USING PLANFORM IMPACT CRATER SHAPES TO INVESTIGATE TECTONIC PATTERNS OF MERCURY

by

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(Under the Direction of CHRISTIAN KLIMCZAK)

ABSTRACT

Fractures in planetary lithospheres are used by impact cratering and other tectonic processes to shape the surface of a planet, as they play important roles in the location or geometry of planetary landforms. On Mercury, distributions of fault-related landforms show a global pattern of preferred orientations. Fractures also produce straight impact crater rims and polygonal planform crater shapes, but their orientations have not been investigated across Mercury's surface. To test if fracture sets govern the shape of craters, all rims of impact craters with diameters between 20 and 400 km were mapped. The orientations of 115,884 rim segments were used to assess if they are part of a tectonic pattern. Results show strong preferred east-west orientations at the poles and weak north-south preferred orientations in mid-latitude and equatorial regions, revealing a global fracture pattern that compares well to previously observed tectonic patterns.

INDEX WORDS: Mercury, Impact Craters, Structural Geology, Tectonics

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DEDICATION

This thesis is dedicated to my grandparents, Fehime, Zekavet, Husnu, and Saip,

who believed in the richness of learning,

and made their children and granddaughter keen on learning.

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CHAPTER 1

INTRODUCTION

Impact cratering and tectonic activity are two major geological processes that have shaped Mercury's surface. Impact cratering is arguably the most common geologic process found on the innermost planet, as the surface is observed to be heavily cratered and because impact craters are found on small and large scales. Therefore, studying impact craters can aid investigations of the tectonic history of the planet, especially where the presence of plan-view polygonal shapes of impact craters reveals pre-existing fractures.

Tectonics of Mercury

Tectonic structures on Mercury were first observed in the 1970s when NASA's Mariner 10 spacecraft imaged about 45% of the surface during its three fly-bys (Murray et al., 1974). The MErcury Surface Space ENvironment GEochemistry and Ranging (MESSENGER) spacecraft, in orbit about Mercury from 2011 to 2015, imaged the entire planet and thus revolutionized our understanding of Mercury's tectonics. Both extensional and shortening structures are found on Mercury. Shortening structures that include several types of thrust fault related landforms are found to be the dominant structure type. But landforms indicative of extensional tectonism, including normal fault-bound grabens, are also present in isolated locations, such as within volcanically flooded impact basins (Byrne et al., 2018).

Among several tectonic processes proposed to have operated on Mercury (Byrne et al., 2018), global contraction (Solomon and Chaiken, 1976; Solomon, 1977) and tidal despinning

(Melosh, 1977; Melosh and Dzurisin, 1978) are the main processes discussed to have affected the types and orientations of tectonic structures on Mercury. Global contraction is the volume decrease of the planet associated with a long, sustained period of cooling and possible phase changes during core formation and crystallization (Solomon, 1977, 1978; Hauck et al., 2004; Grott et al., 2011; Michel et al., 2013; Tosi et al., 2013, 2015). Global contraction is widely accepted to be the main cause of shortening structures on Mercury (Byrne et al., 2018) and, if operating alone, is predicted to produce randomly oriented thrust faults across the planet (Solomon, 1977). However, the global distribution of all mapped shortening structures is found to generally shows north-south orientations in the equatorial and mid-latitudes and either no preferred orientations (Byrne et al., 2018) or concentric pattern around the poles (Crane and Klimczak, 2019).

Tidal despinning is the slowing of rotation to lock Mercury in its current 3:2 spin-orbit resonance with the sun. Such change in spin rate would have been accompanied by the relaxation of an equatorial bulge and polar flattening (e.g., Burns, 1976; Melosh, 1977), which is predicted by rock-mechanical assessment to trigger joints with east-west orientations in the equatorial regions and with no preferred orientations at the poles (Klimczak et al., 2015). If tidal despinning overlapped temporally with global contraction, thrust faults would be predicted to form with north-south orientations in the equatorial and mid-latitude regions and random orientations at the poles (e.g., Klimczak et al., 2015), a prediction that is largely matched by the observations.

While global contraction and tidal despinning are widely discussed, they are not the only processes that may have operated in Mercury's tectonic history. Mantle convection, long-wavelength topographic changes, and planetary reorientation may also have contributed to Mercury's observed tectonic map patterns (Byrne et al., 2018) and predictions of the types and orientations of structures for these processes have yet to be derived and compared to the observations.

Furthermore, to truly understand the tectonic history of the innermost planet, the timing of deformation must be better placed into the overall context of fault mechanics. When we observe faults using remotely sensed data, we observe only the most recent fault activity (Byrne et al., 2018). Yet, it is widely known that faults preferentially form along pre-existing planes of weakness and thus reactivation of joints as faults, or even fault inversion (the reactivation of a normal fault as a thrust fault) are processes that must be accounted for when interpreting overlapping tectonic processes.

Planform Shapes of Impact Craters

Impact craters are landforms that form when small planetary objects, such as meteorites, asteroids, or comets, hit the solid surface of a larger planetary body. Processes occurring during all stages of the cratering event operate radially away or toward the impact site, such that impact craters are commonly circular rimmed depressions. This description generally holds true irrespective of crater size, rock type, or age of the crater (Melosh, 2011). However, plan-view geometries of craters better described as polygonal shapes, such as squares or hexagons, are commonly across planetary surfaces in our Solar System (Öhman et al., 2010). Perhaps the most prominent example of a polygonal impact crater is the nearly square Meteor Crater, Arizona (Shoemaker, 1960), but they are occur widely on all the rocky bodies of the inner Solar System (the Moon: Eppler et al. (1983); Mars: Öhman et al. (2006, 2008), Venus: Aittola et al. (2007, 2010), and Mercury: Weihs et al. (2015)) as well as icy bodies in the outer Solar System (e.g., Beddingfield et al., 2016, 2020).

It is widely accepted that the planform shapes of impact craters are influenced mainly by (*1*) obliqueness of impact (e.g., Elbeshausen et al., 2013; Kenkmann et al., 2014), (*2*) surficial processes of degradation (e.g., Pohn and Offield, 1970), and (*3*) heterogeneities and strength variations in the target (e.g., Murray and Guest, 1970). While most impacts are likely to be oblique with highest probabilities of impact angles to follow a Gaussian distribution centered at 45° (Shoemaker, 1962), the planform crater shape is circular and not be elliptical for impact angles larger than 10–15° (Gault and Wedekind; 1978, Bottke et al., 2000). Only a handful of elliptical craters that likely resulted from highly oblique impact angles are occur on Mercury such that the effect is likely not dominate investigations of planform crater shapes.

Surficial processes of degradation, such as scouring of ejecta from a nearby impact, younger impacts, impact shaking, and ongoing degradation by micrometeorite bombardment and impact gardening, lead to gradual erosion of the impact crater by topographic diffusion (e.g., Fassett and Thomson, 2014) or to sudden changes by superposition of other impacts on the original crater. Surficial processes of degradation act independently of the original crater shape and thus do not substantially alter the underlying bedrock properties. However, the state of degradation of a crater is a measure of the length of time the crater was exposed to the processes causing the degradation. Assessments of degradation states based on crater morphology are widely used to categorize craters into crater classes for stratigraphic purposes (Pohn and Offield, 1970; Spudis and Guest, 1988; Herrick et al., 2018; Kinczyk et al., 2020).

Crater classes range from heavily degraded to very fresh. For Mercury, they generally follow three (e.g., Herrick et al., 2018) or five classes (e.g., Spudis and Guest, 1988; Kinczyk et al., 2020). For the categorization into five classes (Figure 1.1), the “crispness” of several aspects of the impact crater morphology are typically considered: rays, rim, terraces, floor-wall boundary, floor, ejecta, secondary craters, central structures such as peaks or peak rings, and the number of superposed craters (Kinczyk et al., 2020).

Class 1 craters are the most degraded craters. Their rays, terraces or walls, floor-wall boundaries, ejecta deposits, secondary craters, central peaks/rings are so degraded that they are no longer visible (Kinczyk et al., 2020). Their crater floors do not show irregular, hummocky deposits (Kinczyk et al., 2020). Their rims are discontinuous and only stand out slightly above the surrounding terrain (Kinczyk et al., 2020). They show a moderate to high amount of superposed craters.

Class 2 craters are slightly less degraded than those in class 1. In contrast to class 1 craters, class 2 may have continuous but rounded and degraded rims. Larger class 2 craters may have ejecta blankets, but they are discontinuous (Kinczyk et al., 2020). Their central structures are rarely preserved (Kinczyk et al., 2020).

Class 3 craters are moderately degraded. They generally have continuous but rounded and degraded rims, slumped wall terraces, continuous to discontinuous ejecta blankets, subdued central peaks/rings, and a low to moderate density of superposed craters (Kinczyk et al., 2020). Their boundary between crater floor and rim wall is not very clear but can recognizable, and the crater floor may contain hummocky deposits (Kinczyk et al., 2020).

Class 4 craters are fresh craters. They have crisp rim crests, slightly degraded wall terraces, radially textured continuous ejecta blanket, and crisp central structures (Kinczyk et al., 2020). The contact between crater floor and rim wall is distinct in class 4 impact craters (Kinczyk et al., 2020). They have a well-defined secondary crater fields and a low density of superposed craters (Kinczyk et al., 2020).

Class 5 craters are the freshest craters and are the only those craters that have rays (Kinczyk et al., 2020). Rays of class 5 craters are bright and extend at least several radii from the crater rim (Kinczyk et al., 2020), but some craters have rays tracing across an entire hemisphere of Mercury. These craters have very crisp rims, wall terraces, and central peak/rings (Kinczyk et al., 2020). Their floor may contain hummocky deposits and their boundary of crater floor to rim wall is distinct (Kinczyk et al., 2020). They lack superposed craters, and their secondary craters are well-defined and continuous (Kinczyk et al., 2020).

Heterogeneities and strength variations within the bedrock that pre-date the impacts are generally accepted to directly influence the planform shape of the crater while the crater is formed (Shoemaker, 1960; Murray and Guest, 1970; Scott et al., 1977). Heterogeneities and strength variations that affect the shape of the final crater include the strength of the target substrate (regolith vs. rock mass) (e.g., Watters et al., 2017), preexisting structure such as faults, folds, and joints (Eppler et al., 1983; Öhman et al., 2008, 2010; Watters et al., 2011), or a combination of both.

The polygonal plan-view geometries of impact craters are formed during the excavation and modification stages of the impact cratering process when preferentially utilizing the fractures as planes of weakness (Eppler et al., 1983). Excavation of bedrock may occur preferentially and more efficiently along fractures (Eppler et al., 1983; Poelchau et al., 2009; Watters et al., 2011), which causes a strong deviation from the circularity of the crater cavity (Eppler et al., 1983; Öhman et al., 2010). Crater modification leads to formation of the crater rim, which consists of crater rim faults that typically undergo free-surface dip-slip (Spray, 1997). In this stage, preexisting joints are likely to be reactivated as crater rim faults, causing portions of the crater rim to follow the structural trends of the underlying target and, ultimately, forming polygonal craters. Meteor Crater in Arizona has been extensively studied for its polygonal shape, and much of the effects of bedrock heterogeneities, which, at Meteor Crater, are two sets of pre-existing regional joints, on crater shapes on other planets are informed by fieldwork there (e.g., Kumar and Kring, 2008; Poelchau et al., 2009).

Hypothesis

Because the plan-view geometry of craters is related to the fracturing of the bedrock in which the impact crater formed, mapping crater rims and extracting their orientations can help better understand fracture orientations and this knowledge can be applied to the tectonics of a cratered planetary body. If tectonics formed non-random fracture sets that played a role in the orientation of rims of impact craters, then the crater rims collectively would show preferred orientations in one or more directions. Mercury is a tectonically deformed body, and its surface is heavily cratered, making it an ideal study area to test if crater rims show preferred orientations. Many of the impact craters were previously identified as having a polygonal shape (Weihs et al., 2015) and pre-existing fractures or faults in the crust are accepted as the primary controlling factor for their straight rim segments. Mapping and orientation analysis of impact crater rims thus allows for and evaluation of the role of fracture sets that are otherwise not visible in photogeologic data and relate them to Mercury's tectonic pattern.

