011; Murchie et al., 2008; Rothery et al., 2014).

Hollows on Mercury are observed as irregular bright blue-to-white surface deposits, widely believed to be associated with volatile loss. Studying the distribution and morphometric properties of hollows has important implications for understanding the geologic evolution of Mercury (Bickel et al., 2025; Deutsch et al., 2025). Hollows are preferentially located on crater floors, rims, or ejecta (Blewett et al., 2011, 2013; Thomas et al., 2014a, 2014b), typically at low elevations and low slope angles.

Crater chains, or catenae, are formed by a linear arrangement of small, irregularly shaped impact craters. Bright Material is often recognized by bright ejecta rays (Braden & Robinson, 2013; Fegan et al., 2017), while RE is usually associated with crater material (Neish et al., 2013).

3.3.4. Point Features

This category describes isolated dark, bright, or hollow spots. Due to their small size and limited distribution, these surface features were digitized using a point shapefile.

3.3.5. Geologic Contacts

This category represents the boundaries between geological units, which were digitized using polyline shapefiles. Contacts were classified as certain or uncertain based on the clarity of the boundaries between different plains. When the geological contact between two or more plains is sharp and clearly visible—defined within a vertex spacing (streaming length) of 1,000 m—it is considered a certain contact. Where contacts between plains are diffuse, partially exposed, or not well constrained within the 1,000 m streaming length (Figures 2g and 2h), it is considered an uncertain contact.

The limits of crater ejecta are sometimes difficult to digitize because ejecta from nearby craters often merge or overlap. When ejecta boundaries are sharp and clearly visible (typically for fresh and well-preserved craters), a solid black line is used to map them. When ejecta boundaries are uncertain, approximate contacts are digitized to represent the crater ejecta limits. Contacts between crater floor material, walls, and ejecta are typically gradational and are mapped as approximate.

3.3.6. Geologic Units

This feature class of map elements includes six subclasses, divided between plains units and crater material-related units. Based on previously published maps of Mercury quadrangles (Galluzzi et al., 2019; Malliband et al., 2022; Man et al., 2023; Wright et al., 2019), we identify three plains units in the study area (Trask & Guest, 1975), described as follows (Examples shown in Figures 2g and 2h):

Intercrater plains (ICPs) are highly cratered plains, characterized by a significant distribution of craters with diameters ranging from 5 to 10 km, including degraded and buried craters with partially visible or missing rims. These plains are widespread across Mercury's surface (Galluzzi, 2015; Trask & Guest, 1975; Whitten et al., 2014) and are interpreted as the oldest plain units because they are heavily cratered (Galluzzi, 2015; Spudis & Guest, 1988; Whitten et al., 2014). The ICP is thought to have formed during the Tolstojan to pre-Tolstojan period (Galluzzi, 2015; Whitten et al., 2014). The topographic elevation of these plains is approximately 4.5 km above Mercury's average radius.

ICPs are often associated with Low Reflectance Materials (LRM), which appear very dark with low albedo (Denevi et al., 2009) and are typically not linked to flow features or other evidence of volcanic origin. LRMs are distributed across Mercury's surface and may be excavated from depth by impact craters or basins (Denevi et al., 2013; Head et al., 2011; Whitten et al., 2014).

The boundaries between the ICP and the High Reflectance Plains (HRP) are sometimes diffuse and difficult to identify (Galluzzi, 2015; Whitten et al., 2014).

The formation of the ICP remains a subject of debate. Trask and Guest (1975) related the formation of ICP to the Late Heavy Bombardment (LHB) on Mercury, whereas alternative hypotheses suggest a volcanic origin, given that ICP constitute the most widespread plains on Mercury (Kiefer & Murray, 1987; Murray et al., 1974; Spudis & Guest, 1988; Strom, 1977; Trask & Guest, 1975; Whitten et al., 2014) or were alternatively produced by impact melt generated by large impact basins (Galluzzi, 2015; Oberbeck et al., 1977).

Intermediate plains (IP): These plains exhibit a lower crater density compared to the ICP. The IP often occurs between the intercrater plains and SP, rather than forming a morphologically distinctive unit (Whitten et al., 2014). They are transitional in crater density, bridging the very cratered and less cratered plains. IPs typically display a wide range of morphologies and crater size-frequency distributions, which generally include craters partially filled by plains material. Intermediate plains resemble intercrater plains, being composed of secondary crater chains, old crater materials, and SP, but they are typically not thick enough to completely obscure the underlying cratered or SP units.

Smooth plains (SP): These plains are relatively flat and are characterized by sparsely cratered material and a smooth texture (Galluzzi, 2015; Trask & Guest, 1975). The SP represent the freshest and youngest geological unit in the study area and are thought to be volcanic in origin (Denevi et al., 2013; Trask & Guest, 1975; Trask & Strom, 1976). These plains—for example, those in the map region defined by coordinates 72°E–80°E and 22°N–1°S—are formed by lava flows that have undergone minimal degradation and impact cratering (Denevi et al., 2009; Head et al., 2008).

Some patches within the SP exhibit contrasting textures, possibly reflecting different episodes of lava flooding. SP are characterized by a lower crater density compared to IP and ICP. These plains display sharp boundaries with ICP and are believed to date to the early Calorian period, approximately 3.7–3.9 Gyr ago (Byrne et al., 2016; Denevi et al., 2013; Marchi et al., 2013).

Smooth crater floor (scf): This plains unit category is defined by smooth material confined to crater floors. In the case of a fresh impact crater, the smooth crater floor (scf) is interpreted as ponded impact melt (Daniels, 2018; Wright et al., 2019). In older craters, the scf may have formed from subsequent volcanic flooding.

Hummocky crater floor (hcf): The hummocky cratered floor (hcf) is defined as a rough-textured deposit, typically found in craters of the C2 or C3 classes, with a clearly visible rim and internal structure. The hcf deposits may represent the original crater floor, unaffected by impact melt or degradation in the case of fresh craters (Galluzzi et al., 2016), or the degraded internal structures of older impact craters, formed when the floor material is partially buried or modified by distal ejecta from other impacts.

Crater materials (C1, C2, C3): This category describes the three-class system used for crater mapping, following previous Mercury maps (Galluzzi et al., 2016; Giacomini et al., 2022; Guzzetta et al., 2017; Malliband et al., 2022; Man et al., 2023; Mancinelli et al., 2016; Pegg et al., 2021a, 2021b; Wright et al., 2019). This unit includes the mapping of crater walls, floors, central peaks, and ejecta.

We adopted the three-class system to facilitate integration with other recent 3-class maps, simplify the final geologic map, and reduce conflicts between degradation state and superposition relationships (Galluzzi et al., 2016). The system ranges from the oldest craters (C1) to the youngest (C3). Each class is morphologically distinct and reflects different degrees of degradation.

The first class, C1, represents heavily degraded craters, which are generally old and have partially visible, significantly subdued, or missing rims. Craters in this class typically no longer display a central peak, internal structures, or extensive, well-defined ejecta. When ejecta from a C1 crater are visible, they are usually confined near the crater rim, rarely extending over long distances. Only a few large craters in the study area exhibit one or more peak rings, and very few retain small remnants of a central peak. C1 craters are often overlain by fresher materials, such as ejecta from C2 and C3 craters or SP.

The second class, C2, represents craters with a moderate level of degradation compared to C1. Craters in this class typically have visible rims, which may sometimes be subdued or partially missing. C2 craters exhibit discernible ejecta; however, distal ejecta can be difficult to trace and may merge with ejecta from nearby craters.

The third and final class, C3, represents the youngest craters in the study area. These craters are well-preserved, fresh, sharply rimmed, and exhibit crisp morphology. C3 craters retain intact internal structures, including central

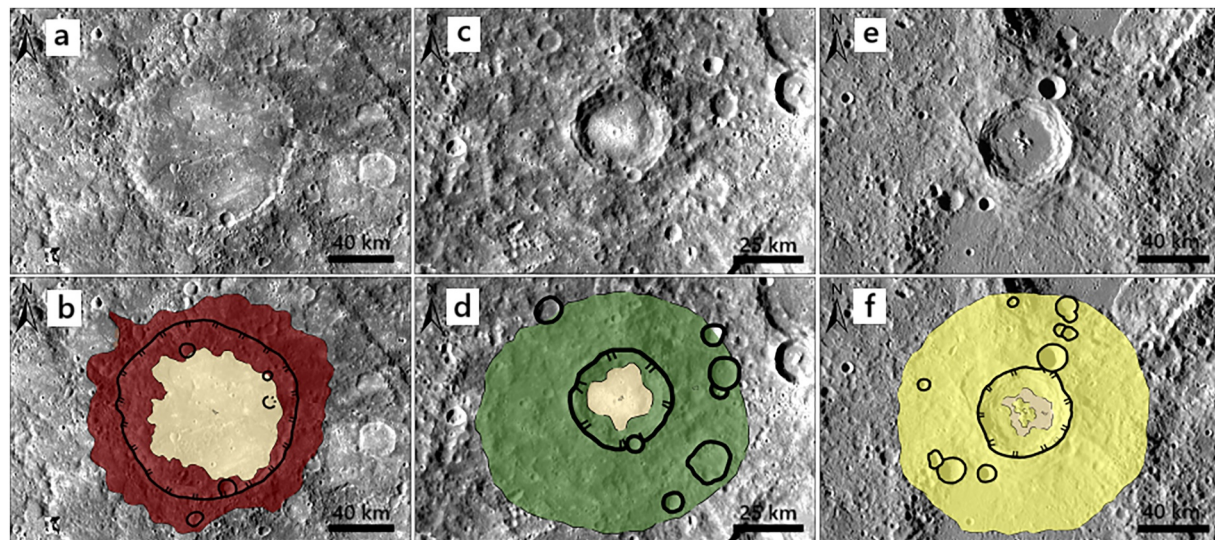


Figure 3. Examples of the 3-class crater system (C1–C3). Panels (a), (c), and (e) show views of the three crater classes over different basemaps. Panels (b), (d), and (f) show the corresponding background interpretations. Red = C1 (most degraded), green = C2 (moderately degraded), and yellow = C3 (least degraded). The view is displayed over the Mercury Dual Imaging System BDR with 30% transparency for crater materials.

peaks, elevated crater wall terraces, and clearly textured ejecta blankets. Contacts between crater materials and internal structures are typically well-defined in this class, due to the sharp and clearly visible boundaries of the C3 impact crater features. Examples of the different crater types are shown in Figure 3, illustrating the 3-class system used for crater digitization.

HRP are defined as a spectral unit; they appear very bright, have high albedo, and exhibit morphological evidence of volcanism (Prockter et al., 2010). Both LRM and HRP are commonly observed within crater materials, the ICP, or overlying other plain units.

The geological units were generated by first delineating the plain units with geological contacts and then applying the corresponding symbology to represent each feature class of the map layer (i.e., ICP, IP, SP, hcf, and scf). For craters and crater materials, the rim was digitized first, followed by the crater floor (hcf and scf) and the central peak. Mapping began with well-preserved, fresh, and young craters that had visible central peaks and ejecta (i.e., C3 craters), followed consecutively by the C2 and C1 crater classes.

The mapping was performed using a stratigraphic approach based on the integrated use of conformity, boundaries, and the principle of superposition: the youngest crater or plain unit is at the top, and the oldest crater or unit is at the base. Crater ejecta were mapped last by digitizing their limits using geological contacts (certain and uncertain) and applying the corresponding crater class symbology (C1, C2, or C3).

Linear structural features, impact crater rims, geological contacts, and surface features were the first map elements to be digitized, prior to importing the geological units (ICP, IP, and SP) and defining the crater classes (C1, C2, and C3).

4. Map Description and Correlation of Units

The geological map of the western half of the Eminescu quadrangle (H09) shown in Figure 4 reveals a varied surface geomorphology, ranging from SP to heavily cratered and tectonized plains. Most of the mapped plains units in Figure 4 are intercrater plains, accounting for 40.50% ICP, 35.40% SP, and 24.20% IP. These plains are primarily located between degraded, buried, or C1 craters. Compared to SP, the IP are less extensive. Typically, the IP occurs between ICP and SP, covering relatively small areas.