To test the hypothesis, all the impact craters in the diameter range between 20 and 400 km must be rigorously mapped to obtain a complete and globally representative dataset. Straight rim segments of the craters must then be identified and analyzed for their distribution and orientation to highlight if and where pre-existing fracture sets show preferred orientations across the innermost planet. Spatial and temporal relationships can be investigated with the different degradation states of the craters from which the straight rim segment were extracted. Therefore, assignment of crater classes to all mapped craters will allow to place orientations of straight rim segments to be placed in stratigraphic context to test if tectonic patterns emerged or changed with time.

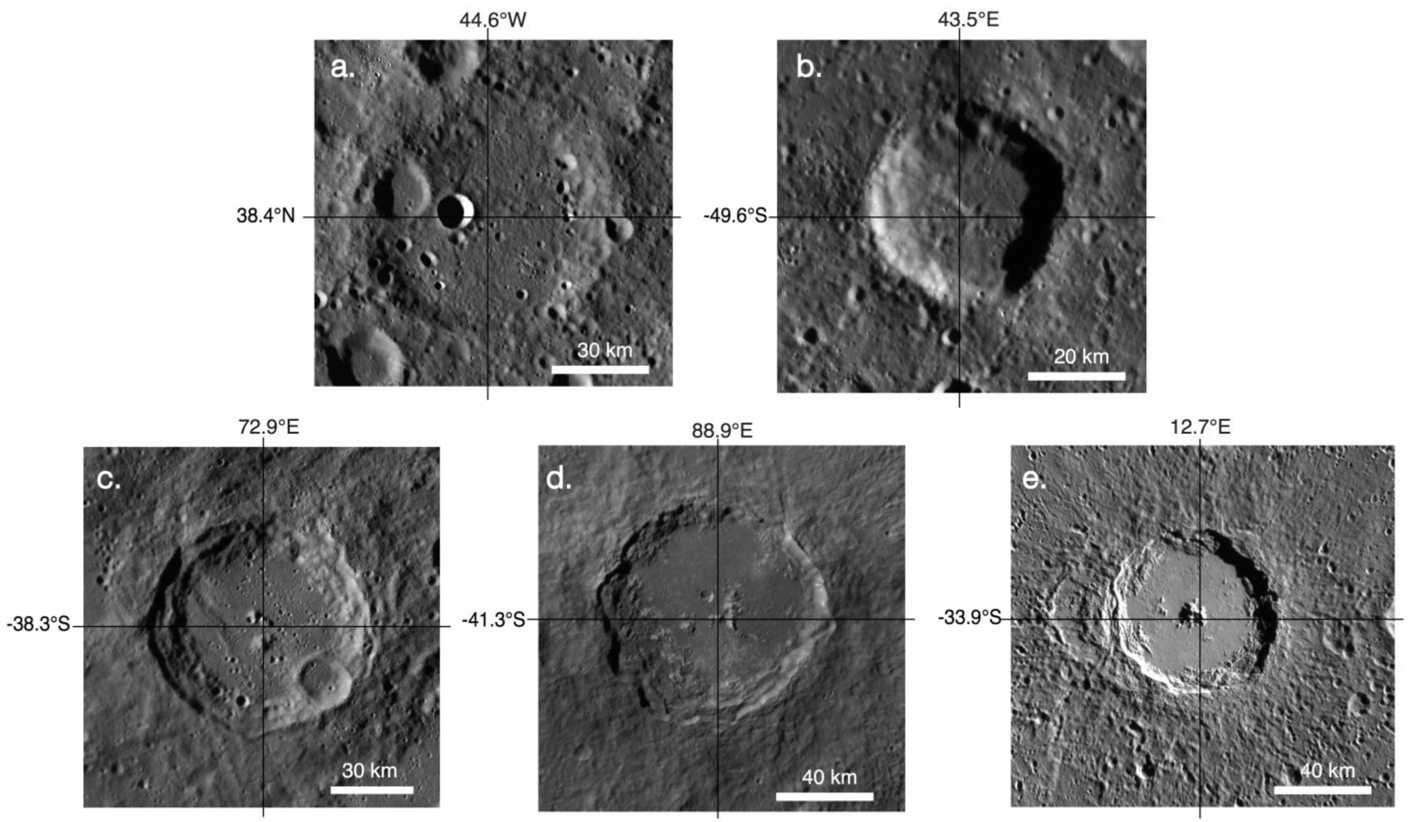

Figure 1.1: Examples of the five different crater classes based on degradation states from the quadrangle H14. a) A very degraded crater located at about -26.9°S 1.9°E with 35.2 km diameter as a crater class 1 example. b) A crater class 2 example with a diameter of 60 km located at 38.4°N 44.6°W. c) Moderately degraded crater with a diameter of 66.4 km as crater class 3 located at -38.3°S 72.9°E. d) 77.8 km diameter crater as a crater class 4 example located at -41.3°S 88.9°E. e) Freshest crater example from a crater class 5 with a diameter of 80.8 km located at -33.9°S 12.7°E.

CHAPTER 2

METHODOLOGY

Research was carried out in two stages. First, impact craters on Mercury were systematically and rigorously mapped. The mapping facilitated the identification and subsequent extraction of length and orientation data for straight rim segments of craters. In the second stage of the research methods, the orientation of the straight rim segments was analyzed and visualized for subsequent interpretation of results.

Impact Crater Mapping

The data for this study was collected from MESSENGER image datasets (Denevi et al., 2018) derived from the Mercury Dual Imaging System (MDIS). The datasets are publicly available from the United States Geologic Survey (USGS) Astropedia lunar and planetary cartographic catalogue (https://astrogeology.usgs.gov/search?pmi-target=mercury). In particular, four datasets are used in this research, including the 166 m/pix MESSENGER MDIS monochrome morphology mosaic (Figure 2.1), two 166 m/pix MESSENGER MDIS high incidence angle mosaics with illumination from east and west, and the 665 m/pix digital elevation model (DEM) of Mercury (Becker et al., 2016). A Geographic Information System (GIS) project was created in ESRI's *ArcGIS* software and the datasets were loaded into the GIS.

I used the existing crater catalogues by Herrick et al. (2018) and Kinczyk et al. (2020) for identification of locations of craters. Craters used in this mapping effort include all impact structures between 20 to 400 km in diameter. The lower cut-off was chosen to limit the number of craters included in this study. The upper cut-off was chosen to avoid inconsistencies of mapping crater rims caused by geometric distortions away from the center of projection of the map (see below). A total of 7,145 impact craters within the specified diameter range were identified on the surface of Mercury and their center locations were plotted in the GIS as a starting point for the crater rim mapping (Figure 2.1).

Within the *ArcGIS* ArcCatalogue, a geodatabase was created. Within the geodatabase, feature classes were added for each of the 15 defined Mercury quadrangles, H-1 to H-15 (Figure 2.1). Line feature classes were chosen as feature class type. The geodatabase was then added to the GIS.

The GIS was set to an azimuthal conformal stereographic projection. Map projected data is prone to distortions. Azimuthal conformal stereographic projections preserve angular relationships through distortions of distances. To minimize length distortions in the mapped line data, Mercury's surface was divided into bins of 10° by 10° (Figure 2.1), and the projection of the map was re-centered onto each bin when mapping that bin. The projection works well on local scales, so that the chosen size of individual map areas of 10° by 10° keeps length distortions to a reasonable minimum. Mapping was carried out no more than 5° away from center of projection at all times, and with that, length distortions of individual segments of crater rims at the edge of the defined bins do not differ from those mapped at the very center by more than ~0.3 km, even for equatorial latitudes, where bins have the largest area. The 10° by 10° map areas do not align perfectly with the quadrangle boundaries. Only craters with their center points within the quadrangle boundary were mapped for bins falling within two quadrangles.

A crater rim is defined here as the uppermost edge of the topographic depression caused by the impact. Pristine craters, such as those from crater classes 4 and 5, also show a raised rim, a morphological elevation associated with this edge (Kenkmann et al., 2014). The mapping was conducted using the uppermost edge of the crater, so the crater rim. All crater rims except those from highly elliptical craters were mapped. Mapping of all crater rims includes those that are incompletely preserved because some, if not all, straight rim portions may still be preserved and thus may contribute important information to the structural analysis. Bias introduced by mapping only crater rim segments instead of full crater rims is substantially minimized when the data set is processed for extraction of straight rim portions (see below).

Visual inspection of crater rims was carried out on small and large scales, but the mapping scale for each crater was set as fixed to 1:2,000,000 to ensure consistency of mapping across the entire globe. As stated above, the crater rims were mapped as line feature classes, i.e. polylines, by tracing the crater rims and automatically placing regularly spaced vertices at 2 km separation using the stream mode in *ArcGIS* (Figure 2.2). Discontinuous crater rims were mapped such that multiple rim segments were merged to form one line feature per crater. Each crater rim was assigned a unique identifier to be able to track individual rim segments in the following structural analysis.

After crater rims were mapped, the crater classes were assigned to each crater rim. Craters larger than 40 km in diameter were assigned the crater class from the catalogue by Kinczyk et al. (2020) and craters 20 to 400 km were assigned the crater class based on the characteristics described in Kinczyk et al. (2020). In addition, the centers of longitude and latitude were assigned to each mapped crater rim (Table A1).

After all crater rims were traced, an analysis was performed to determine those portions of the crater rims that display no change in orientation and thus were considered straight. To do that, the "Simplify Line" tool in the *ArcGIS Toolbox* was used to determine and remove the vertices that did not contribute to defining the plan-view crater shape (Figure 2.3). In particular, the point remove algorithm was selected and multiple tolerances, which define the maximum allowable offset of each vertex from its original location, were tested. Among all tolerances tested, the 750 m worked best to retain the crater shapes but simplify sufficiently to return straight crater rim segments for the whole range of mapped craters.

After the simplification, the crater rim polylines were split into individual segments at the remaining vertices using the “Split Line at Vertices” tool in the *ArcGIS Toolbox.* The spheroidal (geodesic) lengths, coordinates, and orientations of all of the split crater rim segments were computed using the Jenness Enterprises “Tools for Graphics and Shape” *ArcGIS* plug-in (http://www.jennessent.com/arcgis/shapes_graphics.htm). By following this mapping procedure in this thesis, a dataset of impact crater outlines of craters with a diameter range between 20 to 400 km was produced that can be used to assess crater shapes. For further assessment, the calculated values in the attribute table of the simplified, split crater segments were exported as *.txt file from *ArcGIS* for further analysis.

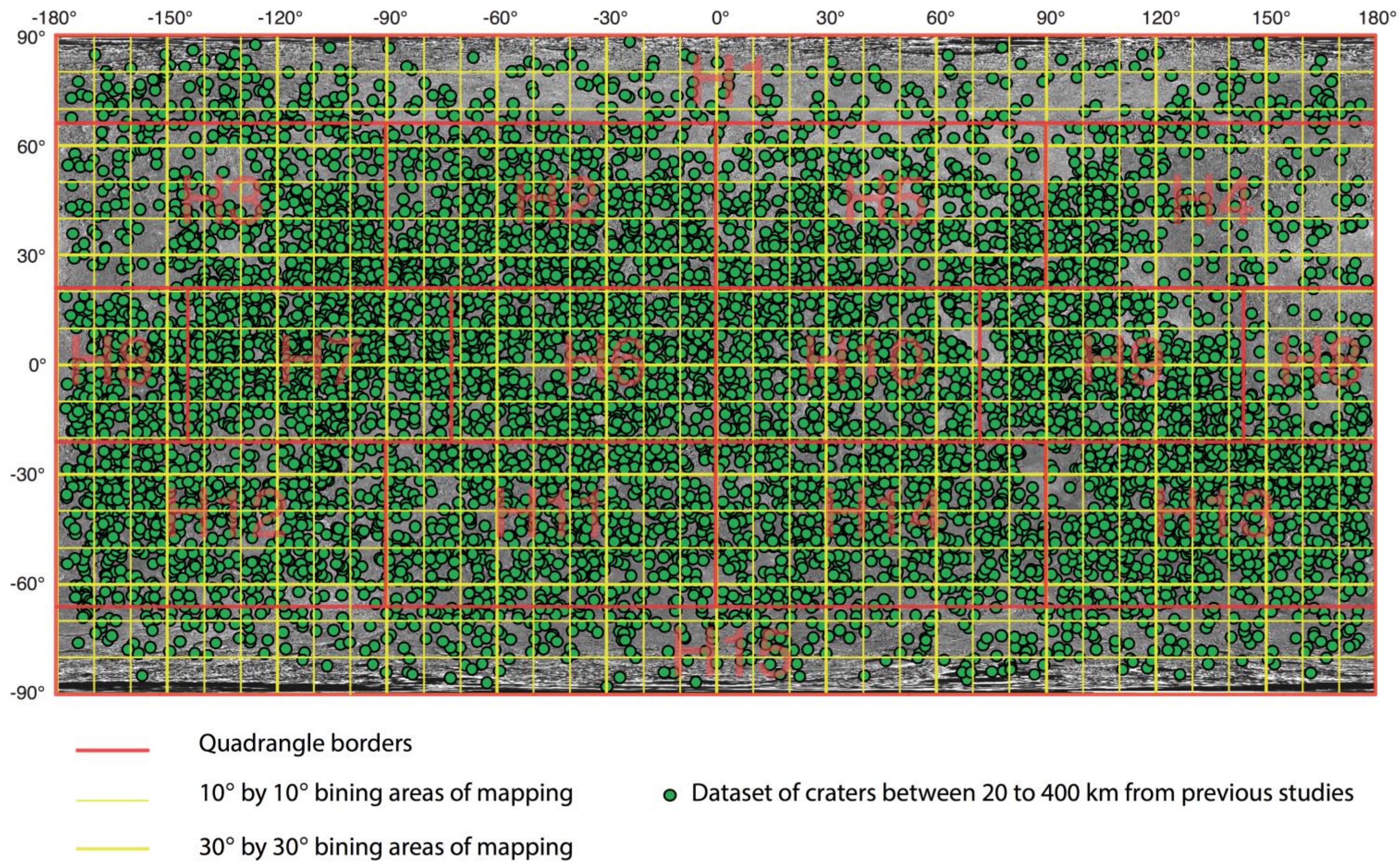

Figure 2.1: Quadrangle map of Mercury in equirectangular projection showing the MDIS monochrome basemap. The black numbers represent lines of latitude (on the left) and longitude (on top) in degrees. Green dots show the centers of impact craters plotted from the existing crater catalogue by Kinczyk et al. (2020). Locations of Mercury's quadrangles (outlined in red from H1 to H15) and 10° by 10° (thin yellow lines) that were used for systematic mapping and analysis of crater rim data are shown.

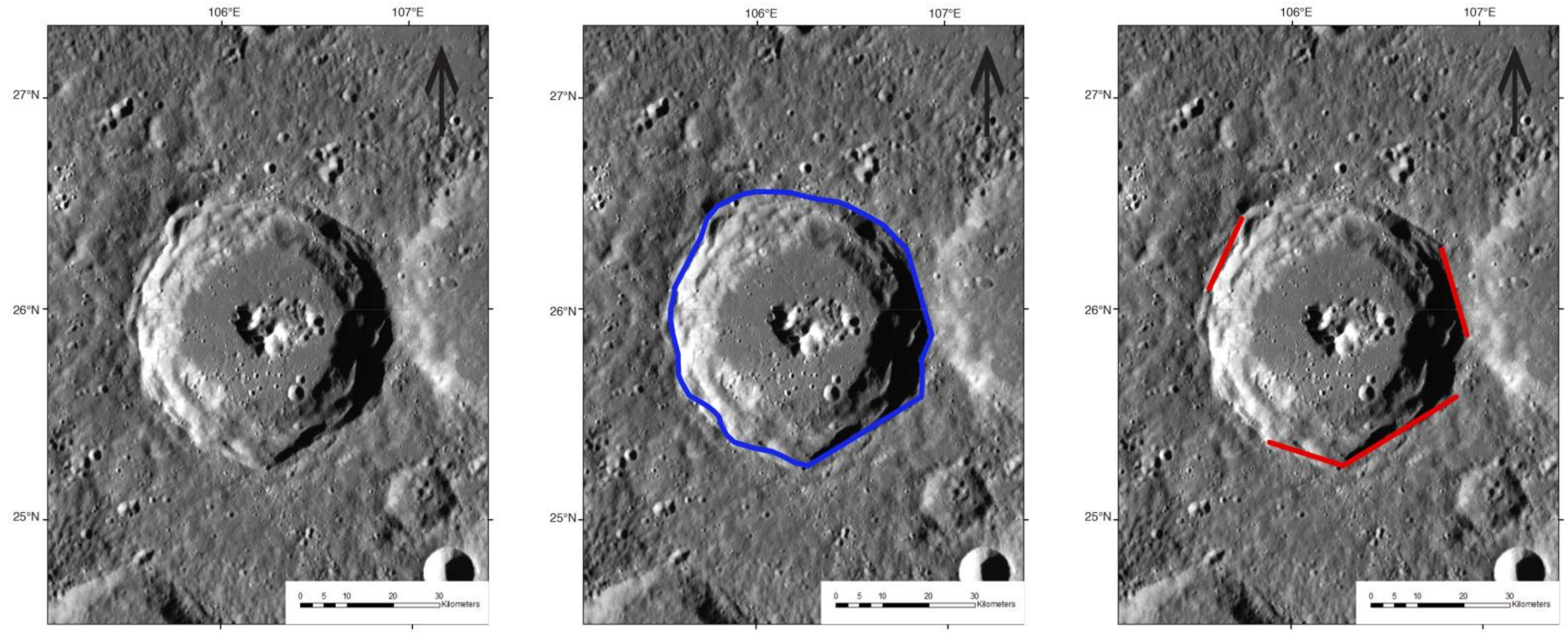

Figure 2.2: An example of the mapped craters is shown. The diameter of the crater is 44 km. The image at the left shows the basemap view of the impact crater. Blue lines in the center image represent the mapped crater rim. The red lines in the right image show straight rim segments longer than 10 km, after simplification and splitting of the mapped crater rim.

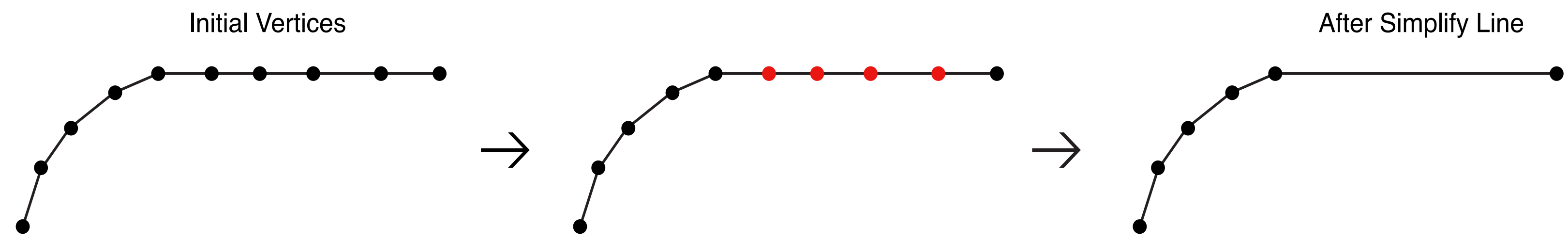

Figure 2.3: Overview of crater rim simplification. The initial polyline feature from mapping in stream mode is shown in the left image, with vertices represented as black dots. In the center image, vertices indicated by red dots do not contribute to the overall geometry of the polyline feature. The right image shows that the red-colored vertices in the second image were removed but the shape remains the same.

Analysis of the Rim Segments

To analyze the rim segments, Mercury's surface was divided into 72 geographical bins using a 30° by 30° equirectangular grid, and all rim segments within the area were grouped together and assessed for their orientations. The rim segments were grouped into twelve 30° longitudinal and six 30° latitudinal bins to identify if any longitudinal or latitudinal variations of straight crater rims exist. To aid with the geographical binning, code was written in the *R* software environment (Team, 2019) (see Appendix B) to divide the crater rim data by the coordinates belonging to the geographical bins.

A total of 115,884 crater rim segments were analyzed. As longer straight rim segments reflect more prominent fracture sets, only rim segments longer than 10 km were used for orientation analysis, and they are considered straight crater rim segments. A total of 28,979 crater rim segments are longer than 10 km, and their orientations were further assessed by plotting rose diagrams for each bin. Rose diagrams are a histrogram or frequency distribution for circular data, thus representing the variation of data from 0° to 360°. Rose diagram code was written to weight the orientations of the straight crater rim segments by their lengths such that longer segments contributed more prominently to the orientation data (see Appendix B). All rose diagrams were divided into 72 bins of 5°. The rose diagrams of all 30° by 30° bins were color-coded to display the density of measurements that went into the analysis. To do that, the total length of all straight crater rim segments was divided by the area of their geographical bin.

First, all straight crater rim segments were plotted using the 30° by 30° bins as well as in latitudinal and longitudinal bins. But since crater classes were assigned to each crater, further analysis is possible to test if there is differences or patterns not only geographically, but also by crater class and thus stratigraphically. Crater rims for the different crater classes were separately evaluated in three subgroups. The grouping includes the most degraded crater classes, i.e., crater classes 1 and 2, moderately degraded impact craters, i.e., crater class 3, and the freshest impact craters, i.e., crater classes 4 and 5. Then, the same 30° by 30° and longitudinal and latitudinal binning procedure was applied to the data in these different subgroups. The structure density color-coding was scaled to be the same for all assessed subgroups, which allowed to observe density changes.

CHAPTER 3

RESULTS

A total of 115,884 extracted crater rim segments they are shown in Figure (3.1), and their length and orientation is provided for each quadrangle in Appendix A-2. In the map, the total of mapped crater rims are shown in gray. For simplicity only the straight rim segments longer than 15 km are shown in red. The intensity of the red indictaes the crater class with the lightest red represents crater class 1 and the darkest red showing craters assigned the crater class 5. The map highlights the known asymmetry in impact crater density on Mercury, where the southern hemisphere is heavily cratered while cratering is sparse in the high northern latitudes. Visual inspection of the map for straight rim orientations shows that they vary in orientation without a clear systematic pattern.

Of the 115,884 crater rim segments, 25% are accepted as straight rim segments (Table 3.1). This breaks down for the crater classes such that 7.7% of 115,884 rim segments are considered straight for craters in class 1, 10.8% of 115,884 rim segments are considered straight for craters in class 2, 4.4% of 115,884 rim segments are considered straight for craters in class 3, 2% of 115,884 rim segments are considered straight for craters in class 4, and 0.2% of 115,884 rim segments are considered straight for craters in class 5. Class 2 impact craters constitute most of the straight rim segments on Mercury. The second majority of the straight rim segments are the part of crater class 1. The number of straight rim segments decreases in classes 3, 4, and 5. The high degradation rate of the rims of class 1 impact craters may explain the fewer number of straight rim segments in class 1 than class 2. The number of straight rim segments declines proportional to the number of impact craters in each crater class.

Of the 7,145 mapped impact craters, 83% have at least one or more straight rim segments (Table 3.1). Craters of class 1 are the most abundant impact crater subgroup with 3,043 impact craters and 76% of them have at least one straight rim segment. Of the 2,795 mapped impact craters of class 2 87% have one or more straight rim segments. Nearly 89% of 958 craters of class 3 show at least one straight rim segment, and about 93% of craters in both classes 4 and 5 have one or more straight rim segments. This breakdown of abundances per crater class indicates that the percentage of craters with one or more straight rim segments are potentially proportional across all crater classes, and the increase of straight rim segments for fresher craters is likely related to them being more easily identified in the images.

The total length of the all mapped impact crater rims is 937,402 km and the rim segments longer than 10 km is 413,807 km. Therefore, only 44% of all impact crater rims were used for the orientation analysis. The 319,843 km length of the crater rims belong to the class 1 craters, and ~39% of them are the rim segments longer than 10 km. The total mapped rim length of the crater class 2 is 386,867 km as the longest mapped rim subgroup, and nearly 46% of them are straight rim segments. Craters of class 3 consist of a total 156,784 km length of crater rims and ~47% portion of them are straight rim segments. The length of the mapped rims of crater classes 4 and 5 are 68,694 km and 5,214 km respectively, and nearly 50% portions of them are considered as straight rim segments. Consequently, 303,826 km of straight rim segments as the degraded impact craters, 73,299 km of straight rim segments as the moderately degraded impact craters, and the 36,683 km of straight rim segments as the fresh impact craters were used for the orientation analysis of different degradation subgroups.