In the NW sector of the map (Figure 4), the SP cover a wide area, extending over tens of kilometers. A few 3-class craters are observed on these NW SP, along with NNW–SSE, WNW–ESE, and ENE–WSW trending lobate scarps and wrinkle ridges. The NW plains exhibit sharp and well-defined boundaries with the ICP to the NW,

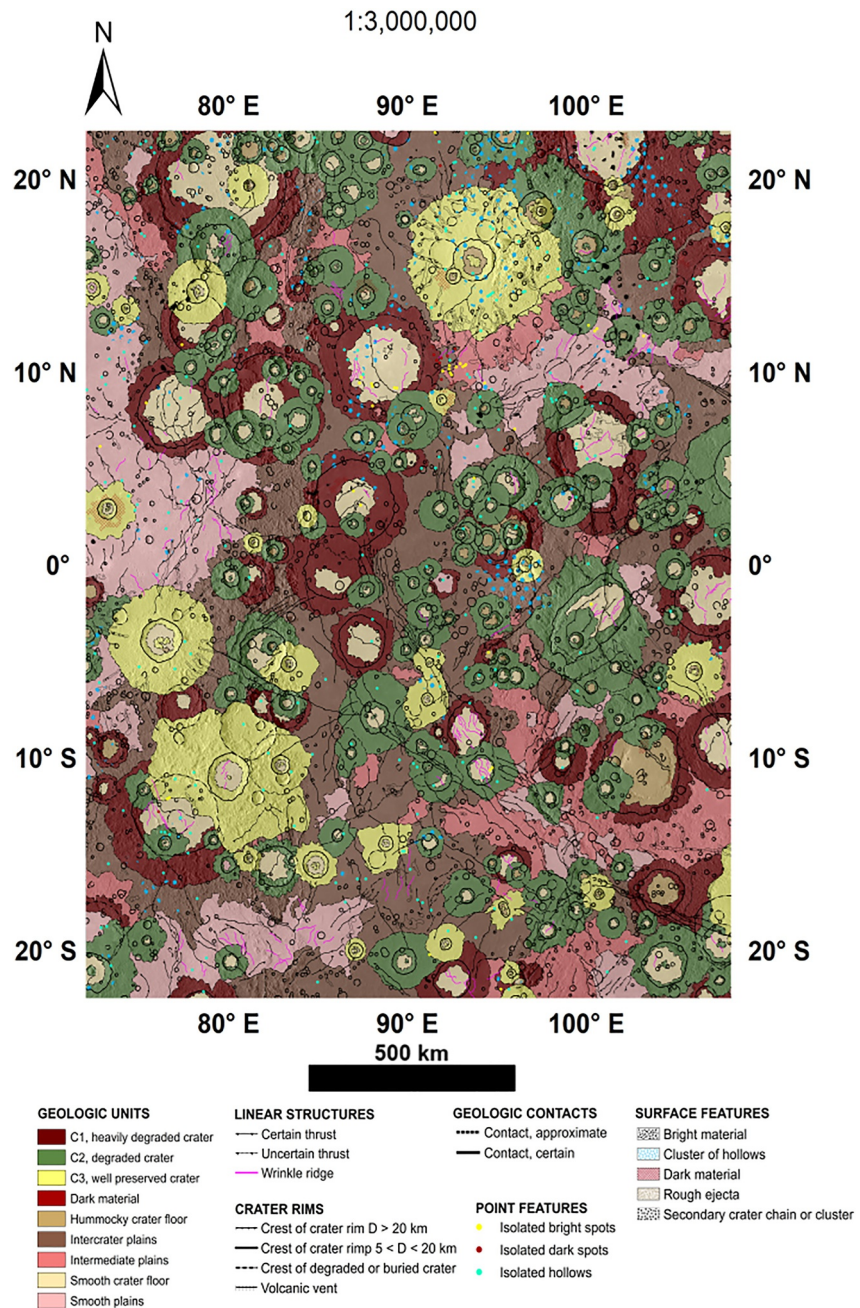


Figure 4. Geological map of the western half of the Eminescu quadrangle (H09), showing the 3-class (C1–C3) crater degradation scheme. The BDR basemap was used as the background layer, and the map units were displayed with 40% transparency.

coalescing with the limits of a major NNW–SSE lobate scarp. The surface also shows evidence of intense cratering activity, expressed by a widespread distribution of craters and impact basins of varying sizes and degrees of degradation.

In the SE sector of the map (Figure 4), a significant group of extended lobate scarp segments occurs across the intercrater and IP. These scarp segments strike WNW–ESE and span approximately 219 km in length. They represent the surface expression of low-angle ($<35^\circ$ dip) thrust faults. The WNW–ESE faults likely formed in response to tectonic shortening under compressional stress, expressed at the surface as widely distributed single or segmented lobate scarps trending in the same direction from west to east. Stratigraphic observations of lobate

scarps and impact craters of varying ages and degradation levels (Banks et al., 2015) indicate that shortening and thrust faulting on Mercury began during or before the Calorian system (Over the last $\sim 3\text{--}4$ Gyr) and continued through the Mansurian and into the Kuiperian systems. We mapped 2,162 craters in the study region, covering a surface area of approximately $2.10^6 \times \text{km}^2$. The craters identified in this work are generally consistent with those reported in the global database of impact craters on Mercury (Fassett et al., 2012; Herrick et al., 2018), with only minor differences in crater diameters. Craters with diameters between 5 and 20 km are the most common, accounting for approximately 69.21% of the total crater population in the area. Large craters with diameters ≥ 20 km represent 13.13% of the craters mapped. Some large, flat-floored craters, ranging from 120 to ~ 220 km in diameter, are typically surrounded by intercrater and IP and, occasionally, by SP. A few craters larger than 120 km exhibit smooth floor infilling, likely related to resurfacing associated with early effusive volcanism in the region.

We observed that some old craters and impact basins with diameters between 70 and 210 km exhibit a notable swarm of wrinkle ridges within their flat floors. A few fresh C3 craters show floors with hummocky deposits surrounding the central peak; these deposits likely represent the original crater floor material, free of impact melt. Other young craters display deformed or segmented central peaks. Ringed peaks are observed in old, large craters with heavily degraded or buried rims. These ringed peaks do not have a distinct map element class and are therefore mapped as part of the hcf. Most craters in the C2 and C3 classes are characterized by thin but extensive ejecta blankets, in contrast to C1 craters, where the ejecta are generally adjacent to the crater rim, partially missing, and usually rough. Some C3 craters exhibit bright rays that extend for several kilometers. Fresh C3 craters can also have significantly extended ejecta relative to their crater size, with ejecta blankets spreading several kilometers from the crater rim.

The crater ejecta we examined are typically axisymmetric, resulting from high-angle impacts. Other ejecta forms result from low-angle impacts, producing planforms that resemble butterfly wings (Herrick et al., 2018; Herrick & Taylor, 2003).

Degraded and buried craters of the C1 class exhibit distinct morphological characteristics compared to C2 and C3 craters. These craters often have rims, walls, and internal structures that are superposed by later impact craters or fresh crater materials. The floors of C1 craters typically consist of smooth, sometimes hummocky materials, often marked by swarms of wrinkle ridges, and appear to have been flooded by external sources. Internal structures, such as central peaks and rings, are subdued but still discernible and can be digitized. Floor materials, including scf or hcf, are generally subdued and are sometimes overlain by CH or bright materials. BMs are often found at low elevations, on gentle slopes, and tend to cluster in areas corresponding to the maximum deposition of ejecta produced by impact. The distribution of surface BM in the study area is limited and shallow. These deposits typically appear as irregular, rimless depressions occurring in clusters, and occasionally as isolated bright spots. They are characterized by high albedo, though still lower than that of hollows. Morphologically, BMs are distinct from hollows, displaying different textures; they have a fresh-appearing morphology and often incise into the margins and ejecta of craters.

Craters of the C1 class typically exhibit a nearly perfect rounded shape and, in some cases, a peak-ring basin. These craters account for 17.65% of the total crater population in the study area. Crater density is relatively high in the NE, NW, and SE sectors of the region, covering between 60% and 75% of the surface. Most of these craters are superposed on ICP rather than IP or SP units. In contrast, the SW sector of the map (Figure 4) shows a lower crater density, covering between 18% and 22% of the surface; most of the plains in this region are ICP, hosting extensive lobate scarps and clusters of wrinkle ridges.

Occasionally, some craters of varying sizes display irregularly shaped rims that are elliptical or elongated rather than circular, such as the Sveinsdóttir crater located at -2.779°N , 100.14°E . The diameters of these irregular craters are measured along the major axis, which corresponds to the longest dimension and defines the direction of elongation.

Volcanic vents appear as irregular depressions without a raised rim, morphologically distinct from impact craters, and are often elongated along a single axis. Explosive volcanic vents are widespread on Mercury (Byrne et al., 2016; Byrne et al., 2016, 2018; Leon-Dasi et al., 2025; Pegg et al., 2021a, 2021b; Thomas et al., 2014a, 2014b). Most of these vents ($\sim 82\%$) are located within impact craters and basins (Jozwiak et al., 2018). In the study area, we identified one putative volcanic vent at -8.46°N , 99.82°E (See Table 2 and Figure 15a).

A frequent surface interconnection between craters and lobate scarps was observed in the study area. Several craters of varying sizes are crosscut by one or more lobate scarps (Cordell & Strom, 1977; Strom, 1977), indicating a sequence of compressional deformational events in the region. The mapped lobate scarps are oriented in multiple directions. Some of these scarps have a crisp appearance, crosscutting and overlying craters and ICP. In total, we mapped 540 lobate scarps and 222 wrinkle ridges in the study area. To reduce uncertainty, lobate scarps lacking clearly defined edges were classified as uncertain. No extensional features, such as grabens or normal faults, were identified; only thrust faults and a few strike-slip faults were observed. These scarps are produced by mechanical failures caused by outward sliding of rock masses, accompanied by reverse fault slips, resulting from crustal compression.

The lobate scarps in the study area exhibit linear to slightly convex slopes, asymmetric shapes with arcuate fault surfaces, and differing steepness on their two sides. The main face of each scarp is relatively steep, while the back scarp shows a gentler slope. Swarms of small scarps are observed, often with similar lengths, steep slopes at comparable elevations, and a striking appearance (See Section 5 and Figure 6). Lobate scarps and wrinkle ridges represent the topographic expression of reverse-slip faulting.

The dip of the lobate scarps in the study area ranges from $\sim 4^\circ$ to $< 35^\circ$. We estimated the fault dips by measuring the shortening and vertical offset of craters that straddle the faults along the scarps. These measurements are consistent with previous studies by (Galluzzi, 2015; Galluzzi et al., 2019) for the Victoria quadrangle (H02) and other regions on Mercury. The lobate scarps mapped in this region reach lengths of up to ~ 437 km and vertical reliefs of up to ~ 3 km. In contrast, the wrinkle ridges are smaller, occurring in connected segments up to ~ 12 km long, with generally shallow reliefs of a few meters. Our measurements closely match earlier reports of lobate scarps and wrinkle ridges in other regions of Mercury (Byrne et al., 2014; Solomon et al., 2008; Strom et al., 1975).

In the study area, lobate scarps frequently superpose and overlay craters, indicating that these linear structures are relatively younger than the craters. Although we did not determine absolute ages for the lobate scarps in the present work, further investigation into the temporal and spatial distribution of lobate scarps and craters is planned for future studies, as it has important implications for the thermal and geological evolution of the region. Wrinkle ridges are particularly well preserved in the SW sector of the map, where they are prominently observed in SP and, in some cases, within crater floors.

A significant distribution of Hollows and hollow clusters are commonly observed along crater ejecta, floors, rims, and central peaks. In the study region, we mapped 188 groups of hollows. These features appear as shallow, flat-floored, steep-sided, rimless depressions, typically surrounded by bright deposits.

The dark materials in the study region are low-reflectance deposits found around or within the internal structures of craters. These materials are generally associated with volatile-related processes and typically occur as thin layers on crater ejecta or within crater floors. Both bright materials and dark materials are considered evidence of surface volatiles (Neumann et al., 2012).

We produced schematic stratigraphy for the map (Figure 5) to illustrate the geological history of the mapped units in the western half of the Eminescu quadrangle (H09). Crater ages were estimated using the three-class system (C1–C3), following the methodology of Spudis & Guest (1988), Banks et al. (2017), and Ernst et al. (2017). Age estimates for the plains materials were adopted from Byrne et al. (2016) for the SP and from Marchi et al. (2013) for the Inter crater Plains.

The chronological relationships and superposition among the mapped units were constrained through crater size–frequency distribution analysis, following the methodology outlined by Crater Analysis Techniques Working Group (1979). Crater counting was not performed across the entire study area; instead, representative sampling sites were selected. Specifically, four areas were analyzed: two within ICP units, one within an IP unit, and one within an SP unit. These sites were chosen based on the presence of the most extensive exposures representative of unit H09, allowing for improved statistical robustness.

A similar sampling-based approach for relative age determination has been adopted in previous studies (e.g., Galluzzi et al., 2016; Giacomini et al., 2022; Guzzetta et al., 2017; Wright et al., 2019; Pegg et al., 2021a, 2021b).

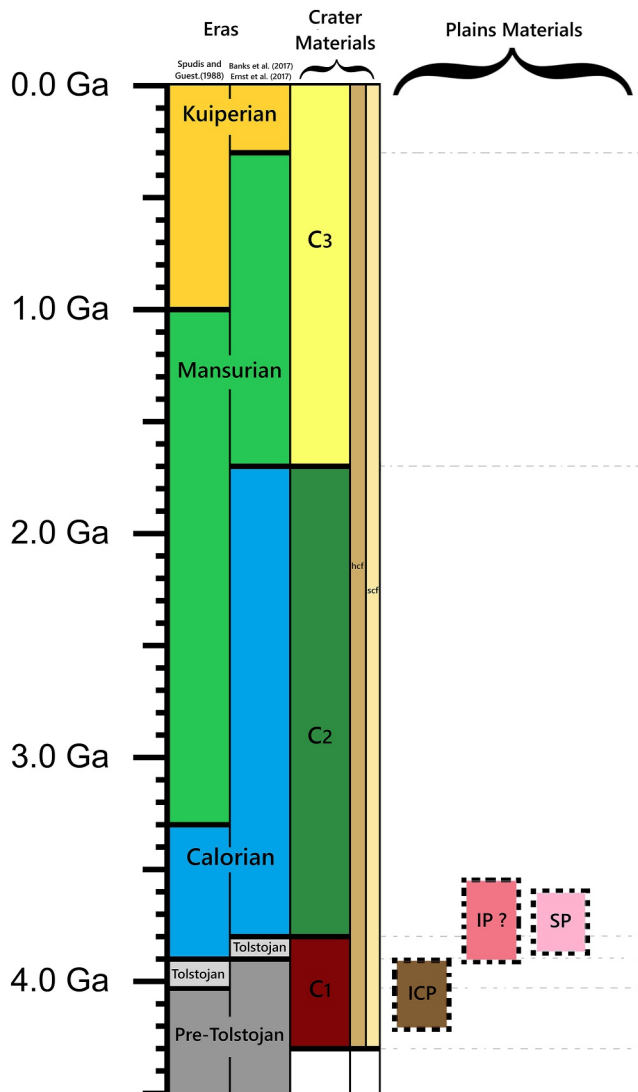


Figure 5. Correlation of map units for the western half of the Eminescu quadrangle (H09) using a three-class crater scheme.

5. Tectonic Setting

The surface geomorphology of the study region is dominated by prominent tectonic landforms, providing clear evidence of contractional deformation. These landforms are expressed on the surface as extensive sets of lobate scarps and swarms of wrinkle ridges trending in multiple directions. Lobate scarps appear as asymmetrical ridges formed by surface-breaking thrust faults resulting from contractional strain (Byrne et al., 2014; Rothery & Massironi, 2010). Wrinkle ridges are commonly observed within the SP and crater floors, displaying a sinuous pattern (Watters, 1988). They appear as short, low-relief arches compared to the lobate scarps and are generally interpreted as the surface expression of contractional tectonic forces.

We focused our analysis on the spatial distribution of lobate scarps and wrinkle ridges, which are relatively evenly distributed across the western half of the Eminescu quadrangle (H09), to better understand the tectonic setting of the study area. The azimuth distribution of these linear structures was derived. Polar plots, divided into 30° trend bins, were generated for both lobate scarps and wrinkle ridges, revealing the following predominant strikes (Figure 6): Lobate scarps: NNE-SSW, ENE-WSW, WNW-ESE and NNW-SSE and wrinkle ridge: NS, NNE-SSW, ENE-WSW, NNW-SSE, NW-SE.

Several lobate scarps display a range of orientations similar to the wrinkle ridges. Although there are notable differences between the northern and southern sectors of the study region, both wrinkle ridges and lobate scarps exhibit comparable orientations in these areas.

Lobate scarps are characterized by a steeply sloping scarp face and a more gently inclined back limb, likely representing a monocline or an asymmetric hanging-wall anticline above a surface-breaking or blind thrust fault resulting from flexural blending. In the SW sector of the map (Figure 4), clusters of parallel lobate scarps are observed, crosscutting intercrater plains, craters, and older basins of varying sizes.

Wrinkle ridges are more complex than lobate scarps and likely consist of paired, synthetic anticlinal folds above blind thrust faults, with secondary thrusts forming superposed ridges. The wrinkle ridges shown in Figure 4 consist of broad arches with sharp ridges, most commonly confined to the floors of old craters or basins. Their origin is attributed to basin-localized compressional stresses.

Overall, lobate scarps and wrinkle ridges are oriented predominantly in NNE-SSW, NNW-SSE, and ENE-WSW directions, with trends varying by $\pm 60^\circ$ from north. The spatial and azimuthal distribution of lobate scarps (Figure 6) provides insights into the orientation and origin of tectonic stresses. The spatial distribution was analyzed by plotting the faults' lengths in 30° azimuth bins, normalized by the area of each bin. The greatest cumulative lengths of these structural features occur in the southern region (Figure 6), with ~92% of the total length oriented within $\pm 50^\circ$ of the north.

The lengths of lobate scarps range from ~3 to 437 km, whereas wrinkle ridges are generally shorter, typically less than 75 km. Some old impact basins and highly degraded craters often host extended surface-breaking thrust faults and swarms of wrinkle ridges on their floors, reflecting post-impact tectonic deformation that occurred after crater formation and subsequent magma infilling or intrusion of the crater floor.

A gradual increase in the frequency and length of lobate scarps and wrinkle ridges is observed from the north toward the south (Figure 6). This increase is accompanied by a higher proportion of ICP compared to IP and SP. The ICP preserves the tectonic history of the region, as inherited thrust faults are expressed on the surface and are likely not buried or overprinted by IP, SP, or thick crater ejecta.

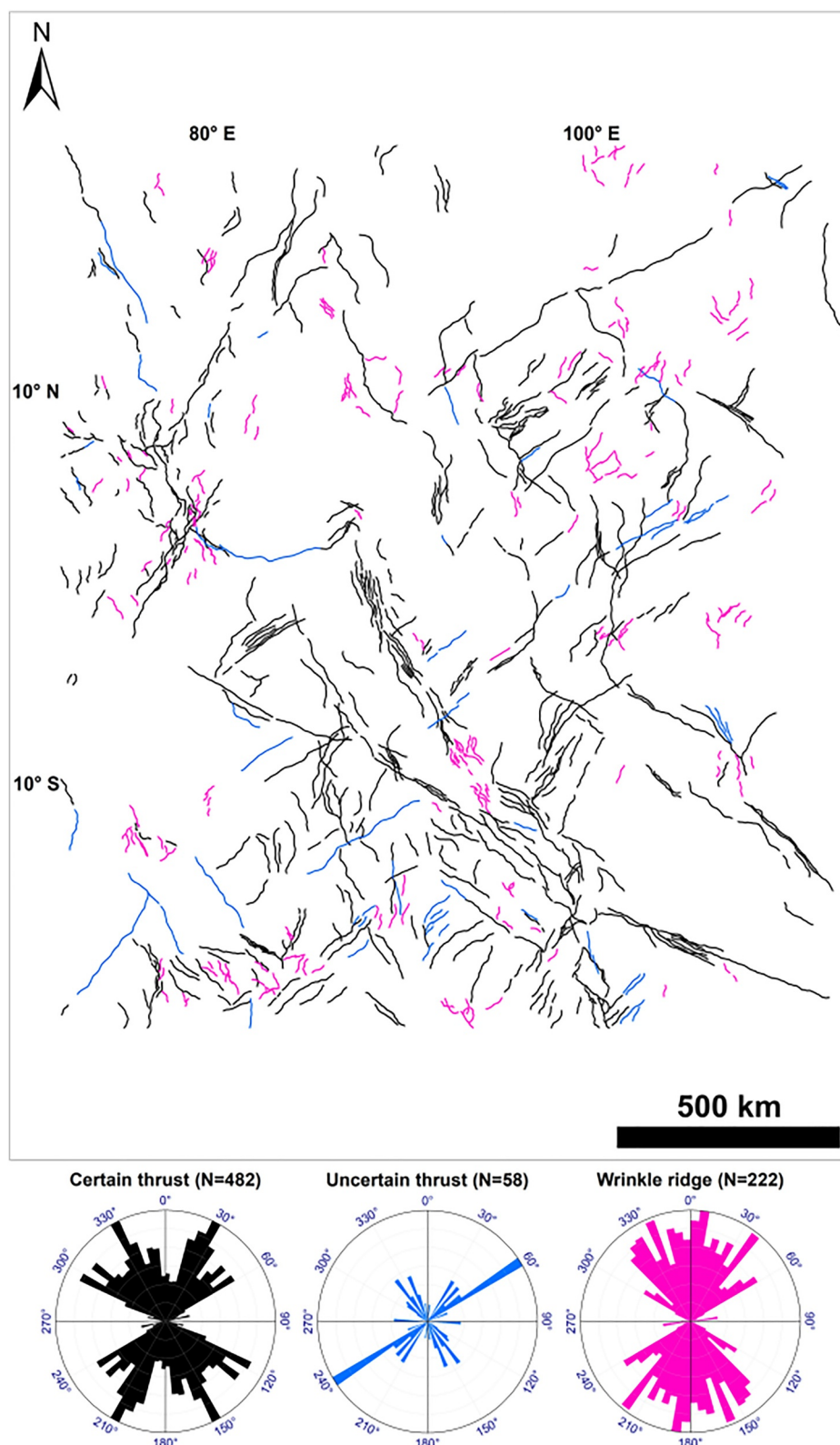


Figure 6. Spatial distribution and orientations of lobate scarps—certain (black), uncertain (blue)—and wrinkle ridges (pink) in the study area. The polar plots at the bottom show the orientation distribution of these linear structures.

A relatively large number of lobate scarps are observed within the ICP in the southern part of the study area (Figure 6). The greatest area-normalized lengths of these tectonic features occur between 0°S and 22°S. The azimuthal distribution of lobate scarps and wrinkle ridges is non-uniform, which may reflect localized deformational events or surface resurfacing due to lava flows. Rose diagrams of the digitized segments indicate a strong preferred orientation (Figure 6).

The dip slope of the lobate scarps ranges between ~25° and 35°, consistent with previous measurements in other regions of Mercury (Byrne et al., 2014; Galluzzi, 2015; Galluzzi et al., 2019; Pegg et al., 2021a, 2021b). Some scarps exhibit lower dip angles (<30°). A set of ENE–WSW trending lobate scarps displays dips to both the east and west at low latitudes. Some lobate scarps and wrinkle ridges between 8°S–21°S and 95°E–100°E appear to be radial to the regional intercrater and IP. Certain scarps exhibit distinctive morphological features along their slopes, such as double ridges and uphill- and downhill-facing scarps. A notable set of ENE- and WNW-trending faults is more prominent in the southern sector of the study region compared to the north. Several wrinkle ridges display spatial relationships with lobate scarps and are observed over ICP or within old crater floors. This suggests that both types of tectonic structures likely formed under the same compressional stress regime or deformational event. We interpret the wrinkle ridges as blind thrust faults, where horizontal shortening is accommodated without reaching the surface. Their emplacement postdates the resurfacing of the basin and impact crater floors that host them, and they are generally located around existing compressional landforms.

In the southeastern sector of the study area, at ~90°E and between 0° and 5°S, a population of NNW–SSE trending scarps ranging from ~12 to 199.5 km is expressed along the ICP and crosscuts C2 and C3 craters (Figures 4 and 6). Adjacent to these NNW–SSE scarps, CH are observed within impact craters and on their proximal ejecta. Additionally, a group of small ENE–WSW oriented scarps is present nearby; these scarps are shorter and occur over ICPs, crater floors, and ejecta (Figure 4).

To the south of the NNW-SSE and ENE-WSW trending scarps, between 80°E and 9°S–3°S, a group of major but segmented WNW-ESE lobate scarps is identified, extending beyond the study area. The NNW-SSE trending scarps border the ENE-WSW and WNW-ESE scarps, forming a highly tectonized zone.

We identified four thrust fault systems in the study region based on the superposition and crosscutting relationships among the lobate scarps. By extension, a fault is considered younger than the fault it cuts and older than the fault that cuts it. Our observations follow standard geological principles for establishing relative fault chronology (Childs et al., 1995), including the principles of superposition, intersection, and recovery.

The first system, NNW-SSE, contains major thrust faults that extend up to ~248 km in length. The second system, WNW-ESE, includes faults concentrated between 0° and 22°S. These faults reach ~342 km in length and are mainly continuous, primarily present in the south, and extend farther than those of the first system. The third system, NNE-SSW, hosts faults up to ~398 km long. These faults are widely distributed in the northeast, with a minor presence in the south. The fourth system consists of ENE-WSW trending structures. These faults are more frequent in the south than in the north and are shorter in length compared to the NNE-SSW system.

The first and third fault systems exhibit similar behavior in terms of fault length, distribution intensity, and continuity. A comparable pattern was observed for the lobate scarps of the second and fourth fault systems. We noted that many lobate scarps occur adjacent to intercrater plains, develop over the ICP, and sometimes sharply delimit SP from ICP. Unlike the floors of some old craters and impact basins, the ICP, IP, and SP units do not show a significant presence of wrinkle ridges. These crisp structures are prominently observed within buried, degraded crater floors and old basins. The wrinkle ridges often merge with lobate scarps, suggesting they may share a similar origin and age (Galluzzi, 2015; Watters & Nimmo, 2010), potentially associated with plains formed by extensive lava resurfacing. In the south, at 100°E and between 2°S and 22°S, a set of ENE-WSW segmented lobate scarps is identified, crosscut by another adjacent set of lobate scarps, forming a cluster of parallel to subparallel fault segments. This deformed zone indicates a significant deformational event responsible for the formation of the fault systems observed in the study area. These deformational events could be associated with volcano-tectonic activity or, potentially, with the global contraction of Mercury.

Lobate scarps display fault-propagation folds and appear as hanging-wall anticlines atop surface-breaking thrust faults (Head et al., 2008; Strom et al., 1975; Wright et al., 2021). Extensional tectonics were not identified and are typically restricted to volcanically infilled impact features (Byrne et al., 2018; Freed et al., 2012; Schleicher et al., 2019). Some steep lobate scarps accommodated more shortening than wrinkle ridges. Examples of lobate

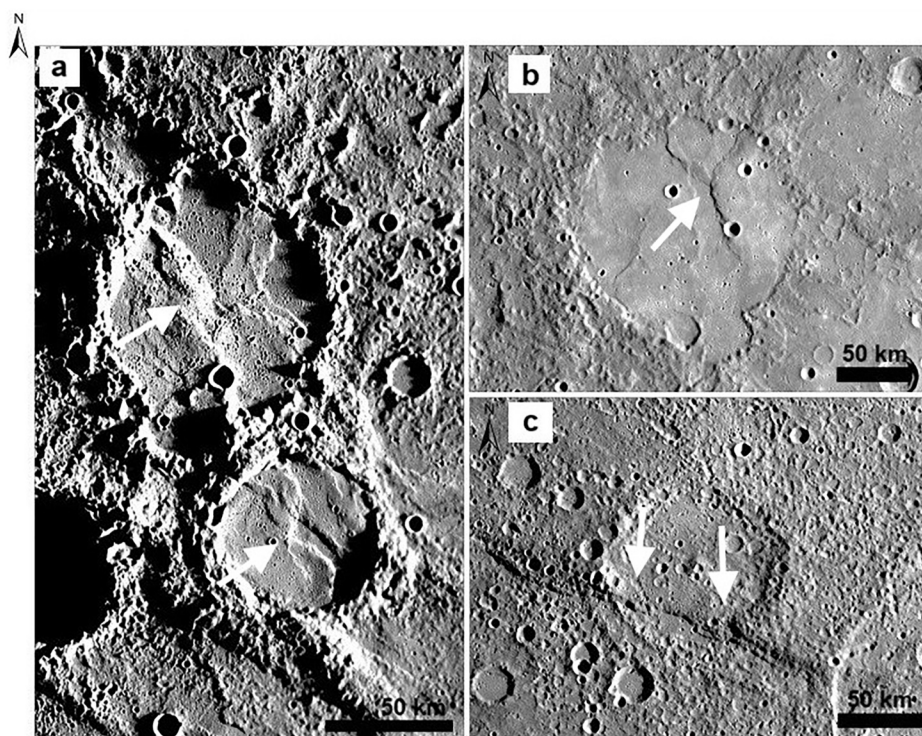


Figure 7. View of Mercury Dual Imaging System BDR monochrome images showing craters crosscut by different lobate scarps: (a) Savage crater (top: 93.405°E, −8.591°N) and Ruysch crater (bottom: 94.123°E, −10.701°N); (b) Unnamed old crater located at 106.906°E, −11.203°N with lobate scarps crosscutting the crater floor; (c) Unnamed crater at 105.422°E, −16.484°N transected by a major lobate scarp. The crater diameters in the panels range from 64 to 130 km.

scarps transecting craters of different sizes are shown in Figures 7 and 8. This suggests that some lobate scarps may have continued developing during the Mansurian System (Banks et al., 2012; Fegan et al., 2017). We used crosscutting relationships between craters and lobate scarps, along with kinematic analysis of fault-slip data (Galluzzi, 2015; Strom et al., 1975; Thomas & Allemand, 1993; Watters & Nimmo, 2010). Lobate scarps are young than most impact craters in the study area. This observation is supported by the superimposition and crosscutting relationships shown in Figures 7 and 8, where lobate scarps are frequently observed overlying impact craters. A feature that cuts across another must be younger than the feature it cuts. A feature or structure is younger than the features or structures beneath it. The spatial distribution of lobate scarps relative to geologic units and impact craters suggests that some of these linear structures were localized along mechanical discontinuities introduced by the rims of heavily degraded and buried craters, crater floors (Figures 7 and 8), or the rings of old impact basins.