Table 3.1: The number of straight rim segments of different crater classes, their percentages among all rim segments on Mercury, the number of impact craters of different crater classes, the abundance of rim segments longer than 10 km, total length of all mapped crater rims, and the total length of the rim segments longer than 10 km are shown.

Crater Class	Total number of craters	Total number of straight rim segments	Total straight rim segments of Mercury (%)	Number of craters with at least one straight rim segment	Craters with at least one straight rim segment (%)	Total length of mapped crater rims (km)	Total length of straight rim segments (km)	Length of straight rim segments of crater rims (%)
Class 1	3,043	8,890	7.7	2,316	76	319,843	125,083	39
Class 2	2,795	12,519	10.8	2,439	87	386,867	178,743	46
Class 3	958	5,078	4.4	849	89	156,784	73,299	47
Class 4	321	2,311	2.0	297	92	68,694	34,079	50
Class 5	28	181	0.2	26	93	5,214	2,603	50
Total	7,145	28,979	25.0	5,927	83	937,402	413,807	44

To assess if a systematic pattern exists, rose diagrams were plotted for all 28,979 rim segments considered straight (Figure 3.2). This analysis reveals variations of all straight rim segments in 72 30° by 30° equirectangular-, as well as over twelve 30° longitudinal-, and six 30° latitudinal geographic regions.

Investigating the latitudinal bands, east-west preferred orientations are clearly identified at latitudes higher than 60°N and lower than 60°S (Figure 3.2). The longitudinal bands do not have any strongly preferred orientations although some subtle variations may exist longitudinally, too (Figure 3.2). The rose diagrams across all individual polar bins show that orientations of straight rim segments have a pronounced preferred east-west orientation (Figure 3.2). Some equatorial and mid-latitudinal regions show weak north-south preferred orientations, whereas other areas in the equatorial and mid-latitudinal regions also show random distributions of straight crater rim azimuths. The structure density correlates well with the crater density, showing that more data informs the orientations away from the north pole and Caloris Basin.

As craters and their straight rim segments were classified into the different crater classes, additional analysis is possible to test whether different subgroups of craters display different patterns. The variations of orientations of the straight rim segments of crater classes 1 and 2 were grouped together and are shown in the rose diagrams in Figure (3.3). The straight rim segments of this subgroup of craters also show strong preferred east-west orientation at the poles and weak or random orientations in mid-latitudinal and equatorial regions, mirroring the orientations of all investigated craters. As this subgroup includes the majority of all craters and straight rim segments the similarity of the pattern in not unexpected.

The variations of orientations of the straight rim segments of craters in class 3 craters are shown in Figure (3.4). Although the rose diagrams of the latitudinal bands indicate that there is a general east-west preferred orientation at the polar regions, there is more variation of straight rim segment orientations, showing northeast-southwest and northwest-southeast preferred orientations in some polar bins, especially in the southern hemisphere. In mid-latitudes and equatorial regions, these straight rim segments show multimodal preferred orientations but without an obvious systematic pattern in the chosen geographic binning.

Straight rim segments of a subgroup containing craters of classes 4 and 5 are presented in Figure (3.5). Even though the dominant preferred orientation is also east-west in the polar regions as judged by the latitudinal bands, there is substantial variation, including north-south orientations in some higher latitude regions. Similar to the orientations of straight crater rims of class 3, the straight crater rims of classes 4 and 5 also show multimodal preferred orientations in mid-latitudinal and equatorial regions.

In sum, the longitudinal and latitudinal bins across all subgroups of straight crater rims compare well to one another, showing east-west orientations at the poles, some weak multimodal or no preferred orientations in the mid- and low latitudes, and generally no strong longitudinal variation of orientations. However, orientations of straight crater rims across Mercury show more variations, more pronounced modes, and some differences among the subgroups. This pattern becomes more pronounced for subgroups that include the fresher craters (crater classes 3 to 5). It must be noted that there is less data for fresher craters, which may be the cause for more pronounced modes. This observation is explained with the increased crispness of rims, which facilitated recognition and mapping of straight rims.

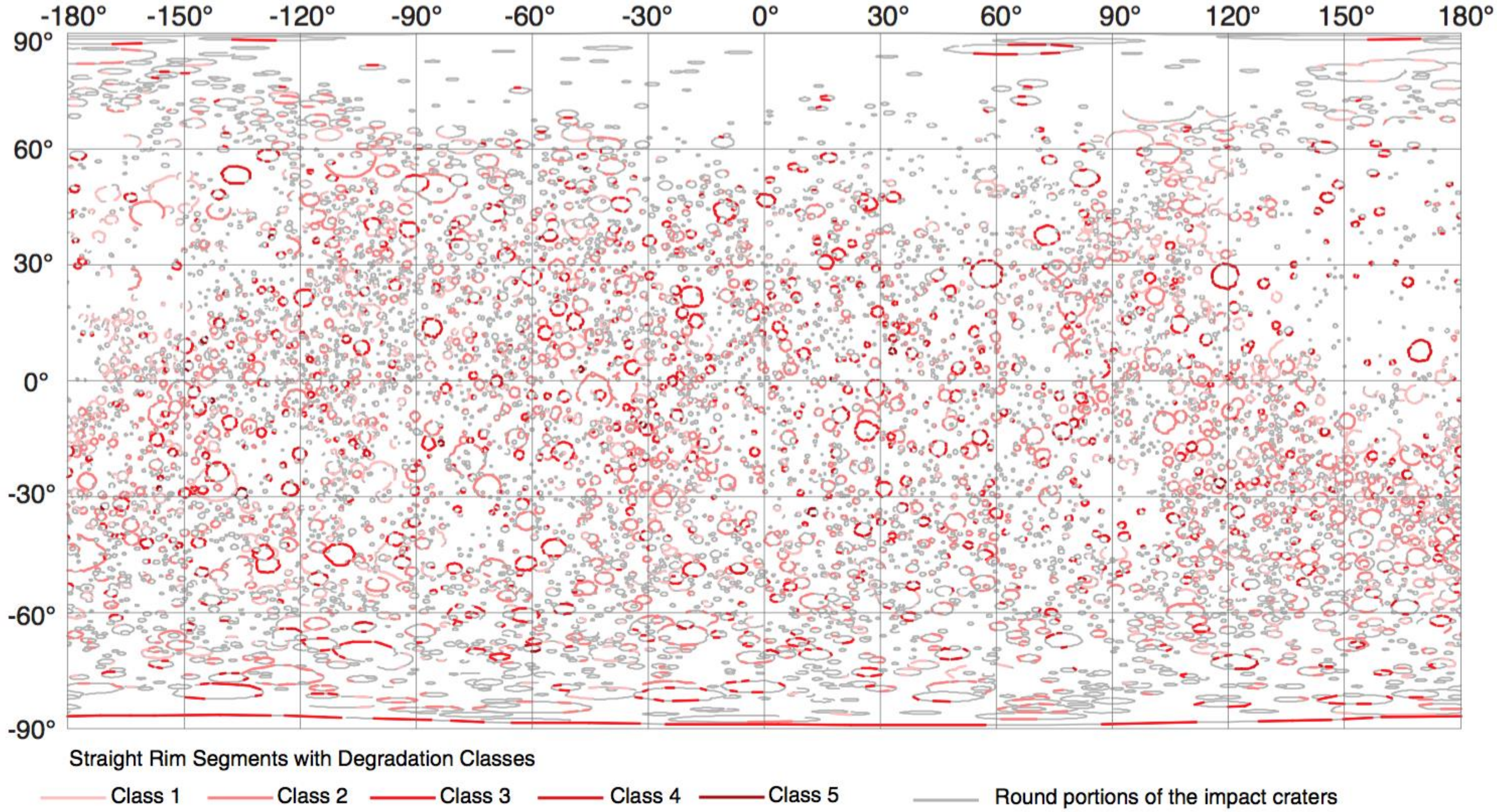

Figure 3.1: Global map of planform shapes of impact crater rims with diameters between 20 and 400 km on Mercury displayed with gray lines in equirectangular projection. Rim segments longer than 15 km are shown to correspond to craters of class 1 to class 5 with increasing darkness of red.

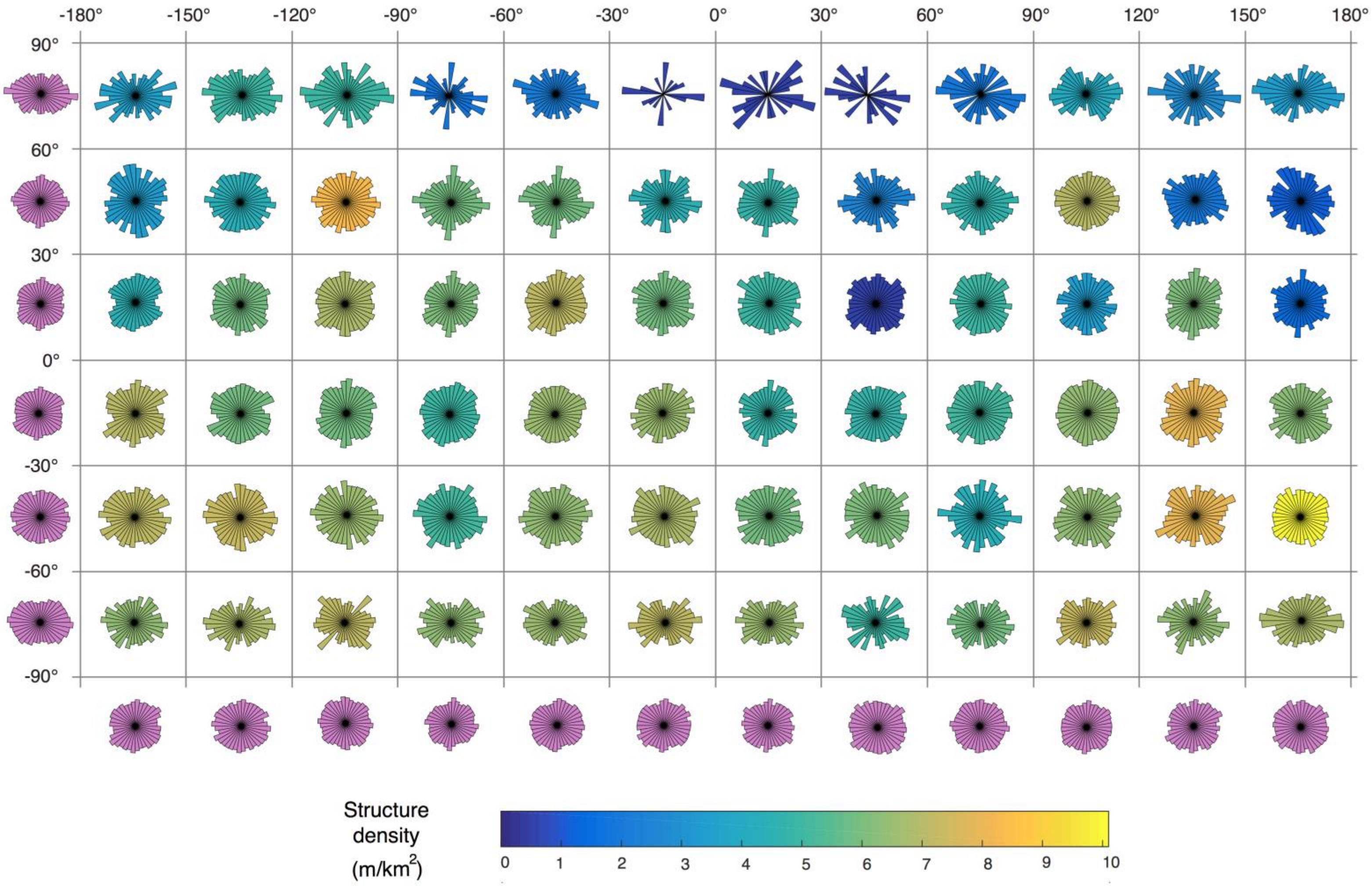

Figure 3.2: Distribution of straight rim segments on Mercury shown in equirectangular projection. Color-coding was applied based on the density of measurements. Pink rose diagrams include entire longitudes (bottom row) and latitudes (left column).