Figure 7 shows craters of different classes crosscut by one or more lobate scarps and surrounded by ICP, IP, and SP. Figure 8 shows a C1-class crater cut by a major lobate scarp. The crater floor displays several lobate scarps of different dimensions and wrinkle ridges. This C1 crater is discussed in detail in Section 5.2.

5.1. Beagle Rupes and Sveinsdóttir Crater

The morphology of Beagle Rupes is distinct from that of other scarps in the study area. Beagle Rupes exhibits an asymmetric north–south profile, with a steep frontal face and a gentle slope on the lateral side (Figure 9). Most of the scarps surrounding Beagle Rupes are relatively short, ranging from a few meters to 9 km in length, and are characterized by shallow relief. Beagle Rupes is interpreted as a thrust or reverse fault, indicative of lithospheric compression in the study area, and is expressed as two convex arc segments trending north–south, extending approximately 260 km in length (Rothery & Massironi, 2010).

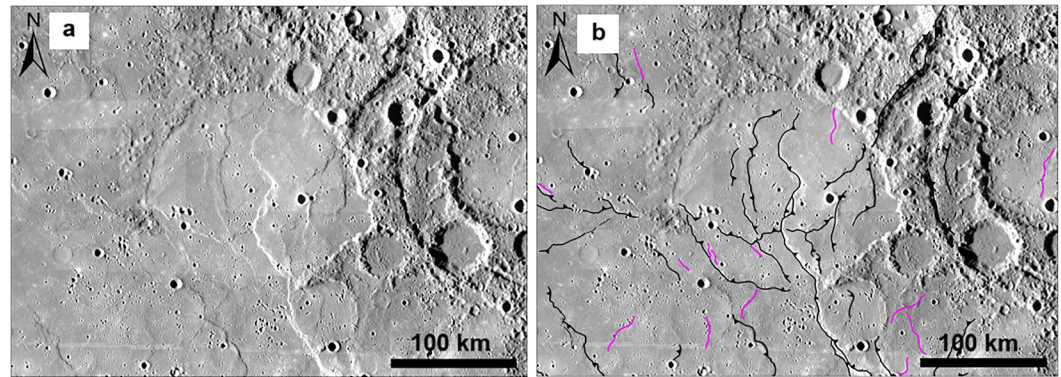


Figure 8. Views over Mercury Dual Imaging System High-Incidence West showing Faulkner crater (8.115°N, 76.995°E) crosscut by different lobate scarps and wrinkle ridges: (a) Tectonized floor of Faulkner crater (C3-class). The smooth crater floor indicates resurfacing related to volcanic flows in the area. (b) Background interpretation. The pink lines in panel (b) represent wrinkle ridges, lobate scarps are outlined with black lines, and the triangular teeth indicate the dip direction of the thrust.

The fault scarp extends over 650 km, with a maximum relief of approximately 1 km. The sense of faulting involves an overthrust of the right side over the left. The north–south arcuate segment of Beagle Rupes bends at its northern end into a straight ENE-trending scarp oriented roughly 45°N, and at its southern end into a straight ESE-trending scarp oriented roughly 45°S (Figure 9). These surface-cutting thrust faults require a significant amount of stress to form and slip, resulting in one steep side of the scarp.

Early work by Rothery & Massironi (2010) interpreted the Beagle Rupes scarp as part of a linked fault system, originating from a frontal scarp connected to transpressive lateral ramps. The hanging-wall block of the thrust fault is likely underlain by a detachment horizon that constitutes the fault zone at depth. Due to the NS arcuate orientation of the Beagle Rupes frontal scarp, the shortening direction is approximately EW. Furthermore, considering Mercury's global contraction, each relay ramp could accommodate both pure shortening and a strike-slip component.

The shortening produced by Beagle Rupes is explained by right-lateral slip along the northern ramp and left-lateral transpressive slip along the southern ramp. These interpretations are consistent with earlier observations by Rothery & Massironi (2010). The hanging-wall block of the thrust fault is underlain by a basal decollement or detachment horizon, which constitutes the fault zone at depth. The decollement extends at least 150 km eastward from the frontal scarp (Rothery & Massironi, 2010). In Figure 9, the horizontal displacement along the thrust faults beneath the lobate scarp must have been at least one to several kilometers to account for the observed deformation of the Sveinsdóttir impact crater.

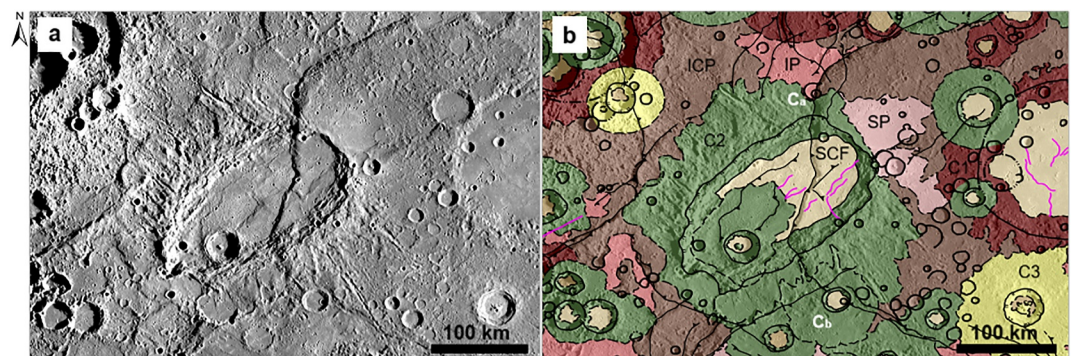


Figure 9. Beagle Rupes lobate scarp and the Sveinsdóttir impact crater image centered at −2.25°N, 100.156°E. (a) View from Mercury Dual Imaging System High-Incidence East. (b) Background interpretation and geologic mapping (Map units displayed with 30% transparency).

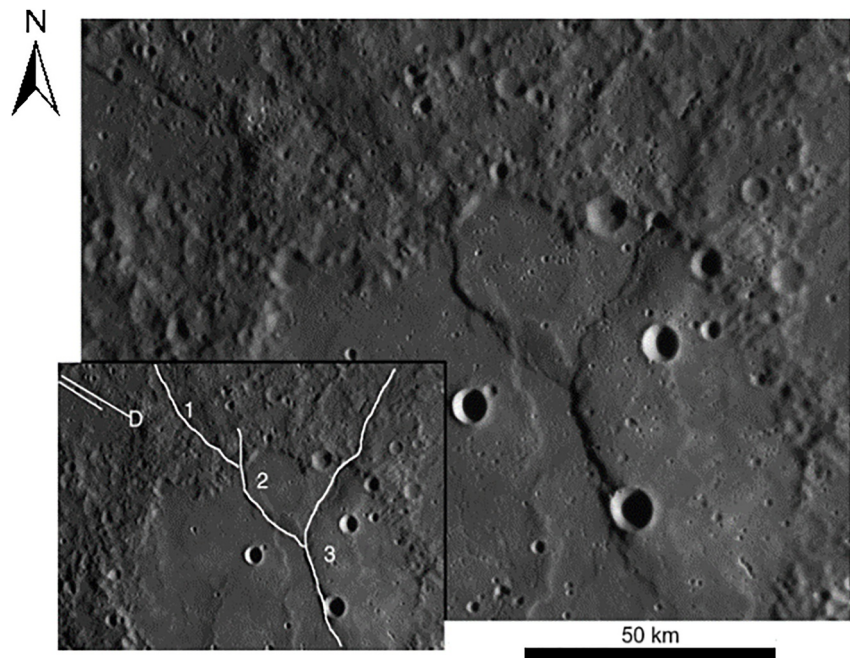


Figure 10. Positive flower structure in an unnamed crater located southeast of Beagle Rupes. The panel shows three successively younger overlying scarps, with their relative age sequence indicated by crosscutting relationships. Letter **D** marks the termination of the southern side of the Beagle Rupes lateral ramp. The main background frame shows a few wrinkle ridges associated with the Beagle Rupes system. Image based on MESSENGER narrow-angle camera data (After Rothery & Massironi, 2010; modified).

Most of the plains surrounding Beagle Rupes and the Sveinsdóttir crater are ICP, with minor contributions from IP and SP. A group of wrinkle ridges is observed on the smooth floor of the Sveinsdóttir crater, oriented NE-SW. These ridges result from compressional tectonics within the crater, caused by horizontal shortening.

The northern segment of Beagle Rupes crosscuts a ~ 17 km-diameter impact crater (Centered near 0.3°N , 101°E , labeled Ca in Figure 9) situated between ICP and IP. Based on their crosscutting relationship and superposition, this crater appears to be older than the scarp. Further south, the southern segment of Beagle Rupes intersects a larger impact crater, approximately 28 km in diameter (Labeled Cb in Figure 9). In this case, the crater appears to be younger than the scarp, as the scarp segment does not extend into the crater floor, supporting the interpretation that this crater formed after the development of Beagle Rupes.

Solomon et al. (2008) argued for a shortening of at least one to several kilometers for the Beagle Rupes scarps. This observation was based on an unnamed crater (-9°N , 107.438°E) approximately 17 km in diameter, located about 30 km from the northern rim of the Sveinsdóttir crater and cut by a frontal scarp. Further, Watters et al. (2009) proposed 1 km as a lower limit, while Rothery & Massironi (2010) discussed a shortening ranging from at least 1 km to an average of 3 km for the Beagle Rupes scarp.

The NE-SW trending segment of the Beagle Rupes scarp cuts a ~ 9 -km diameter impact crater centered near 7.9°S , 108.2°E . This crater is located near the rim of a larger degraded crater (~ 133 km in diameter) flooded by SP and subsequently deformed by wrinkle ridges, as shown in Figure 10. A positive flower structure has been identified within this ~ 133 km crater. Such structures are typically the surface expression of strike-slip faults in a shear zone, intersecting with converging or diverging crustal blocks (Huang & Liu, 2017). The positive flower structure observed in Figure 10 accommodates compressive stress produced by a shallow antiform and upward-diverging thrust faults. This structure is characterized by reverse separations and horizontal shortening.

Figure 10 shows that the structure is transferred to three successively overlying joint scarps. The third scarp of this structure crosscuts the second scarp, which in turn crosscuts the first scarp. These crosscutting linear features suggest a propagation sequence for the Beagle Rupes thrust fault. Based on their superposition and crosscutting relationships, we infer that these overlying and coalescent scarps formed in close temporal succession. The first

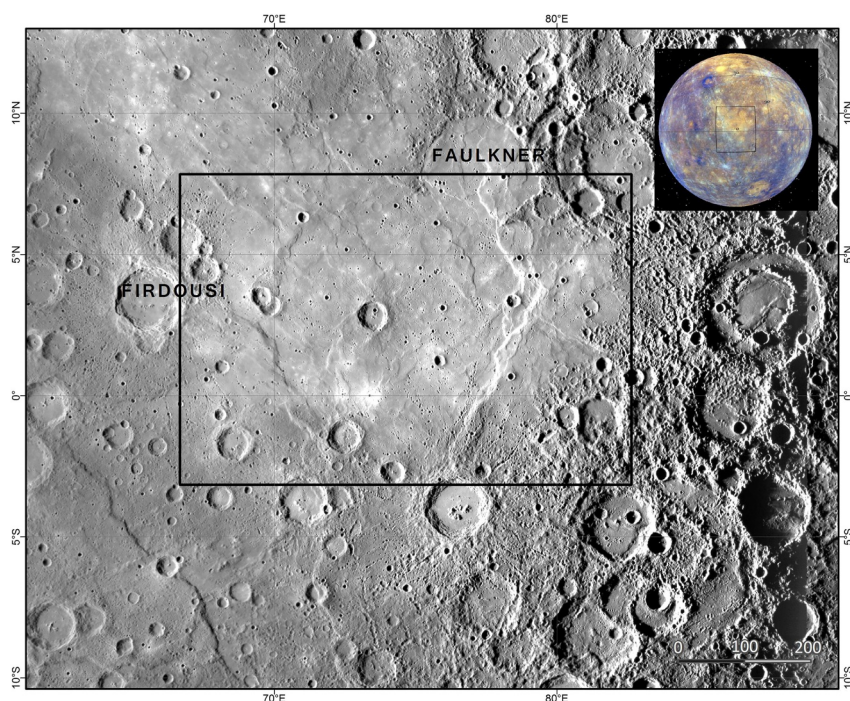


Figure 11. The b12 basin is surrounded by SP, Intermediate plains, and ICP. On the west side of the basin lies the Firdousi crater, while the Faulkner crater is located to the northeast (after López et al., 2015, modified). The black box approximately shows the extent of Figure 12.

segment of these structures (Noted as 1 in Figure 10) formed first, followed by the second scarp and then the third scarp.