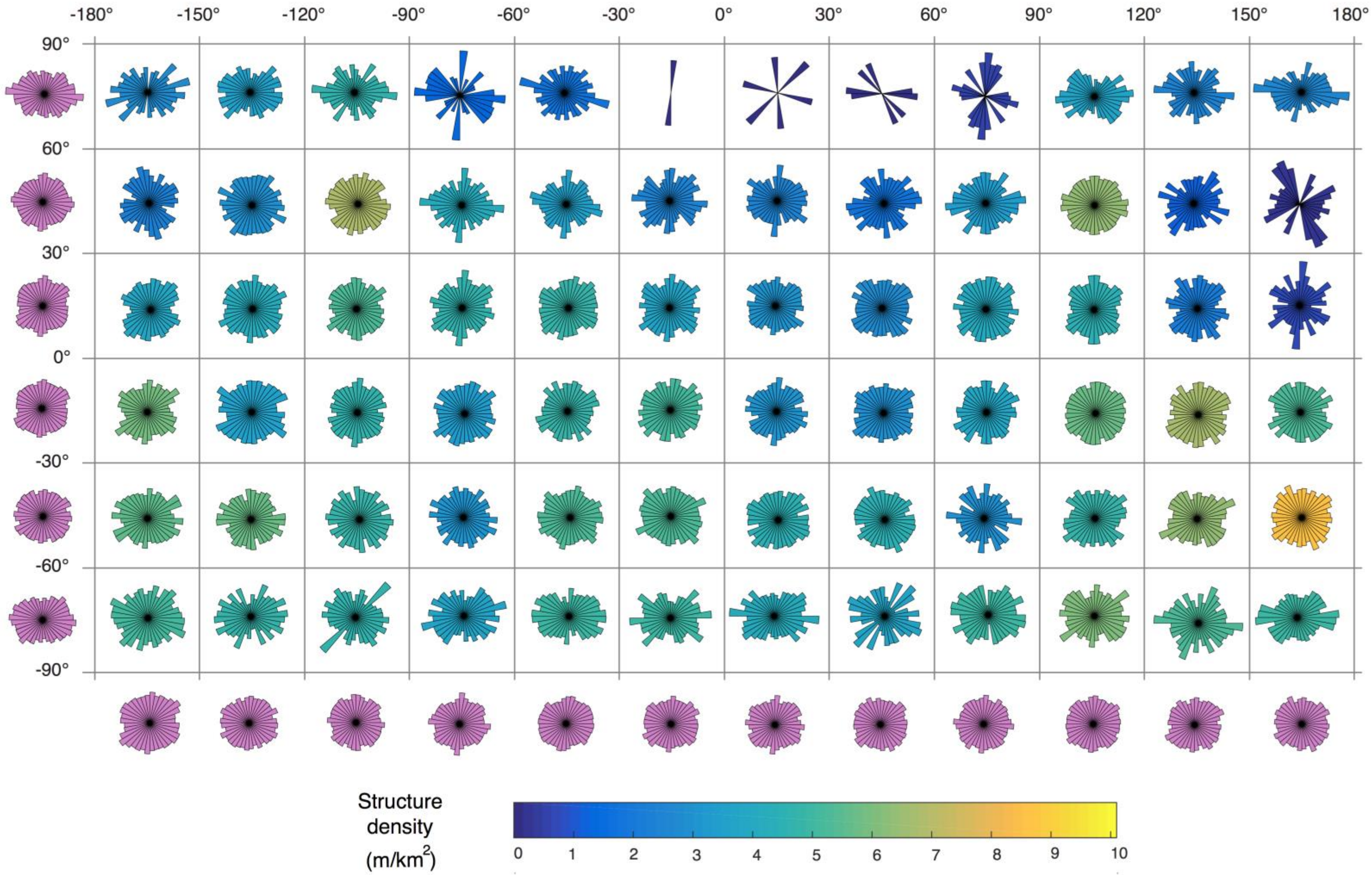

Figure 3.3: Orientation distribution of the straight rim segments of the degraded impact craters: classes 1 and 2.

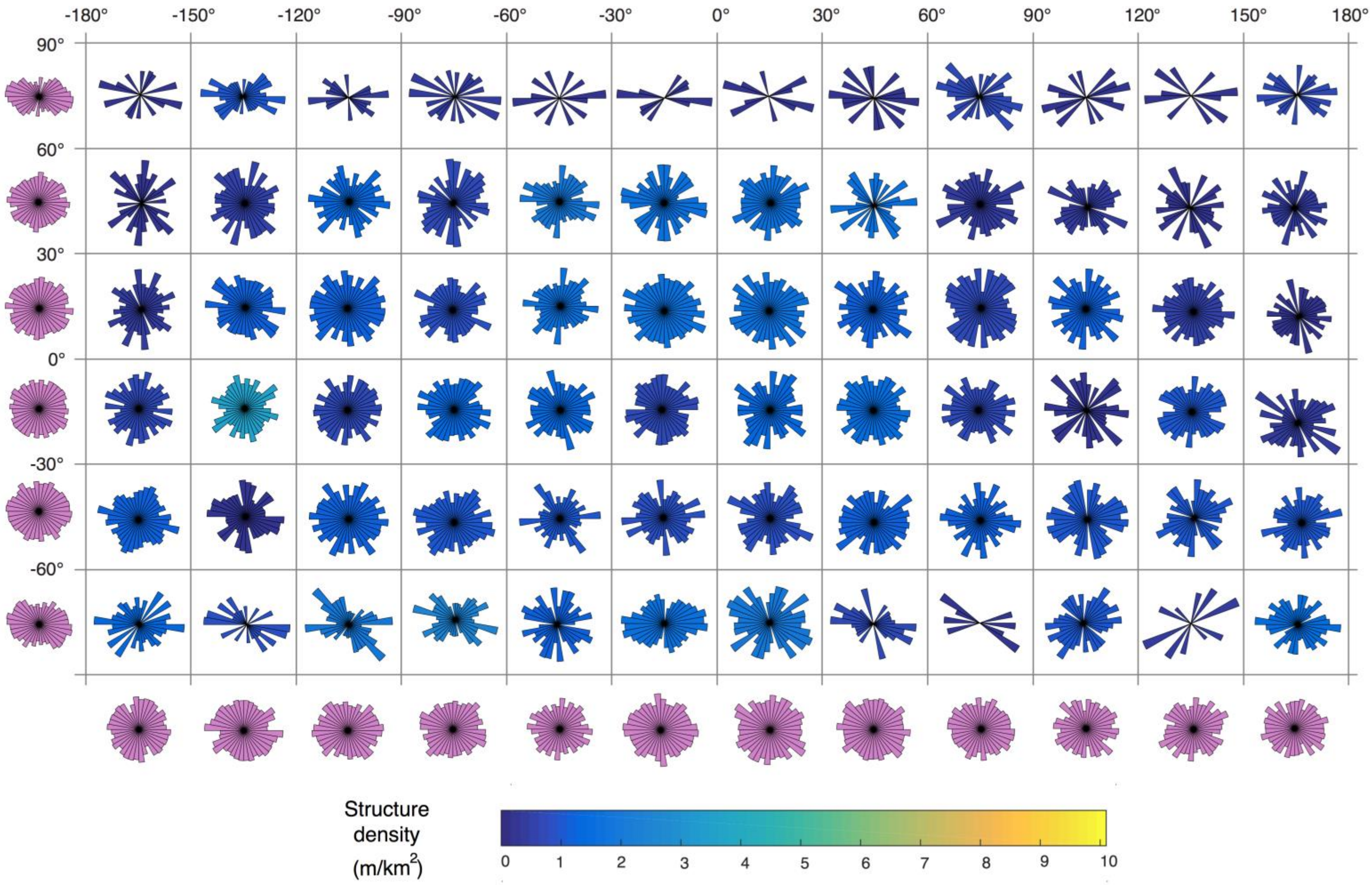

Figure 3.2: Orientation distributions of the straight rim segments of moderately degraded (Class 3) impact craters.

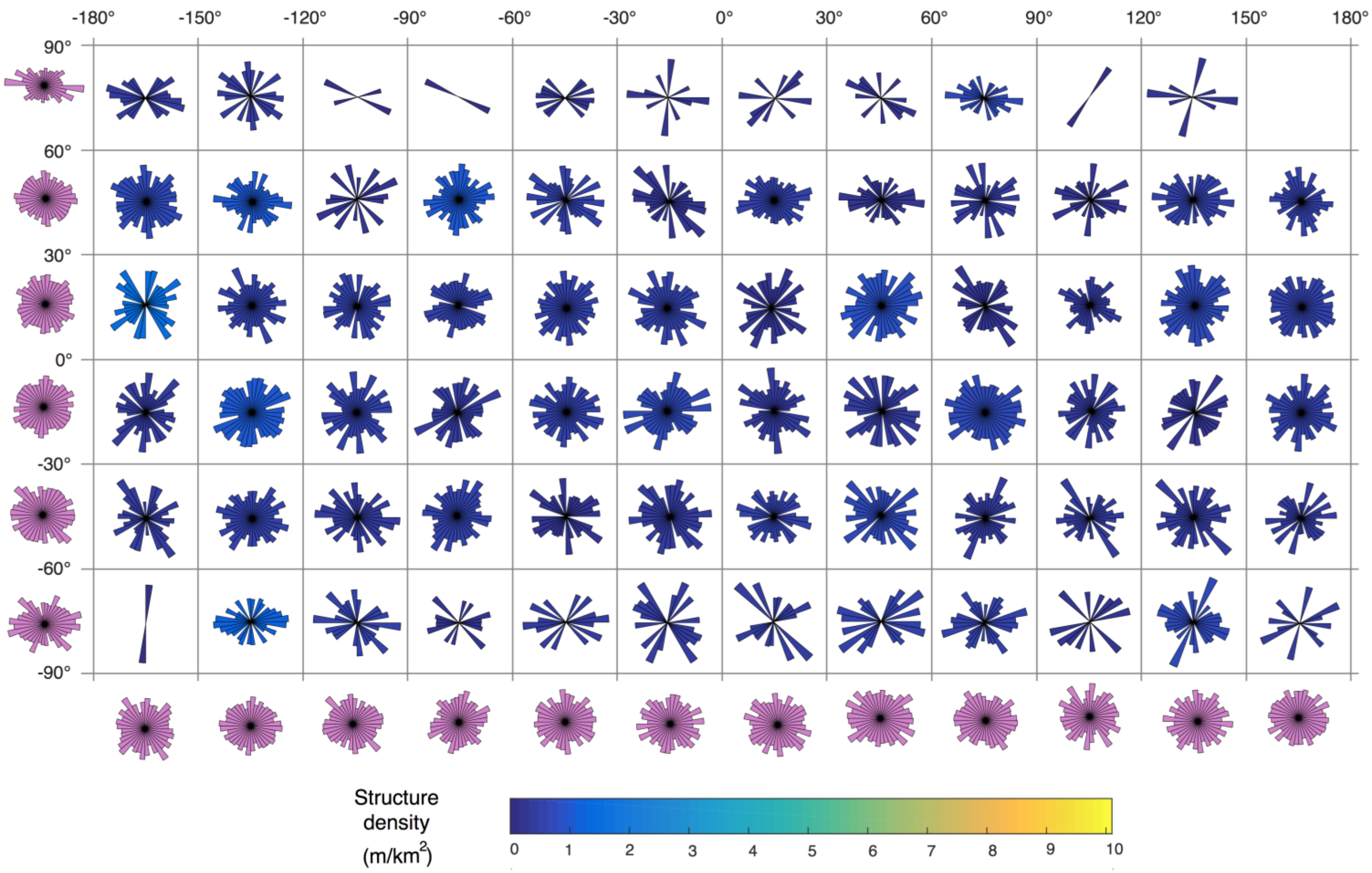

Figure 3.3: The distribution of the straight rim segment orientations of the fresh craters: classes 4 and 5

CHAPTER 4

DISCUSSION

Straight rim segments of impact crater rims form parallel to, or directly utilized along pre-existing fractures on the bedrock. Most of the impact craters mapped include one or more straight rim segments. Therefore, pre-existing fracture sets in Mercury's lithosphere can be interpreted using these findings. Fracture sets that were previously hidden were revealed by the straight rim segment analysis in this thesis. The fractures revealed by the impact craters show a specific pattern. The straight rim segments, and thus the previously hidden fracture sets, show pronounced east-west preferred orientation at the poles, while weak north-south orientation in some equatorial and mid-latitudinal regions. Also, in some equatorial and mid-latitudinal regions they have random orientations.

The global pattern of fractures revealed by the planform shapes of impact craters on Mercury can be compared to previously observed distributions of fault-related landforms. The fracture pattern revealed by the straight rim segments shows the preferred east-west orientation in latitudes upward of 60°. Crane and Klimczak (2019) discovered that shortening landforms in Mercury's high northern latitudes, north of 70°N, also display a preferred east-west orientation, indicating that they too may have used the same pre-existing set of fractures. The latitudinal variations of fracture patterns revealed by the planform geometry of impact craters shows some similarities to previously mapped shortening structures by Byrne et al. (2014) in equatorial and mid-latitudinal regions, showing a general north-south regional pattern. Again, this indicates that cratering and faulting processes likely used the same fracture sets that pre-existed in Mercury's lithosphere.

The global pattern of fractures revealed by the planform shapes of impact craters on Mercury can also be compared to predictions of fractures resulting from global contraction alone, tidal despinning alone, or for the scenario where these two processes overlapped. Such comparison is valuable for assessing these predictions. Global contraction is predicted to form randomly oriented thrust faults (Solomon, 1977). If pre-exiting fracture in Mercury's lithosphere were randomly oriented and thrust faults and craters utilized them, both thrust faults and craters would show random global orientations. Neither faults nor straight crater rims show globally random orientations, indicating that global contraction did not operate to reactivate randomly oriented fractures.

Tidal despinning alone is predicted to produce joints with preferred east-west orientations in the equator and random orientations at the poles (Klimczak et al., 2015). The broad pattern observed for fractures causing straight crater rims neither matches with this predicted global joint pattern in polar regions nor in mid-latitudinal and equatorial regions of Mercury. While a few preferred east-west orientations of straight rim segments are observed in the equatorial and mid-latitude regions, especially in the freshest crater subgroups, they are not pronounced enough to justify a local match of the pattern. Thus, the fracture pattern observed on Mercury is unlike that predicted to have formed from tidal despinning alone.

Tidal despinning that temporally overlapped with global contraction is predicted to form north-south orientations of thrust fault in the equatorial and mid-latitudinal regions and random orientations at the poles (e.g., Klimczak et al., 2015). This prediction is largely matched by the latitudinal variations of shortening landforms (Byrne et al., 2014). However, only weakly preferred north-south orientations in some but not all equatorial and mid-latitudinal regions occur in fracture sets from straight crater rim segments, and their orientations are uniform at the poles. This finding shows that thrust faults predicted to have formed from tidal despinning overlapping temporally with global contraction would not have used the pre-existing fracture sets used by impact craters.

The impact process itself also fractures the lithosphere, a process widely referred to as impact damage, introducing radial and concentric fractures around the site of impact (Kenkmann et al., 2013). After billions of years of impact cratering, this may cause any planetary lithosphere to be heavily fractured along random orientations. Any fracture pattern induced by tectonic processes other than cratering would be superposed on this random fracture pattern. Therefore, interpretation of preferred orientations in fracture sets revealed by straight impact crater rims must account for the presence of additional randomly oriented fractures that serve to weaken the modes of preferred orientations in statistical assessments of such orientation data. In areas where non-cratering tectonic processes did not contribute substantially to fracturing the lithosphere, a random fabric may prevail, such that some of the random orientations of fractures may be attributed to the impact cratering alone.

This research revealed previously hidden fractures and their systematic changes across the surface of Mercury. The variations of fracture patterns were interpreted by visual inspection of data that was divided in equirectangular, longitudinal, and latitudinal geographic regions. Future analyses of the data that goes beyond the scope of this thesis could include statistical assessments of the modes of fracture orientations or geospatial analyses to geographically divide the straight rim segments based on geologic or geophysical boundaries. Binning of fracture data with bin boundaries outlining distinct geochemical terranes of Mercury (McCoy et al., 2018) could further highlight to what extent compositional played a role in forming tectonic patterns. In conjunction with the stratigraphic information revealed by the crater class assessment, these future analyses could further improve our understanding of tectonic activity on Mercury.

CHAPTER 5

CONCLUSION

Straight rim segments of impact craters on Mercury reveal a previously unknown global pattern: a strongly pronounced pattern of east-west preferred orientations at the poles with some weak north-south orientations at the mid-latitudes and equatorial regions. This pattern is caused by fracture sets that existed in the lithosphere before the impacts occurred and thus were used to form the crater rims. In addition to geographic variations of fracture patterns across Mercury, crater class analysis reveals variations based on the degradation state of the craters that allows placing the fracture utilization by the cratering process into a stratigraphic context. Findings of the analysis of straight rim segments based on crater classes show that the latitudinal and longitudinal variations of fracture orientations are similar across all degradation stages, but that there are more and more pronounced fracture sets revealed by fresher craters and that regional/local changes of fracture utilization through time may have played a role. These results contribute toward understanding global tectonics as well as the reactivation of pre-existing fractures as crater rims and faults on the innermost planet.

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APPENDIX A

Table A1: Impact crater data of Mercury

Quadrangle	Crater ID	Crater Class	Longitude (decimal degrees)	Latitude (decimal degrees)
H1	1	3	0.77989	69.52893
H1	2	3	1.66885	68.84583
H1	3	4	0.48987	66.45241
H1	4	4	28.63608	69.05198
H1	5	3	21.57481	66.80417
H1	6	4	32.25882	69.79508
H1	7	4	43.48027	65.54775
H1	8	5	61.67922	67.42834
H1	9	4	81.26325	66.68509
H1	10	1	108.02747	67.62751
H1	11	1	117.84250	68.27206
H1	12	1	128.00435	67.81110
H1	13	1	122.12475	65.78074
H1	14	2	134.75023	66.71166
H1	15	5	131.27657	68.73882
H1	16	4	133.03674	70.08124
H1	17	1	149.45526	67.54494
H1	18	2	146.27906	69.91394
H1	19	2	156.86086	69.97441
H1	20	2	153.00822	68.26425
H1	21	3	164.95086	67.34033
H1	22	1	167.75384	69.81929
H1	23	2	171.73035	69.57131
H1	24	2	178.05746	68.00318
H1	25	3	-8.48719	66.94301
H1	26	2	-45.38276	66.51252
H1	27	2	-50.51649	66.55838
H1	28	3	-52.73527	69.73337
H1	29	2	-49.09362	66.23351
H1	30	2	-59.59262	67.61505
H1	31	3	-90.79851	70.11137
H1	32	2	-99.82119	67.11591
H1	33	2	-109.64709	67.36973
H1	34	2	-104.95348	68.08225
H1	35	2	-108.20873	69.66689
H1	36	1	-107.33841	68.31346

H1	39	2	-114.10594	66.97810
H1	38	2	-116.27714	68.82214
H1	37	1	-120.88371	66.53853
H1	40	1	-112.40462	66.30018
H1	41	3	-125.53364	66.68684
H1	42	2	-122.10550	67.30248
H1	44	2	-120.79399	67.94195
H1	43	3	-120.80952	69.54388
H1	45	2	-123.10736	69.05863
H1	47	1	-128.98918	68.30891
H1	46	1	-128.51101	66.91484
H1	49	4	-131.99912	67.17834
H1	50	2	-128.38973	69.20895
H1	51	3	-133.40238	69.17308
H1	53	3	-135.76757	67.72425
H1	52	2	-134.80561	68.62235
H1	48	2	-135.18090	67.13233
H1	57	2	-141.27943	68.95045
H1	56	3	-146.06440	69.41577
H1	55	3	-149.70011	66.69088
H1	54	1	-147.92945	67.80664
H1	61	1	-157.20007	66.43549
H1	60	1	-153.09106	66.27318
H1	59	1	-153.70837	68.05593
H1	58	2	-152.73499	69.18062
H1	62	4	-179.83393	68.23855
H1	63	1	-175.68691	71.36414
H1	64	2	-176.78768	74.00295
H1	66	2	-172.14476	74.27435
H1	65	1	-175.36066	75.73236
H1	67	1	-178.93437	78.20141
H1	68	1	-170.93573	71.24417
H1	69	2	-169.49950	70.16027
H1	71	2	-166.78302	73.01375
H1	72	2	-162.39568	74.06996
H1	70	1	-161.79932	71.61838
H1	73	1	-168.60247	73.69497
H1	76	2	-170.64478	77.03820
H1	75	2	-164.54437	76.57990
H1	74	1	-167.97068	74.70693
H1	79	2	-155.87568	70.23013
H1	78	2	-152.04995	71.57353
H1	77	3	-158.77337	72.23998

H1	81	4	-161.65117	75.55856
H1	82	1	-159.37667	74.53921
H1	80	1	-154.35515	76.28971
H1	83	1	-157.68783	76.45925
H1	84	1	-159.61948	77.02755
H1	86	4	-160.04221	79.18927
H1	90	3	-146.28235	77.51613
H1	89	1	-139.20666	76.26147
H1	87	2	-142.24976	78.67649
H1	88	1	-139.07594	77.66362
H1	91	2	-148.21851	72.61194
H1	92	2	-148.45464	70.47308
H1	98	1	-134.32251	76.32282
H1	97	3	-137.32709	75.32271
H1	93	3	-142.02545	72.24099
H1	94	4	-134.85597	71.79268
H1	95	1	-129.94019	73.06850
H1	99	2	-136.74256	70.12169
H1	96	1	-129.39132	74.71745
H1	102	2	-122.50383	78.09641
H1	103	3	-124.47240	75.98538
H1	105	2	-120.82388	72.14677
H1	106	1	-124.41628	74.68223
H1	104	1	-126.80838	76.35447
H1	107	3	-121.53255	71.43074
H1	101	1	-131.31955	79.05015
H1	100	3	-125.32945	79.53358
H1	112	3	-112.65583	76.77820
H1	111	2	-113.80200	75.20359
H1	110	3	-110.64826	72.13078
H1	109	2	-119.55499	71.06583
H1	108	2	-116.21854	73.92472
H1	115	2	-108.53252	71.37784
H1	114	2	-108.39548	70.22485
H1	113	3	-103.88089	70.62368
H1	116	2	-107.58032	72.06246
H1	118	2	-108.62717	73.13105
H1	117	3	-104.04162	73.04449
H1	119	3	-93.90838	77.83649
H1	121	3	-83.94436	71.24529
H1	120	3	-79.28673	78.14242
H1	122	3	-75.08963	72.42497
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H3	214	2	-144.64798	38.09855
H3	215	1	-140.15102	36.09636
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H3	234	1	-138.75765	21.66197
H3	235	2	-151.75293	30.82017
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H4	201	2	117.76962	36.06005
H4	202	1	110.96801	36.44525
H4	203	1	113.56877	39.32220