These structures are associated with strike-slip kinematic indicators, typically found along reactivated rims of ancient, buried basins and, in most cases, linked to frontal thrusts acting as lateral ramps. The crater in Figure 10 displays a buried and degraded rim and is classified as a C1 crater. Its floor is smooth, indicating resurfacing related to volcanic activity that filled the crater after its formation. Magma infilling of old craters and basins is evident in the study area; several ancient craters and their surrounding intercrater plains exhibit smooth floors, thought to have formed from widespread volcanic flows. Joint scarps formed after this crater floor resurfacing, while wrinkle ridges were observed on the floor, indicative of compressional stress and crustal contraction in the region. A few fresh craters, ranging from ~6 to ~9 km in diameter, are present on the crater floors and occur spatially near the scarps.

5.2. Compressive Tectonics in Unnamed b12 Basin

Here, we study the tectonic context of the old basin centered at 3.7°N, 74.5°E (Figure 11), known as b12 (Fassett et al., 2012). The b12 basin is situated in the transitional zone between SP and ICP. Smooth plains dominate the western, northwest, and southwest sides of the basin, whereas the eastern, northeast, and southeast sides are limited by ICP, extensively modified by impact craters of various sizes and degrees of degradation. The basin floor is smoother, indicating recent infilling by volcanic deposits, which has subsequently been deformed by horizontal compressive stresses. On the eastern side of the basin, a few other old basins with diameters of approximately 198 and 220 km are observed, with one or more basin rings visible within the ICP. The western side of b12 shows a lower crater density compared to the eastern side.

Bright materials and hollows have been observed on the floor of b12 and in the surrounding SP to the northwest. These intriguing surface features appear as shallow, sub-kilometer-scale, flat-floored, and rimless depressions. Hollows likely form through the loss of volatile substances from the surface, and their fresh morphology, along with the lack of superposed craters or structures, suggests that their formation has continued until relatively recently (Thomas et al., 2014a, 2014b).

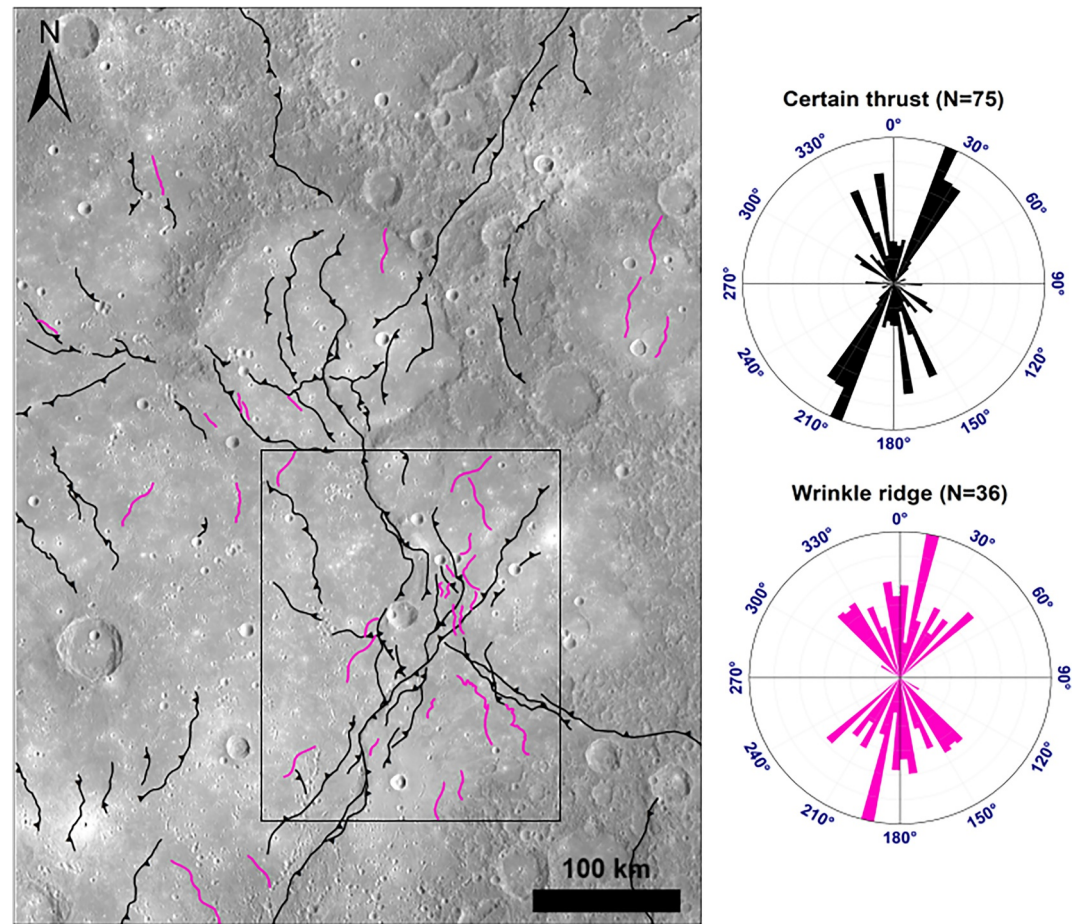


Figure 12. Shear zone of the b12 old basin (black box). View over Mercury Dual Imaging System High-Incidence East, centered at 2.185°N, 79.214°E. The polar plots show the trends of the lobate scarps ($N = 68$) and wrinkle ridges ($N = 45$), derived from the polylines' lengths. The black box shows the approximative extent of Figure 13.

The basin-related compressive stress field produced extensive sets of lobate scarps and wrinkle ridges of varying sizes and orientations. These compressive tectonic landforms represent thrust faults and may also reflect large-scale folding in the area. The tectonic features crosscut and deform the smooth floor of b12, indicating a complex stress history of compressive deformation in the region.

We identified three main orientations for the lobate scarps within the b12 basin (Figure 12): NNE–SSW, NNW–SSE, and WNW–ESE. The wrinkle ridges are oriented NNE–SSW, NS, ENE–WSW, and NNW–SSE (Figure 12). Several wrinkle ridges trend in the same directions as the lobate scarps, both within the basin and in the surrounding plains. This observation suggests that the formation of these linear features may have been synchronous or occurred within a short time interval. The scarps within the b12 basin range in length from ~12 to 230 km and exhibit vertical displacements from a few meters up to 720 m.

We analyzed the crosscutting relationships and superposition among the different lobate scarps. We identified three tectonic deformational phases within the b12 basin: The first phase produced the NNW–SSE wrinkle ridges; the second phase generated the WNW–ESE and NNW–SSE lobate scarps; and the third phase produced the NNE–SSW lobate scarps, accompanied by NS, NNE–SSW, and ENE–WSW wrinkle ridges with left-lateral transpressional kinematics. These three phases are confined to the b12 basin and do not extend beyond the basin boundaries. The lobate scarps and wrinkle ridges within b12 are most likely the result of intense tectonic and volcanic activity in the region. The wrinkle ridges are classified into two groups based on their orientations and spatial distribution relative to the lobate scarps. The first group consisted of spatially isolated wrinkle ridges oriented NNW–SSE. This group appears to have formed before the lobate scarps, according to López et al. (2015).

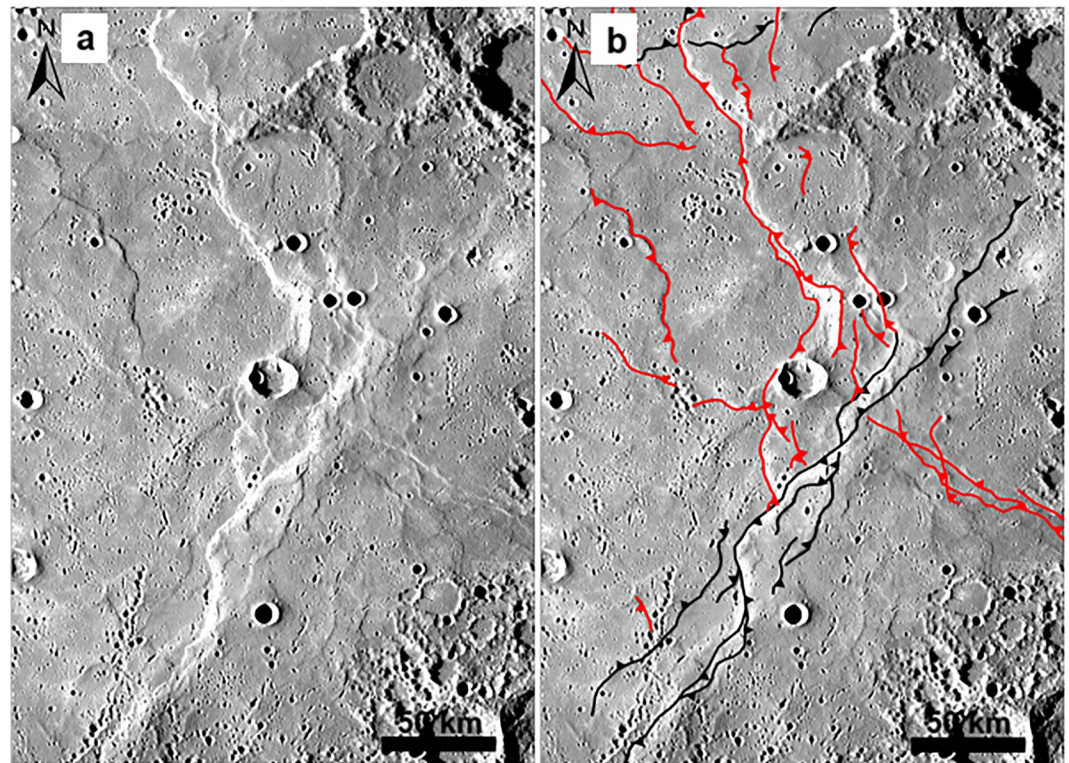


Figure 13. Crosscutting lobate scarps on the eastern side of the b12 basin. View over Mercury Dual Imaging System High-Incidence West, centered at 3.18°N, 78.388°E: (a) NNW-SSE and WNW-ESE lobate scarps (Red lines) transected by an NNE-SSW lobate scarp (black lines); (b) Background interpretation of (a).

The second group, composed of wrinkle ridges oriented NS, NNE-SSW, and ENE-WSW, appears spatially associated with the lobate scarps, and their formation seems to be synchronous with the NNE-SSW-trending lobate scarps. Illumination conditions can significantly affect the number of tectonic structures mapped on Mercury (Byrne et al., 2018), but they cannot fully explain the absence of EW-trending faults. The absence of E-W-trending linear structures was also reported in Mariner 10 data (Strom et al., 1975). The lack of EW-trending lobate scarps or wrinkle ridges within the basin and adjacent plains may be attributed to illumination conditions in the MESSENGER MDIS data set and the mission's polar orbit, which could bias the identification of EW-oriented structures (Byrne et al., 2018). However, the possibility that no regional tectonic events capable of generating EW-trending thrust faults or wrinkle ridges occurred, or that the tectonic setting did not favor the development of such structures, should also be considered.

The temporal distribution of the lobate scarps and wrinkle ridges in b12 suggests that these features may have formed after the emplacement of the Calorian SP, around <3.9 Gyr ago (Fassett et al., 2012). We propose that the formation of these structures could be even younger than 3.9 Gyr ago, based on their crisp appearance, low crater density, and occurrence along the SP. These shortening structures are expressed over volcanic deposits that have been deformed by horizontal compressive stresses. An open question remains whether these features formed due to stresses induced by global contraction, bending stresses from volcanic loading, or some combination of both.

Although strike-slip faults are not commonly observed in the study area, we identified a left-lateral transcurrent fault within a restraining bend (Figure 14). The kinematics of this strike-slip fault are associated with the NNE-SSW lobate scarp and result in the formation of a pop-up structure. This structure consists of two parallel thrust faults, typical of fold-and-thrust belts, expressed on the surface as uplifted blocks formed by compression between thrust faults with opposing vergence.

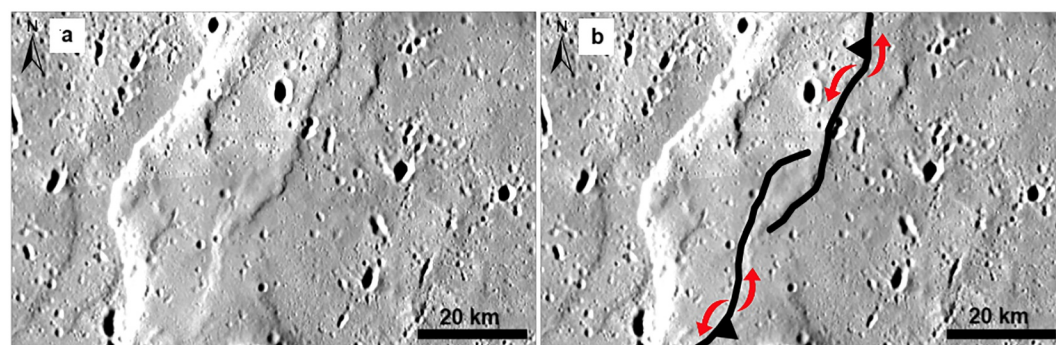


Figure 14. Strike-slip fault and restraining step-over in the southeast of b12, view over Mercury Dual Imaging System BDR, centered at 1.52°N, 78.145°E: (a) NNE-SSW-oriented strike-slip fault with a gentle restraining bend; (b) Background interpretation.

6. Discussion

The map presented in Figure 4 helped identify notable surface features within the western half of the Eminescu quadrangle (H09) on Mercury. In this section, we propose a list of geologic features as potential targets for imaging by the ESA/JAXA BepiColombo space mission (El Yazidi, 2023; El Yazidi et al., 2023). The selection of these scientific targets is motivated by their relevance for advancing our understanding of Mercury's geology. The proposed sites include a broad range of plains, volcanic features, tectonic structures, impact craters, hollows, and surface deposits such as bright or dark materials. The Spectrometer and Imagers for MPO BepiColombo—Integrated Observatory SYStem (SIMBIO-SYS) team (Cremonese et al., 2020) identified and classified each candidate target by category, rank, type class, and priority (Table 1). The diversity of these targets, spanning both surface materials and geological features, will help address many unresolved questions regarding Mercury's geology, including the origin of hollows and bright deposits, as well as the planet's volcanic and tectonic history. This aligns with the mission objectives to provide a comprehensive exploration of Mercury and its environment, focusing on the planet's formation and evolution, including studies of its surface, interior, magnetosphere, and exosphere.

The potential sites listed in Table 2 are accessible within the mission's nominal orbit and do not require special spacecraft maneuvers for imaging. Each target is characterized by a unique identification number, central, maximum and minimum latitude and longitude (Table 2). The identification numbers refer to the working groups responsible for investigations of Mercury's interior and surface studies, as defined by the global collaborative mapping effort of Mercury's surface (Galluzzi, 2019). The proposed targets in Table 2 belong to Working Group 6 (WG6): Surface and Composition and Laboratory Activities on Surface Analogues, and Working Group 8 (WG8): Stratigraphy and Geological Mapping.

For a better understanding of the geologic context and surface composition of the proposed targets, we consider it important that these sites be observed using multiple instruments onboard the BepiColombo space mission, including spectral, geomorphological, and surface analysis tools. Figure 15 shows examples of potential scientific targets proposed in this work to support the ESA/JAXA BepiColombo mission. These classes are described in Table 1. The sites in Table 2 represent the outcome of the geologic mapping efforts conducted for the western half of the Eminescu quadrangle (Figure 4).

7. Conclusion

The western half of the Eminescu (H09) quadrangle is characterized by compressive tectonics, expressed through a wide distribution of lobate scarps and wrinkle ridges resulting from intensive compressive stress in the study area. Many of these tectonic structures are located over the plains units and frequently crosscut crater floors. Our results show that lobate scarps and wrinkle ridges played a fundamentally major role in the deformational history of the western half of the Eminescu quadrangle (H09); however, volcanic processes also had a significant role in resurfacing the plains units. Given the general lack of observable volcanic features with significant relief on the

Table 1

Category and Priority-Ranking Classes for the Proposed Targets

Category	Plains: Sample areas of morphological and geochemical interest, such as faculae, bright crater rays, and bright or dark surface materials. Craters: Any unusual crater, or crater containing peculiar features, that requires study of its geological context or further investigation. Structures: Scarps, faults, ridges, or any other linear features of interest. Volcanic: Volcanic vents, putative vents, pitted grounds, or pyroclastic deposits. Hollows: Hollow fields, putative hollows, clusters, or isolated hollow spots. Other features: Dark spots, bright spots, putative layering, or landslides.
Rank	Rank 1: This is the lowest rank and usually includes targets that have already been covered by MESSENGER at lower resolution, so global mapping is sufficient to study features of this rank. Rank 2: This is a low rank, similar to the previous one, but higher-resolution coverage could help study certain areas of interest. Rank 3: This is a medium-rank class, dedicated to known large features that would benefit from improved observation conditions. Rank 4: This class is for high-rank targets, defined as previously unknown features whose study requires higher resolution or better compositional information. Rank 5: This is the highest-rank class and includes the main science goals or very small unknown features whose study requires fundamentally important data sets.

surface, we conclude that the volcanism was largely fissural. In this type of volcanism, lava erupts from fissures opened in the crust by the upward movement of magma toward the surface.

A set of lobate scarps and wrinkle ridges has been identified, oriented in the NNE-SSW, ENE-WSW, and NNW-SSE directions. The similar trends of these two types of features suggest that these compressive landforms belong to the same tectonic event. The lobate scarps studied in this work are the result of regional-scale compressional tectonic events intermixed with lava flow fronts. We also acknowledge the contribution of global contraction of Mercury, occurring when the planet's interior and lithosphere cooled, generating significant thermal stress responsible for the formation of lobate scarps (Solomon, 1978, 1979).

Our investigation of the tectonic context of the b12 basin indicates three global deformational phases responsible for the formation of lobate scarps and wrinkle ridges. The first deformational phase produced the NNW-SSE wrinkle ridges; the second phase generated the WNW-ESE and NNW-SSE lobate scarps; and the third phase produced the NNE-SSW lobate scarps accompanied by NS, NNE-SSW, and ENE-WSW wrinkle ridges, with left-lateral transpressional kinematics. In contrast to an earlier work by López et al. (2015), our results indicate three distinct stages of compressive deformation within the buried b12 basin.

Based on crater morphometric characteristics, we infer that craters in the western half of the Eminescu (H09) quadrangle on Mercury range in age from pre-Tolstojan to Kuiperian. Some craters with diameters of 5–20 km exhibit fresh materials, crisp rims, and well-preserved ejecta, suggesting they most likely formed during the Kuiperian. Larger craters exceeding 20 km in diameter (Orgel et al., 2020) can be divided into two classes: (a) fairly fresh craters without preserved rays, likely of Mansurian age, and (b) craters with degraded rims and plains-filled floors, where the limits of ejecta are difficult to determine, likely of Calorian age. A few large craters with partially visible rims and mostly obscured ejecta are thought to date to the Tolstojan or pre-Tolstojan periods.

In this work, we conclude that the western half of the Eminescu quadrangle experienced early, intensive compressive tectonics and cratering processes. The prominent geological features in this region are linked to tectonic disruption associated with deformational events, potentially in combination with large-volume effusive volcanism on Mercury. The preliminary results presented here, based on the geologic map of the western half of the Eminescu (H09) quadrangle, provide a foundation for future studies of fault systems and for constraining the magnitude of horizontal shortening accommodated in this area.

Table 2

List of Geologic Sites Proposed as Potential Science Targets Within the Western Half of the Eminescu Quadrangle (H09) for the ESA/JAXA BepiColombo Mission

Target ID	Cen Lat	Cen Lon	Category	Type	Rank	OTH INST ^a
600111	18.59	88.00	plains	bright deposits	2	MERTIS
600112	16.05	75.00	plains	bright deposits	2	MERTIS
600113	19.62	81.00	craters	Landslide in Crater	4	MERTIS
600114	0.74	78.00	craters	Young Crater	2	MERTIS
600115	8.62	92.00	craters	Young Crater	4	MIXS + MERTIS + MGNS
600116	14.24	88.00	other features	Dark spot	3	MIXS + MERTIS + MGNS
600117	−3.93	76.00	craters	Bagryana crater	2	MERTIS
600118	15.81	94.00	craters	Complex crater	4	MERTIS
600119	−9.99	122.00	craters	Complex crater	3	MERTIS
600120	0.05	73.00	craters	Small crater	2	MERTIS
600121	2.84	73.00	craters	Small crater	2	MIXS + MERTIS + MGNS
600122	−12.47	117.00	craters	crater floor	4	MIXS + MERTIS + MGNS
600123	1.27	76.00	craters	Crater with landslide	4	MERTIS
600124	−5.17	83.00	Hollows	hollows field	4	MIXS + MERTIS
600125	6.45	96.00	craters	Crater with landslide	3	MERTIS
600126	18.17	102.00	craters	central peak	5	MERTIS
600127	−11.03	125.00	other features	Unclassified features	3	MERTIS
600128	−8.86	103.00	craters	Crater with Landslide	3	MERTIS
600129	2.53	84.00	craters	Elliptical irregular	3	MERTIS
600130	−12.34	76.00	hollows	hollows field	4	MIXS + MERTIS
600131	6.82	103.00	hollows	hollows field	4	MIXS + MERTIS
600132	1.22	113.00	hollows	hollows field	4	MIXS + MERTIS
600133	1.02	114.00	hollows	hollows field	4	MIXS + MERTIS
600134	−11.67	107.00	hollows	hollows field	4	MIXS + MERTIS
600135	−19.72	108.00	hollows	hollows field	4	MIXS + MERTIS
800118	7.91	77.00	Structures	Faulted Floor of Crater	4	MERTIS
800119	−18.89	115.00	Structures	Tectonic features	3	MERTIS
800120	−2.84	100.00	Structures	Beagle Rupes and Sveinsdottir crater	4	MERTIS
800121	−12.15	96.00	Structures	Broad valley in tectonic plains	2	MERTIS
800122	−16.07	94.00	Structures	Tectonic depression	2	MERTIS
800123	0.72	115.00	Structures	Tectonic Morphology	3	MERTIS
800124	0.24	113.00	Craters	Deformed crater floor	3	MERTIS
800125	−17.07	110.00	Structures	Faulted Floor of Crater	3	MERTIS
800126	−6.01	97.00	plains	Tectonized plains	3	MERTIS
800127	−8.46	99.82	Volcanic	Putative volcanic vents	3	MERTIS + SERENA
800128	−17.48	99.00	Structures	Tectonic intersection	3	MERTIS
800129	8.04	94.00	Craters	Deformed crater	2	MERTIS
800117	3.20	78.00	Structures	Tectonic zone	4	MERTIS + BELA

^aOTH INST: Other Instruments; BELA: BepiColombo Laser Altimeter; MERTIS: Mercury Radiometer and Thermal Infrared Spectrometer; MIXS: Mercury Imaging X-ray Spectrometer; MGNS: Mercury Gamma ray and Neutron Spectrometer; SERENA: Search for Exospheric Refilling and Emitted Natural Abundances. The TARGET ID indicates the progressive number of the target within the WG (e.g., Target 600111 means WG6, target No. 111).

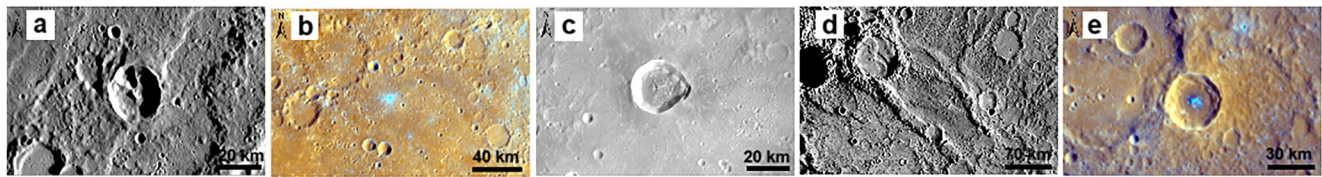


Figure 15. Views over different basemaps of some proposed science targets: (a) Crater with a potential volcanic vent (Target ID 800127) on the northwest side of the crater rim. (b) Terrain sample (Target ID 600111) with high-albedo bright materials. (c) Fresh, young impact crater (Target ID 600113) with a smooth floor and visible central peak. (d) Crater-lobate scarp joint feature (Target ID 800121) in the ICP, creating a complex surface feature. (e) Impact crater with a possible hollow in the central peak (Target ID 600124).

Inclusion in Global Research Statement

This research project was initially conducted at the Center for Studies and Activities for Space (CISAS) at the University of Padova and completed within the ESA Archival Research Visitor Program. Funding for the project was provided by the CARIPARO scholarship at the University of Padova, the ESA Science Faculty (funding reference ESA-SCI-SC-LE-209), and by P. D'Incecco through ASI/INAF Grant 2022-16-HH.0. This work is the result of international collaboration among researchers at CISAS/UNIPD, ESTEC/ESA, ARES/NASA, Kobe University, INAF, Arctic Planetary Science Institute, FST/UTM, and INCT/UDA.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Description of the Type of data: We used multiple data sets from NASA MESSENGER MDIS. These data were produced by the MESSENGER team (Denevi et al., 2018; Hawkins et al., 2007). **Repository Name:** The MESSENGER MDIS data used in this study are publicly available from NASA's Planetary Data System (<https://pds-imaging.jpl.nasa.gov/portal/>). These data sets are all credited to NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institute of Washington. The Mercury MESSENGER DEM product was produced by the US Geological Survey (https://astrogeology.usgs.gov/search/map/mercury_messenger_global_dem_665m) using the MESSENGER MDIS NAC, the WAC camera, stereo photogrammetry data (Becker et al., 2016), and the Integrated Software for Imagers and Spectrometers version 3 (<https://isis.astrogeology.usgs.gov/8.3.0/>). This data is publicly available (<https://www.usgs.gov/>). The data used in the study and a digital copy of the shapefiles and basemaps are available at El Yazidi et al. (2025). Zenodo. Doi: <https://doi.org/10.5281/zenodo.15616182>. We used the full-featured professional System Research Institute (ESRI)'s ArcMap 10.7.1 Geographic Information System software to map, visualize, and analyze data. We processed data in a GIS-ready format through USGS ISIS3 software. The final map products were produced in ESRI ArcGIS and assembled in Ink-scape 1.3.2.0.