H4	204	1	121.31899	32.48504
H4	205	2	122.99405	36.68592
H4	206	4	136.46228	29.42785
H4	207	4	133.15801	34.74267
H4	208	1	140.89996	31.57663
H4	209	3	146.40505	31.38649
H4	210	3	145.83474	35.74705
H4	211	2	140.08949	38.64888
H4	212	3	157.54461	30.32745
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H4	215	2	158.78465	38.21797
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H4	218	4	167.08872	36.33683
H4	219	4	165.61261	37.18810
H4	220	2	167.40075	37.58076
H4	221	1	163.67384	39.30072
H4	222	2	165.84823	39.26545
H4	223	1	172.84203	38.16127
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H4	225	2	174.53126	38.18529
H4	226	3	175.62964	38.03436
H4	227	2	178.44243	39.19118
H4	228	2	92.25449	27.58925
H4	229	1	94.04796	21.48379
H4	230	1	93.32091	22.03459
H4	231	3	94.79648	21.96905
H4	232	1	97.55612	25.40691
H4	233	1	95.89419	24.70167
H4	234	1	96.03926	23.13960
H4	235	1	95.47552	27.80654
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H4	237	1	97.73350	28.55086
H4	238	1	91.10157	25.76104
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H4	244	1	106.33067	29.12783
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H4	251	3	106.86901	25.75969
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H4	253	2	108.32145	25.68071
H4	254	3	105.33037	23.72278
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H4	267	1	112.28238	29.46739
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H4	274	2	142.61888	23.86433
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H4	279	4	145.69077	27.14026
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H5	26	1	18.48671	49.92754
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H5	30	1	22.63716	51.02867
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H5	33	1	25.35959	52.78781
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H5	47	2	32.36332	57.69629
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H5	82	4	0.96225	45.07978
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H5	93	1	9.50601	41.36677
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H5	95	2	14.14059	45.39936
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H5	115	1	19.65571	46.82101
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H5	117	1	23.41312	47.46639
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H5	119	1	23.42690	48.82889
H5	120	2	27.78429	49.22793
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H5	124	3	33.84641	48.76537
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H5	131	2	59.79848	47.76505
H5	132	3	58.68244	48.12221
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H5	138	2	62.48605	48.70061
H5	139	1	63.26150	49.42014
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H5	145	2	68.80219	42.92835
H5	146	4	65.71965	47.69913
H5	147	2	69.43466	49.36906
H5	148	1	77.32587	42.22975
H5	149	1	73.33012	42.72483
H5	150	3	71.28005	43.92997
H5	151	2	75.01622	48.27107
H5	152	1	76.36717	48.31653
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H5	154	1	79.62527	49.35584
H5	155	1	80.64078	45.36367
H5	156	2	83.72525	48.94194
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H5	159	2	87.13819	43.92392
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H5	162	2	84.56120	42.17550
H5	163	1	84.81665	40.86287
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H5	165	1	88.53640	41.51345
H5	166	4	88.32381	42.76078
H5	167	1	89.76822	44.09379
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H5	170	1	83.66024	44.35683
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H5	172	1	3.81618	37.52796
H5	173	1	9.61867	39.28541
H5	174	2	7.44133	34.95829
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H5	178	3	17.10653	31.90810
H5	179	1	20.27878	30.88463
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H5	181	3	20.64532	33.31713
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H5	183	3	14.69319	33.58043
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H5	187	4	14.68691	36.09026
H5	188	2	13.39034	37.54215
H5	190	3	16.84930	37.16266
H5	191	2	18.88339	35.97040
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H5	195	2	24.74030	30.21326
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H5	197	2	27.02570	30.87201
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H5	200	1	29.04249	30.89807
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H5	202	1	28.48675	31.69564
H5	203	2	28.98007	32.99607
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H5	206	3	23.73142	35.52918
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H5	208	3	21.71424	32.64458
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H5	210	1	28.09312	38.35225
H5	211	2	30.80866	38.64789
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H5	214	2	31.23892	38.50359
H5	215	1	33.74425	38.34764
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H5	219	1	36.02471	34.03584
H5	220	3	31.27262	34.60856
H5	221	1	35.55353	32.72430
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H5	225	1	40.00121	32.42186
H5	226	1	40.12516	33.68650
H5	227	2	41.93486	37.77666
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H5	230	1	49.42447	39.43851
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H5	246	1	57.57562	35.41685
H5	247	1	59.11342	37.80366
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H5	251	1	61.24053	32.83627
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H5	323	2	19.44123	24.84294
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H5	353	2	39.14846	20.89231
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H5	362	3	30.90720	24.71310
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H5	370	1	40.24873	24.90622
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H5	375	3	46.70536	23.72335
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H7	211	3	-118.24356	2.65610

H7	212	1	-119.29028	3.60085
H7	213	2	-119.77485	4.04630
H7	214	1	-119.09650	4.33261
H7	215	3	-118.69790	1.55374
H7	216	2	-117.28428	1.68917
H7	217	3	-114.59873	0.65998
H7	218	2	-113.94272	1.90265
H7	219	2	-113.45898	1.18682
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H7	221	1	-113.22949	4.72560
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H7	223	2	-111.08664	1.37443
H7	224	1	-110.33694	0.59819
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H7	226	2	-110.05115	3.56515
H7	227	2	-110.36011	4.37147
H7	228	1	-110.20969	6.13466
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H8	39	2	-176.65758	10.50453
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H8	43	1	-175.02074	16.76649
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H8	54	1	-170.79138	1.32199
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H8	58	1	-167.68170	0.70684
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H9	99	3	124.06044	10.40143
H9	100	4	133.49981	11.96191
H9	101	3	133.09922	13.84278
H9	102	4	135.50067	11.93419
H9	103	3	130.40082	17.39521
H9	104	1	138.15078	19.49750
H9	105	2	137.42270	18.65357
H9	106	1	141.13870	10.31468
H9	107	2	141.17915	15.67910
H9	108	1	142.76737	19.75027
H9	109	2	144.06596	20.44682
H9	110	4	141.83584	7.13913
H9	111	3	142.82646	3.61383
H9	112	1	143.54395	5.50431
H9	113	1	141.74440	3.25203
H9	114	2	139.51591	6.71079
H9	115	1	140.63094	6.22352
H9	116	2	140.24433	1.43714
H9	117	4	138.04418	1.57406
H9	118	1	137.60962	3.46880
H9	119	2	137.88332	0.55512
H9	120	1	134.38002	1.59195
H9	121	2	136.91805	4.29458
H9	122	1	132.93078	3.05348
H9	123	1	132.54190	4.86621
H9	124	1	136.15771	6.56172
H9	125	3	137.40111	5.39075
H9	126	1	133.17746	2.54605

H9	127	1	130.99667	8.22338
H9	128	1	126.26132	3.38108
H9	129	2	128.67200	2.93183
H9	130	3	129.00380	5.00675
H9	131	1	128.47804	6.02415
H9	132	2	129.94503	4.67601
H9	133	2	126.32094	3.75746
H9	134	2	128.28159	1.69024
H9	135	1	129.93872	-0.47821
H9	136	2	128.39500	-0.01714
H9	137	1	126.48044	1.53349
H9	138	1	124.64113	1.34416
H9	139	3	121.79676	2.15749
H9	140	2	121.55214	4.47625
H9	141	2	120.88171	4.74436
H9	142	1	122.95515	4.84509
H9	143	1	124.65978	4.21555
H9	144	2	121.03819	0.89666
H9	145	3	122.44893	0.04532
H9	146	1	119.53175	-0.69697
H9	147	1	124.15472	6.36308
H9	148	3	124.53143	9.25095
H9	149	4	125.97989	10.29114
H9	150	3	119.12446	0.53221
H9	151	1	117.04740	1.13685
H9	152	2	116.74784	2.98563
H9	153	1	117.98365	2.20297
H9	154	1	118.82505	0.81118
H9	155	2	113.11006	-0.78439
H9	156	1	110.68705	2.42941
H9	157	2	112.60961	3.69826
H9	158	2	113.74014	3.85089
H9	159	2	110.42670	0.40357
H9	160	1	111.59334	4.76070
H9	161	3	110.82422	5.85143
H9	162	1	118.16092	4.15984
H9	163	1	117.25900	5.94692
H9	164	1	118.17317	8.11251
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H9	166	2	103.06329	2.36672
H9	167	1	103.36567	2.92993
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H9	172	2	106.23521	1.87308
H9	173	1	105.30326	1.21965
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H9	178	1	107.41472	5.97840
H9	179	1	103.46582	6.90310
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H9	189	3	90.70296	8.22396
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H9	193	1	90.00526	6.13920
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H9	200	2	94.54848	0.73250
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H9	280	1	94.70157	-2.66145
H9	281	1	94.96523	-3.28945
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H9	533	2	73.17739	-12.11115
H9	534	1	80.20724	-21.05353
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H10	4	2	4.64104	18.28772
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H10	6	1	3.08198	17.25952
H10	7	2	7.00718	18.82918
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H10	10	3	2.99340	15.24126
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H10	13	2	3.79366	9.77768
H10	14	1	4.57845	9.92330
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H15	143	2	168.21317	-70.66785
H15	144	1	-168.40423	-72.83190
H15	145	1	-168.86712	-71.18072
H15	146	2	-170.22556	-73.98572
H15	147	1	178.27395	-75.70455
H15	148	1	168.32512	-76.19875
H15	149	1	177.63966	-77.36960
H15	150	1	170.64491	-77.67185
H15	151	2	164.09890	-78.39224
H15	152	2	-169.27528	-78.35262
H15	153	1	-174.65590	-76.75756
H15	154	2	174.93025	-78.12191
H15	155	1	162.72326	-79.54045
H15	156	3	170.86911	-81.81930
H15	157	3	-178.07973	-82.16147
H15	158	2	171.37576	-80.00532
H15	159	2	-176.76162	-84.52292
H15	160	3	153.25331	-83.60056
H15	161	2	154.45914	-81.39879
H15	162	1	142.96131	-81.34500
H15	163	1	161.85571	-86.31465
H15	164	3	111.43395	-83.75908
H15	165	2	133.91162	-82.92635
H15	166	1	122.81975	-82.00760
H15	167	2	111.83909	-82.11967
H15	168	2	138.99265	-79.36933
H15	169	1	128.94839	-85.80597
H15	170	2	143.88756	-74.83410

H15	171	2	137.94000	-75.33282
H15	172	2	150.61248	-75.25452
H15	173	4	146.04205	-73.88403
H15	174	1	152.49966	-78.75853
H15	175	1	148.02703	-77.26064
H15	176	2	145.77434	-72.36001
H15	177	2	150.45383	-71.07266
H15	178	1	134.95765	-71.62543
H15	179	2	136.22086	-73.30981
H15	180	4	124.52566	-74.50183
H15	181	1	117.04049	-70.22021
H15	182	1	119.67782	-73.85855
H15	183	1	130.12336	-71.80071
H15	184	1	123.84623	-76.09018
H15	185	1	129.72134	-77.12391
H15	186	2	129.11168	-79.31522
H15	187	3	124.19522	-79.01119
H15	188	2	118.04789	-79.05851
H15	189	1	113.71968	-77.27140
H15	190	3	108.16709	-77.63809
H15	191	3	109.01043	-76.68580
H15	192	1	103.74576	-78.81082
H15	193	1	133.77991	-79.18101
H15	194	2	99.18481	-81.04639
H15	195	2	77.69161	-81.75736
H15	196	2	90.91980	-83.48750
H15	197	1	79.11146	-84.46274
H15	198	1	82.67238	-80.99556
H15	199	2	69.29830	-87.53321
H15	200	2	90.74453	-85.84358
H15	201	2	68.37131	-82.32767
H15	202	2	77.36874	-80.84966
H15	203	2	61.97461	-85.43630
H15	204	1	81.67295	-83.36894
H15	205	1	65.58954	-85.14365
H15	206	1	104.39344	-71.13735
H15	207	2	96.92379	-72.55403
H15	208	2	100.49365	-73.60071
H15	209	2	105.10605	-74.49116
H15	210	2	105.09385	-76.12586
H15	211	2	97.76623	-75.34767
H15	212	1	99.57061	-72.95080
H15	213	1	91.85777	-73.57236

H15	214	3	86.87477	-76.16074
H15	215	1	83.96119	-76.29598
H15	216	1	81.84884	-75.33146
H15	217	4	77.32762	-75.18727
H15	218	1	69.80218	-72.94891
H15	219	1	75.13813	-75.74444
H15	220	2	67.37216	-70.96973
H15	221	2	74.08075	-77.81278
H15	222	1	83.58864	-78.19682
H15	223	1	88.55711	-78.50059
H15	224	1	84.51425	-79.93430
H15	225	1	96.32816	-78.34282
H15	226	2	98.07924	-79.43475
H15	227	1	85.20562	-79.50335
H15	228	1	92.43937	-79.81786
H15	229	1	95.78948	-80.45335
H15	230	2	69.96934	-81.53953
H15	231	1	35.31389	-85.91166
H15	232	1	56.52865	-79.98604
H15	233	1	56.38118	-80.61186
H15	234	1	63.62814	-81.79514
H15	235	1	70.87887	-80.88981
H15	236	3	41.92334	-82.66963
H15	237	1	19.95974	-82.51199
H15	238	1	15.76591	-83.07225
H15	239	1	13.53529	-85.73221
H15	240	1	6.91934	-81.46195
H15	241	1	24.41911	-86.40464
H15	242	1	1.21582	-81.99348
H15	243	2	-17.52178	-88.12526
H15	244	2	-10.56685	-85.49068
H15	245	1	-31.29776	-86.22731
H15	246	1	-18.43102	-85.10179
H15	247	2	-5.56069	-72.72399
H15	248	2	7.41130	-71.35920
H15	249	4	0.72707	-69.75226
H15	250	2	-0.24606	-71.61208
H15	251	2	-0.87360	-71.87034
H15	252	1	-1.26969	-71.00878
H15	253	2	-0.48272	-73.69991
H15	254	1	10.92842	-73.38303
H15	255	1	14.20850	-74.32869
H15	256	1	14.65390	-75.08887