References

- Banks, M. E., Watters, T. R., Strom, R. G., Solomon, S. C., Braden, S. E., Chapman, C. R., et al. (2012). Stratigraphic relationships between lobate scarps and young impact craters on Mercury: Implications for the duration of lobate scarp formation. *Lunar Planet. Sci.*, 43. Abstract #2684.
- Banks, M. E., Xiao, Z., Braden, S. E., Barlow, N. G., Chapman, C. R., Fassett, C. I., & Marchi, S. S. (2017). Revised constraints on absolute age limits for Mercury's Kuiperian and Mansurian stratigraphic systems. *Journal of Geophysical Research: Planets*, 122(5), 1010–1020. <https://doi.org/10.1002/2016JE005254>
- Banks, M. E., Xiao, Z., Watters, T. R., Strom, R. G., Braden, S. E., Chapman, C. R., et al. (2015). Duration of activity on lobate-scarp thrust faults on Mercury. *Journal of Geophysical Research: Planets*, 120(11), 1751–1762. <https://doi.org/10.1002/2015JE004828>
- Becker, K. J., Robinson, M. S., Becker, T. L., Weller, L. A., Edmundson, K. L., Neumann, G. A., et al. (2016). First global digital elevation model of Mercury. *Lunar Planet. Sci.*, 47. Abstract #2959.
- Benkhoff, J., Murakami, G., Baumjohann, W., Besse, S., Bunce, E., Casale, M., et al. (2021). BepiColombo - Mission overview and science goals. *Space Science Reviews*, 217(90), 90. <https://doi.org/10.1007/s11214-021-00861-4>
- Bickel, V. T., Deutsch, A. N., & Blewett, D. T. (2025). Hollows on Mercury: Creation and analysis of a global reference catalog with deep learning. *Journal of Geophysical Research*, 2(1), e2024JH000431. <https://doi.org/10.1029/2024JH000431>
- Blewett, D. T., Chabot, N. L., Denevi, B. W., Ernst, C. M., Head, J. W., Izenberg, N. R., et al. (2011). Hollows on Mercury: MESSENGER evidence for geologically recent volatile-related activity. *Science*, 333(6051), 1856–1859. <https://doi.org/10.1126/science.1211681>

Acknowledgments

M. El Yazidi sincerely thanks Valentina Galluzzi and Matteo Massironi for their support in providing a digital copy of the MESSENGER MDIS data, the mapping guidelines and rules, and for reviewing the potential science targets to support the SIMBIO-SYS instrument and the ESA/JAXA BepiColombo space mission. The authors also thank the MESSENGER Team at Arizona State University, the Johns Hopkins Applied Physics Laboratory, and Carnegie Science for making the MDIS data publicly available, which made this analysis possible. This work was initially funded by a CARIPARO scholarship at CISAS, University of Padova, and completed through the ESA Archival Research Visitor Programme. We acknowledge additional support from ESA through the Science Faculty (funding reference ESA-SCI-SC-LE-209) and from P. D'Incecco via Istituto Nazionale di Astrofisica ASI/INAF Grant n.2022-16-HH.0. Open access publishing facilitated by Istituto nazionale di astrofisica, as part of the Wiley - CRUI-CARE agreement.

- Blewett, D. T., Stadermann, A. C., Susorney, H. C., Ernst, C. M., Xiao, Z., Chabot, N. L., et al. (2016). Analysis of MESSENGER high-resolution images of Mercury's hollows and implications for hollow formation. *Journal of Geophysical Research*, 121(9), 1798–1813. <https://doi.org/10.1002/2016JE005070>
- Blewett, D. T., Vaughan, W. M., Xiao, Z., Chabot, N. L., Denevi, B. W., Ernst, C. M., et al. (2013). Mercury's hollows: Constraints on formation and composition from analysis of geological setting and spectral reflectance. *Journal of Geophysical Research: Planets*, 118(5), 1013–1032. <https://doi.org/10.1029/2012JE004174>
- Braden, S. E., & Robinson, M. S. (2013). Relative rates of optical maturation of regolith on Mercury and the moon. *Journal of Geophysical Research: Planets*, 118(9), 1903–1914. <https://doi.org/10.1002/jgre.20143>
- Byrne, P. K., Klimczak, C., Celâl Şengör, A. M., Solomon, S. C., Watters, T. R., & Hauck, S. A. (2014). Mercury's global contraction much greater than earlier estimates. *Nature Geoscience*, 7(4), 301–307. <https://doi.org/10.1038/ngeo2097>
- Byrne, P. K., Klimczak, C., & Şengör, A. M. C. (2018). The Tectonic character of Mercury. In S. C. Solomon, L. R. Nittler, & B. J. Anderson (Eds.), *Mercury: The view after MESSENGER* (Vol. 10, pp. 249–286). Cambridge University Press. <https://doi.org/10.1017/9781316650668.4.011>
- Byrne, P. K., Ostrach, L. R., Fassett, C. I., Chapman, C. R., Denevi, B. W., Evans, A. J., et al. (2016). Widespread effusive volcanism on Mercury likely ended by about 3.5 Ga. *Geophysical Research Letters*, 43(14), 7408–7416. <https://doi.org/10.1002/2016GL069412>
- Childs, C., Watterson, J., & Walsh, J. J. (1995). Fault overlap zones within developing normal fault systems. *Geological Society*, 152(3), 535–549. <https://doi.org/10.1144/gsjgs.152.3.0535>
- Cordell, B. M., & Strom, R. G. (1977). Global tectonics of Mercury and the moon. *Physics of the Earth and Planetary Interiors*, 15(2–3), 146–155. [https://doi.org/10.1016/0031-9201\(77\)90027-9](https://doi.org/10.1016/0031-9201(77)90027-9)
- Crater analysis techniques working group. (1979). Crater analysis techniques working group. *Icarus*, 37(2), 467–474. [https://doi.org/10.1016/0019-1035\(79\)90009-5](https://doi.org/10.1016/0019-1035(79)90009-5)
- Cremonese, G., Capaccioni, F., Capria, M. T., Doressoundiram, A., Palumbo, P., Vincendon, M., et al. (2020). SIMBIO-SYS: Scientific cameras and spectrometer for the BepiColombo Mission. *Space Science Reviews*, 216(75), 75. <https://doi.org/10.1007/s11214-020-00704-8>
- Daniels, J. (2018). Impact melt emplacement on Mercury. In *Western libraries electronic thesis and dissertation repository*. No. 5657 Retrieved from <https://ir.lib.uwo.ca/etd/5657>
- Davies, M. E., Dwornik, S. E., Gault, D. E., & Strom, R. G. (1978). Atlas of Mercury, NASA Spec. Publ. SP, SP-423. 1978NASSP.423...D.
- Denevi, B. W., Chabot, N. L., Murchie, S. L., Becker, K. J., Blewett, D. T., Domingue, D. L., et al. (2018). Calibration, projection, and final image products of MESSENGER's Mercury dual imaging system. *Space Science Reviews*, 214(1), 1–52. <https://doi.org/10.1007/s11214-017-0440-y>
- Denevi, B. W., Ernst, C. M., Meyer, H. M., Robinson, M. S., Murchie, S. L., Whitten, J. L., et al. (2013). The distribution and origin of smooth plainson Mercury. *Journal of Geophysical Research: Planets*, 118(5), 891–907. <https://doi.org/10.1002/jgre.20075>
- Denevi, B. W., Robinson, M. S., Solomon, S. C., Murchie, S. L., Blewett, D. T., Domingue, D. L., et al. (2009). The evolution of mercury's crust: A global perspective from MESSENGER. *Science*, 324(5927), 613–618. <https://doi.org/10.1126/science.1172226>
- De Toffoli, B., Galluzzi, V., Massironi, M., Besse, S., Schmidt, G. W., Barraud, O., et al. (2024). Hollows on mercury: A comprehensive analysis of spatial patterns and their relationship to craters and structures. *Earth and Space Science*, 11(12), e2024EA003854. <https://doi.org/10.1029/2024EA003854>
- Deutsch, A. N., Bickel, V. T., & Blewett, D. T. (2025). Hollows on Mercury: Global classification of degradation states and insight into hollow evolution. *Journal of Geophysical Research: Planets*, 130(2), e2024JE008747. <https://doi.org/10.1029/2024JE008747>
- Domingue, D. L., Murchie, S. L., Denevi, B. W., Ernst, C. M., & Chabot, N. L. (2015). Mercury's global color mosaic: An update from MESSENGER's orbital observations. *Icarus*, 257, 477–488. <https://doi.org/10.1016/j.icarus.2014.11.027>
- El Yazidi, M. (2023). Structural analysis of the fault networks in Noctis Labyrinthus (Mars) and preliminary geological mapping for 1/2 of the Eminescu (H09) quadrangle in Mercury. *IRIS, Catalogo Ricerca UNIPD, 08.01 - Tesi di Dottorato UNIPD*. <https://hdl.handle.net/11577/3469755>
- El Yazidi, M., Galluzzi, V., Giacomini, L., & Massironi, M. (2023). Geological mapping and target selection for the Western of eminescu (H09) quadrangle (Mercury) in support to SIMBIO-SYS instrument of ESA/JAXA BEPICOLOMBO Mission. *Lunar Planet. Sci.*, 54. <https://doi.org/10.13140/RG.2.2.34438.14405>
- El Yazidi, M., Sefton-Nash, E., Orgel, C., De Marchi, G., Filiberto, J., Bradak, B., et al. (2025). Geological mapping and structural analysis of the western half of the Eminescu quadrangle (H09), Mercury [Dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.15616182>
- El Yazidi, M., Tognon, G., Galluzzi, V., Giacomini, L., & Massironi, M. (2021). Geology of the Eminescu (H09) quadrangle: Mapping status. *Lunar Planet. Sci. Abstract #EPSC2021-682. Europlanet Science Congress*. <https://doi.org/10.5194/epsc2021-682>
- Ernst, C. M., Denevi, B. W., & Ostrach, L. R. (2017). Updated absolute age estimates for the Tolstoj and Caloris basins, Mercury, Lunar Planet. *Science*, 48. Abstract 2934.
- Fassett, C. I., Head, J. W., Baker, D. M. H., Zuber, M. T., Smith, D. E., Neumann, G. A., et al. (2012). Large impact basins on Mercury: Global distribution, characteristics, and modification history from MESSENGER orbital data. *Journal of Geophysical Research*, 117(E12), E00L08. <https://doi.org/10.1029/2012JE004154>
- Fegan, E. R., Rothery, D. A., Marchi, S. S., Massironi, M., Conway, S. J., & Anand, M. (2017). Late movement of basin-edge lobate scarps on Mercury. *Icarus*, 288, 226–234. <https://doi.org/10.1016/j.icarus.2017.01.005>
- Freed, A. M., Blair, D. M., Watters, T. R., Klimczak, C., Byrne, P. K., Solomon, S. C., et al. (2012). On the origin of graben and ridges within and near volcanically buried craters and basins in Mercury's northern plains. *Journal of Geophysical Research*, 117(E12), E00L06. <https://doi.org/10.1029/2012JE004119>
- Galluzzi, V. (2015). Structural analysis of the Victoria quadrangle (H2) of Mercury based on NASA MESSENGER data Ph.D thesis. *University of Napoli*. <https://doi.org/10.6092/UNINA/FEDOA/10434>
- Galluzzi, V. (2019). Multi-mapper projects: Collaborative Mercury Mapping. In H. Hargitai (Ed.), *Planetary cartography and GIS* (pp. 207–218). https://doi.org/10.1007/978-3-319-62849-3_9
- Galluzzi, V., Ferranti, L., Massironi, M., Giacomini, L., Guzzetta, L., & Palumbo, P. (2019). Structural analysis of the Victoria quadrangle fault systems on Mercury: Timing, geometries, kinematics and relationship with the high-Mg Region. *Journal of Geophysical Research*, 124(10), 2543–2562. <https://doi.org/10.1029/2019JE005953>. 10th ed.
- Galluzzi, V., Guzzetta, L., Ferranti, F., Di Achille, G., Rothery, D. A., & Palumbo, P. (2016). Geology of the Victoria quadrangle (H02), Mercury. *Journal of Maps*, 12(sup1), 227–238. <https://doi.org/10.1080/17445647.2016.1193777>
- Giacomini, L., Galluzzi, V., Massironi, M., Ferranti, L., & Palumbo, P. (2022). Geology of the Kuiper quadrangle (H06), Mercury. *Journal of Maps*, 18(2), 246–257. <https://doi.org/10.1080/17445647.2022.2035268>

- Goudge, T. A., Head, J. W., Kerber, L., Blewett, D. T., Denevi, B. W., Domingue, D. L., et al. (2014). Global inventory and characterisation of pyroclastic deposits on Mercury: New insights into pyroclastic activity from MESSENGER orbital data. *Journal of Geophysical Research: Planets*, 119(3), 635–658. <https://doi.org/10.1002/2013JE004480>
- Guzzetta, L., Galluzzi, V., Ferranti, L., & Palumbo, P. (2017). Geology of the Shakespeare quadrangle (H03), Mercury. *Journal of Maps*, 13(2), 227–238. <https://doi.org/10.1080/17445647.2017.1290556>
- Hargitai, H., Wang, J., Stooke, P. J., Karachevtseva, I., Kereszturi, A., & Gede, M. (2017). Map projections in planetary cartography. In M. Lapaine & E. Usery (Eds.), *Choosing a map projection. Lecture notes in geoinformation and cartography*. Springer. https://doi.org/10.1007/978-3-319-51835-0_7
- Hawkins, S. E., Boldt, J. D., Darlington, E. H., Espiritu, R., Gold, R. E., Gotwols, B., et al. (2007). The Mercury dual imaging system on the MESSENGER spacecraft. *Space Science Reviews*, 131(1–4), 247–338. <https://doi.org/10.1007/s11214-007-9266-3>
- Head, J. W., Chapman, C. R., Strom, R. G., Fassett, C. I., Denevi, B. W., Blewett, D. T., et al. (2011). Flood volcanism in the northern high latitudes of Mercury revealed by MESSENGER. *Science*, 333(6051), 1853–1856. <https://doi.org/10.1126/science.1211997>
- Head, J. W., Murchie, S. L., Prockter, L. M., Robinson, M. S., Solomon, S. C., Strom, R. G., et al. (2008). Volcanism on Mercury: Evidence from the first MESSENGER flyby. *Science*, 321(5885), 69–72. <https://doi.org/10.1126/science.1159256>
- Herrick, R. R., Bateman, E. M., Crumpacker, W. G., & Bates, D. (2018). Observations from a global database of impact craters on mercury with diameters greater than 5 km. *Journal of Geophysical Research: Planets*, 123(8), 2089–2109. <https://doi.org/10.1029/2017JE005516>
- Herrick, R. R., & Taylor, N. K. F. (2003). The shape and appearance of craters formed by oblique impact on the Moon and Venus. *Meteoritics and Planetary Science*, 38(11), 1551–1578. <https://doi.org/10.1111/j.1945-5100.2003.tb00001.x>
- Huang, L., & Liu, C. Y. (2017). Three types of flower structures in a divergent-wrench fault Zone. *Journal of Geophysical Research*, 122(12), 10478–10497. <https://doi.org/10.1002/2017JB014675>
- Jozwiak, L. M., Head, J. W., & Wilson, L. (2018). Explosive volcanism on Mercury: Analysis of vent and deposit morphology and modes of eruption. *Icarus*, 302, 191–212. <https://doi.org/10.1016/j.icarus.2017.11.011>
- Kerber, L., Head, J. W., Blewett, D. T., Solomon, S. C., Wilson, L., Murchie, S. L., et al. (2011). The global distribution of pyroclastic deposits on Mercury: The view from MESSENGER flybys. *Planet. Space Sci.*, 59(15), 1895–1909. <https://doi.org/10.1016/j.pss.2011.03.020>
- Kerber, L., Head, J. W., Solomon, S. C., Murchie, S. L., Blewett, D. T., & Wilson, L. (2009). Explosive volcanic eruptions on Mercury: Eruption conditions, magma volatile content, and implications for interior volatile abundances. *Earth and Planetary Science Letters*, 285(3–4), 263–271. <https://doi.org/10.1016/j.epsl.2009.04.037>
- Kiefer, W. S., & Murray, B. C. (1987). The formation of Mercury's smooth plains. *Icarus*, 72(3), 477–491. [https://doi.org/10.1016/0019-1035\(87\)90046-7](https://doi.org/10.1016/0019-1035(87)90046-7)
- Leon-Dasi, M., Besse, S., Jozwiak, L. M., Jawin, E. R., & Doressoundiram, A. (2025). Timing of explosive volcanism on Mercury: A morphological and spectral analysis. *Icarus*, 429, 116421. <https://doi.org/10.1016/j.icarus.2024.116421>
- Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2015). *Geographic information science and systems* (4Th ed.). John Wiley and Sons.
- López, V., Ruiz, J., & Vázquez, A. (2015). Evidence for two stages of compressive deformation in a buried basin of Mercury. *Icarus*, 254, 18–23. <https://doi.org/10.1016/j.icarus.2015.03.018>
- Malliband, C. C., Rothery, D. A., Balme, M. R., Conway, S. J., Pegg, D. L., & Wright, J. (2022). Geology of the derainquadrangle (H10), Mercury. *Journal of Maps*, 19(1), 1–10. <https://doi.org/10.1080/17445647.2022.2112774>
- Man, B., Rothery, D. A., Balme, M. R., Conway, S. J., Wright, J., Pegg, D. L., et al. (2023). Geology of the Neruda quadrangle (H13), Mercury. *Journal of Maps*, 19(1), 2256353. <https://doi.org/10.1080/17445647.2023.2256353>
- Mancinelli, P., Minelli, F., Pauselli, C., & Federico, C. (2016). Geology of the Raditladi quadrangle, Mercury (H04). *Journal of Maps*, 12(sup1), 190–202. <https://doi.org/10.1080/17445647.2016.1191384>
- Marchi, S., Chapman, C. R., Fassett, C. I., Head, J. W., Botke, W. F., & Strom, R. G. (2013). Global resurfacing of Mercury 4.0–4.1 billion years ago by heavy bombardment and volcanism. *Nature*, 499(7456), 59–61. <https://doi.org/10.1038/nature12280>
- Murchie, S. L., Klima, R. L., Denevi, B. W., Ernst, C. M., Keller, M. R., Domingue, D. L., et al. (2015). Orbital multispectral mapping of Mercury with the MESSENGER Mercury Dual Imaging System: Evidence for the origins of plains units and low-reflectance material. *Icarus*, 254, 287–305. <https://doi.org/10.1016/j.icarus.2015.03.027>
- Murchie, S. L., Mick, A., Prockter, L. M., Rivkin, A., Guinness, E., & Ward, J. (2017). Mdis CDR/RDRSOFTWARE interface specification.
- Murchie, S. L., Watters, T. R., Robinson, M. S., Head, J. W., Strom, R. G., Chapman, C. R., et al. (2008). Geology of the Caloris basin, Mercury: A view from MESSENGER. *Science*, 321(5885), 73–76. <https://doi.org/10.1126/science.1159261>
- Murray, B. C., Belton, M. J., Danielson, G. E., Davies, M. E., Gault, D. E., Hapke, B., et al. (1974). Mercury's surface: Preliminary description and interpretation from mariner 10 pictures. *Science*, 185(4146), 169–179. <https://doi.org/10.1126/science.185.4146.169>
- Neish, C. D., Blewett, D. T., Harmon, J. K., Coman, E. I., Cahill, J. T. S., & Ernst, C. M. (2013). A comparison of rayed craters on the Moon and Mercury. *Journal of Geophysical Research: Planets*, 118(10), 2247–2261. <https://doi.org/10.1002/jgr.20166>
- Neumann, G. A., Cavanaugh, J. F., Sun, X., Mazarico, E. M., Smith, D. E., Zuber, M. T., et al. (2012). Bright and dark polar deposits on Mercury: Evidence for surface volatiles. *Science*, 339(6117), 296–300. <https://doi.org/10.1126/science.1229764>
- Oberbeck, V. R., Quaide, W. L., Arvidson, R. E., & Aggarwal, H. R. (1977). Comparative studies of lunar, martian, and mercurian craters and plains. *Journal of Geophysical Research*, 82(11), 1681–1698. <https://doi.org/10.1029/JB082i011p01681>
- Orgel, C., Fassett, C. I., Michael, G., Riedel, C., van der Bogert, C. H., & Hiesinger, H. (2020). Re-examination of the population, stratigraphy, and sequence of Mercurian basins: Implications for Mercury's early impact history and comparison with the Moon. *Journal of Geophysical Research*, 125(8), e2019JE006212. <https://doi.org/10.1029/2019JE006212>
- Pegg, D. L., Rothery, D. A., Balme, M. R., & Conway, S. J. (2021b). Explosive vent sites on Mercury: Commonplace multiple eruptions and their implications. *Icarus*, 365, 114510. <https://doi.org/10.1016/j.icarus.2021.114510>
- Pegg, D. L., Rothery, D. A., Balme, M. R., Conway, S. J., Malliband, C. C., & Man, B. (2021a). Geology of the Debussy quadrangle (H14), Mercury. *Journal of Maps*, 17(2), 718–729. <https://doi.org/10.1080/17445647.2021.1996478>
- Prockter, L. M., Ernst, C. M., Denevi, B. W., Chapman, C. R., Head, J. W., Fassett, C. I., et al. (2010). Evidence for young Volcanism on Mercury from the Third MESSENGER Flyby. *Science*, 329(80), 668–671. <https://doi.org/10.1126/science.1188186>
- Rothery, D. A., & Massironi, M. (2010). Beagle Rupes - Evidence for a basal decollement of regional extent in Mercury's lithosphere. *Icarus*, 209(1), 256–261. <https://doi.org/10.1016/j.icarus.2009.12.009>
- Rothery, D. A., Thomas, R. J., & Kerber, L. (2014). Prolonged eruptive history of a compound volcano on Mercury: Volcanic and tectonic implications. *Earth and Planetary Science Letters*, 385, 59–67. <https://doi.org/10.1016/j.epsl.2013.10.023>
- Schleicher, L. S., Watters, T. R., Martin, A. J., & Banks, M. E. (2019). Wrinkle ridges on Mercury and the Moon within and outside of mascons. *Icarus*, 331, 226–237. <https://doi.org/10.1016/j.icarus.2019.04.013>

- Skinner, J. A., Huff, A. E., Black, S. R., Buban, H. C., Fortezzo, C. M., Gaither, T. A., et al. (2022). Planetary geologic mapping Protocol -2022: U.S. Geological Survey techniques and Methods11-B13.
- Skinner, J. A. Jr., Huff, A. E., Fortezzo, C. M., Gaither, T., Hare, T. M., Hunter, M. A., & Buban, H. (2019). Planetary geologic mapping—program status and future needs. *U.S. Geological Survey Open-File Report 2019-1012*, 40. <https://doi.org/10.3133/ofr20191012>
- Snyder, J. P. (1987). Map projections: A working manual. *Wayback Machine, USGS Professional Paper 1395, Report: ix*, 385. <https://doi.org/10.3133/pp1395>
- Solomon, S. C. (1978). On volcanism and thermal tectonics on one-plate planets. *Geophysical Research Letters*, 5(6), 461–464. <https://doi.org/10.1029/GL005i006p00461>
- Solomon, S. C. (1979). Formation, history and energetics of cores in the terrestrial planets. *Physics of the Earth and Planetary Interiors*, 19(2), 168–182. [https://doi.org/10.1016/0031-9201\(79\)90081-5](https://doi.org/10.1016/0031-9201(79)90081-5)
- Solomon, S. C., McNutt Jr., R. L., Watters, T. R., Lawrence, D. J., Feldman, W. C., Head, J. W., et al. (2008). Return to Mercury: A global perspective on MESSENGER's first Mercury flyby. *Science*, 321(5885), 59–62. <https://doi.org/10.1126/science.1159706>
- Spudis, P. D., & Guest, J. E. (1988). Stratigraphy and geologic history of Mercury. In F. Vilas, C. R. Chapman, & M. S. Matthews (Eds.), *Mercury* (pp. 118–164). University of Arizona Press.
- Strom, R. G. (1977). Origin and relative age of lunar and Mercurian intercrater plains. *Physics of the Earth*.
- Strom, R. G., Trask, N. J., & Guest, J. E. (1975). Tectonism and volcanism on Mercury. *Journal of Geophysical Research*, 80(17), 2478–2507. <https://doi.org/10.1029/JB080i017p02478>
- Tanaka, K. L., Skinner, J. A., & Hare, T. M. (2011). Planetary geologic mapping handbook – 2009. In *Abstracts of the annual meeting of planetary geologic mappers*. Retrieved from <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100017213.pdf>
- Thomas, P. G., & Allemand, P. (1993). Quantitative analysis of the extensional tectonics of Tharsis Bulge, Mars: Geodynamic implications. *Journal of Geophysical Research*, 98(E7), 13097–13108. <https://doi.org/10.1029/93JE01326>
- Thomas, R. J., Rothery, D. A., Conway, S. J., & Anand, M. (2014a). Hollows on Mercury: Materials and mechanisms involved in their formation. *Icarus*, 229, 221–235. <https://doi.org/10.1016/j.icarus.2013.11.018>
- Thomas, R. J., Rothery, D. A., Conway, S. J., & Anand, M. (2014b). Mechanisms of explosive volcanism on Mercury: Implications from its global distribution and morphology. *Journal of Geophysical Research: Planets*, 119(10), 2239–2254. <https://doi.org/10.1002/2014JE004692>
- Tobler, W. (1987). Measuring spatial resolution. In *Proceedings, land resources information systems conference* (pp. 12–16).
- Trask, N. J., & Guest, J. E. (1975). Preliminary geologic terrain map of Mercury. *Journal of Geophysical Research*, 80(17), 2461–2477. <https://doi.org/10.1029/JB080i017p02461>
- Trask, N. J., & Strom, R. G. (1976). Additional evidence of Mercurian volcanism. *Icarus*, 28(4), 559–563. [https://doi.org/10.1016/0019-1035\(76\)90129-9](https://doi.org/10.1016/0019-1035(76)90129-9)
- Watters, T. R. (1988). Wrinkle ridge assemblages on the terrestrial planets. *Journal of Geophysical Research*, 93(B9), 10236–10254. <https://doi.org/10.1029/jb093ib09p10236>
- Watters, T. R., & Nimmo, F. (2010). The tectonics of Mercury. In *Planetary tectonics* (Vol. 11, pp. 15–80). Cambridge University Press. <https://doi.org/10.1017/cbo9780511691645.003>
- Watters, T. R., Solomon, S. C., Robinson, M. S., Head, J. W., André, S. L., Hauck, S. A., & Murchie, L. S. (2009). The tectonics of mercury: The view after MESSENGER's first flyby. *Earth and Planetary Science Letters*, 285(3–4), 283–296. <https://doi.org/10.1016/j.epsl.2009.01.025>
- Whitten, J. L., Head, J. W., Denevi, B. W., & Solomon, S. C. (2014). Intercrater plains on Mercury: Insights into unit definition, characterization, and origin from MESSENGER datasets. *Icarus*, 241, 97–113. <https://doi.org/10.1016/j.icarus.2014.06.013>
- Wright, J., Byrne, P. K., & Rothery, D. A. (2021). Planet Mercury: Volcanism in a theatre of global contraction, with examples from the Hokusai quadrangle. *Journal of Volcanology and Geothermal Research*, 417, 107300. <https://doi.org/10.1016/j.jvolgeores.2021.107300>
- Wright, J., Rothery, D. A., Balme, M. R., & Conway, S. J. (2019). Geology of the Hokusai quadrangle (H05), Mercury. *Journal of Maps*, 15(2), 509–520. <https://doi.org/10.1080/17445647.2019.1625821>