H15	257	2	11.02238	-75.68861
H15	258	1	-0.32684	-75.78663
H15	259	1	14.99166	-77.07602
H15	260	1	19.03940	-76.69957
H15	261	2	18.95513	-75.87920
H15	262	2	-9.90162	-73.10632
H15	263	2	8.74247	-76.67704
H15	264	1	-9.00681	-74.53836
H15	265	1	-8.62153	-75.83649
H15	266	3	16.02086	-71.78168
H15	267	3	19.49560	-72.82567
H15	268	2	25.34425	-70.64085
H15	269	2	30.11807	-72.77847
H15	270	2	31.72107	-74.88916
H15	271	1	40.11782	-75.78158
H15	272	4	47.92688	-71.98574
H15	273	2	60.06971	-72.14729
H15	274	3	23.17588	-75.87084
H15	275	1	38.68489	-71.79680
H15	276	1	34.46907	-72.98436
H15	277	1	44.63215	-73.97630
H15	278	1	-12.60022	-79.24886
H15	279	3	5.34416	-79.26825
H15	280	1	17.85141	-78.54863
H15	281	2	22.60903	-78.90596
H15	282	3	28.27615	-77.98745
H15	283	2	33.53150	-79.90873
H15	284	1	16.34526	-79.43981
H15	285	1	11.07860	-80.38661
H15	286	1	59.62779	-70.31397
H15	287	2	54.43485	-75.45848
H15	288	1	57.77941	-76.44466
H15	289	2	59.65902	-77.49212
H15	290	1	50.20209	-74.17332
H15	291	1	59.65720	-73.33757
H15	292	2	45.20561	-78.13453
H15	293	2	-147.05246	-76.95379
H15	294	4	-136.30311	-77.86571
H15	295	2	-127.41034	-76.56719
H15	296	1	-127.34124	-75.69324
H15	297	2	-130.52498	-75.58179
H15	298	2	-127.34360	-73.66903
H15	299	1	-117.55380	-78.30838

H15	300	1	-118.66744	-73.94353
H15	301	2	-131.09834	-71.55153
H15	302	2	-127.17719	-72.79625
H15	303	2	-134.01273	-72.02513
H15	304	1	-128.93882	-70.49210
H15	305	1	-136.46944	-72.38182
H15	306	2	-140.00112	-72.75458
H15	307	5	-144.57325	-72.12379
H15	308	1	-143.90173	-70.98826
H15	309	3	-154.30361	-73.99332
H15	310	1	-165.22598	-70.73718
H15	311	1	-157.50631	-71.73707
H15	312	1	-151.17971	-70.65048
H15	313	2	-113.66141	-72.82503
H15	314	1	-104.63004	-73.27975
H15	315	1	-113.12068	-71.43385
H15	316	1	-112.98070	-73.57121
H15	317	1	-101.27706	-72.11104
H15	318	1	-93.15381	-73.74841
H15	319	1	-86.01628	-71.53230
H15	320	2	-89.46429	-74.62772
H15	321	1	-90.15505	-75.59384
H15	322	1	-83.70688	-72.41486
H15	323	1	-78.04414	-72.85470
H15	324	1	-75.87353	-68.89699
H15	325	1	-70.60917	-72.67705
H15	326	3	-65.84371	-71.06946
H15	327	2	-70.51145	-70.71836
H15	328	1	-68.80873	-72.79646
H15	329	2	-67.81032	-73.40014
H15	330	1	-59.70154	-73.08634
H15	331	2	-58.16487	-74.16384
H15	332	2	-64.61134	-76.73247
H15	333	1	-79.37980	-75.68787
H15	334	2	-75.98307	-75.53902
H15	335	1	-76.79610	-77.60833
H15	336	1	-60.03003	-74.97260
H15	337	3	-69.67623	-77.24084
H15	338	1	-85.36330	-78.33871
H15	339	2	-75.14067	-79.28348
H15	340	2	-58.35888	-75.46034
H15	341	2	-59.89019	-79.54258
H15	342	1	-61.33776	-78.02713

H15	343	1	-72.11437	-80.06074
H15	344	1	-51.13295	-75.60018
H15	345	2	-45.22646	-75.58556
H15	346	1	-45.33675	-74.22982
H15	347	3	-43.17245	-76.71575
H15	348	1	-46.66311	-78.51014
H15	349	1	-39.67196	-78.46881
H15	350	1	-24.59775	-76.25388
H15	351	2	-28.14963	-75.54704
H15	352	2	-24.54235	-74.34579
H15	353	1	-22.22491	-73.96401
H15	354	2	-28.01637	-73.29469
H15	355	1	-31.13181	-73.97276
H15	356	2	-38.66588	-73.72811
H15	357	2	-25.60660	-71.62300
H15	358	1	-24.29482	-71.70610
H15	359	1	-33.85505	-72.87546
H15	360	2	-35.89535	-71.72065
H15	361	2	-37.74843	-72.20996
H15	362	1	-21.55920	-71.27321
H15	363	1	-33.31219	-69.99461
H15	364	2	-45.68324	-71.76760
H15	365	2	-49.06157	-72.64306
H15	366	2	-49.49131	-71.82496
H15	367	1	-50.97408	-71.31595
H15	368	3	-50.74762	-80.04927
H15	369	3	-16.83263	-82.67910
H15	370	2	-24.55043	-77.65019
H15	371	1	-38.17760	-79.84803
H15	372	1	-49.66617	-81.76386
H15	373	1	-6.70153	-81.89749
H15	374	1	-56.12651	-81.26138
H15	375	1	-63.07754	-82.26778
H15	376	2	-72.91284	-83.03153
H15	377	2	-66.52935	-84.37603
H15	378	2	-51.98307	-85.76534
H15	379	2	-79.58814	-84.52167
H15	380	2	-92.40219	-85.50339
H15	381	3	-77.44775	-86.86484
H15	382	2	-97.56885	-83.14852
H15	383	1	-88.26297	-85.98759
H15	384	2	-84.06504	-81.61802
H15	385	1	-61.43837	-87.31409

H15	386	3	-118.39875	-81.48308
H15	387	1	-105.09095	-84.40671
H15	388	3	71.35518	-88.97461
H15	389	3	-132.79551	-81.72265
H15	390	3	-149.14039	-79.49410
H15	391	1	-123.88351	-79.99247
H15	392	2	-154.85880	-77.96239
H15	393	1	-158.29377	-79.79934
H15	394	2	-113.16811	-80.09198
H15	395	2	-160.67105	-77.20693
H15	396	1	-162.55047	-79.24901
H15	397	2	-106.43127	-77.72381
H15	398	2	-92.49746	-77.55327
H15	399	1	-100.84746	-76.91110
H15	400	1	-97.50302	-79.25145

APPENDIX B

B1 – R Code to Analyze Rim Segments in 30° by 30° bins

```
# Adding necessary libraries
library(writexl)
library(boot)
library(MASS)
library(CircStats)
library(circular)
# Importing the data file of the all rim segments of Mercury.
mercurycraters <- read.table(file = "Quad_All.txt", sep = ";",
header=TRUE)
# Extracting the straight rim segments (segments longer than 10 km).
mercury_Craters <- mercurycraters[mercurycraters$Sph_Len>10000, ]
# Reducing data variance of azimuth between 0 to 180.
mercury_Craters$End_Az <- ifelse (mercury_Craters$End_Az>180,
mercury_Craters$End_Az - 180, mercury_Craters$End_Az)

# Define the list for the bins.
binList <- list()
# jj defines the total bin number.
jj = 0
# Group the bins in the interval of [-180,180] on the x axis with the
step size of 30.
for (xx in -5:6)
{
# Group the bins in the interval of [-90,90] on the y axis with the
step size of 30.
      for(yy in -2:3)
      {
            jj = jj + 1
            # Extract the bin inside related interval.
            tempBin <- mercury_Craters[mercury_Craters$Sph_Mid_X >
xx*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y >  yy*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]
            # Add the bin to the list.
            binList[[jj]] = tempBin

      }

}

# Save all the bins in individual excel files.
for (hh in 1:jj)
```

```
{
      tempFileName = paste('~/Desktop/ MercuryR/Straight Rim
Segments/Bins/', toString(hh), '.xlsx')

      #Use writexl package
      write_xlsx(binList[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jj)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every straight rim
segments(srs) in the related bin.
      for (rowIndex in 1:nrow(binList[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binList[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] = binList[[binIndex]][rowIndex,
endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] = binList[[binIndex]][rowIndex,
endAzCol] + 180
            }
      }

      # Draw and save the rose diagram.
      # Transforming data into circular form.
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rose750.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 3.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "Weighted"))
      dev.off()

}
```

B2 – R Code to Analyze Rim Segments in Longitudinal and Latitudinal Bands of Bins

```
# Adding necessary libraries
library(writexl)
library(boot)
library(MASS)
library(CircStats)
library(circular)
# Importing the data file of the all rim segments of Mercury.
mercurycraters <- read.table(file = "Quad_All.txt", sep = ";",
header=TRUE)
# Extracting the straight rim segments (segments longer than 10 km).
mercury_Craters <- mercurycraters[mercurycraters$Sph_Len>10000, ]
# Reducing data variance of azimuth between 0 to 180.
mercury_Craters$End_Az <- ifelse (mercury_Craters$End_Az>180,
mercury_Craters$End_Az - 180, mercury_Craters$End_Az)
# Define the list for the longitudinal bins.
binListLong <- list()
# jj defines the total bin number for longitude.
jjLong = 0
# Group the bins in the interval of [-180,180] on the x axis with the
step size of 30.
for (xx in -5:6)
{
      jjLong = jjLong + 1
      # Extract the bin inside related interval.
      tempBin <- mercury_Craters[mercury_Craters$Sph_Mid_X > xx*30 -
30, ]
      tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]

      # Add the bin to the list.
      binListLong[[jjLong]] = tempBin
}

# Define the list for the latitudinal bins.
binListLat <- list()
# jj defines the total bin number for latitude.
jjLat = 0
# Group the bins in the interval of [-90,90] on the y axis with the
step size of 30.
for (yy in -2:3)
{
      jjLat = jjLat + 1
      # Extract the bin inside related interval.
      tempBin <- mercury_Craters[mercury_Craters$Sph_Mid_Y >  yy*30 -
30, ]
      tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]

      # Add the bin to the list.
      binListLat[[jjLat]] = tempBin
```

```
}

# Save all the bins in individual excel files for longitudes
for (hh in 1:jjLong)
{
	tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Longitude Bins/', toString(hh), '_Long.xlsx')

	#Use writexl package
	write_xlsx(binListLong[[hh]], tempFileName)
}

# Save all the bins in individual excel files for latitudes.
for (hh in 1:jjLat)
{
	tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Latitude Bins/', toString(hh), '_Lat.xlsx')

	#Use writexl package
	write_xlsx(binListLat[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth for longitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLong)
{

	azimuthVector <- c()
	counter = 0
	# Add the azimuth value (and +180) of every srs in the related
bin.
	for (rowIndex in 1:nrow(binListLong[[binIndex]]))
	{
		print(rowIndex)
		# Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
		for (lenIndex in 1:binListLong[[binIndex]][rowIndex,
sphLenCol])
		{
			counter = counter + 1
			azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol]
			counter = counter + 1
			azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol] + 180
		}
	}

	# Draw and save the rose diagram for longitudinal bands.
	# Transforming data into circular form.
```

```
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLong.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 3.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLong"))
      dev.off()

}

# Define the column numbers for length and azimuth for latitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLat)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLat[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binListLat[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol] + 180
            }
      }
      # Draw and save the rose diagram for latitudinal bands.
      # Transforming data into circular form.
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLat.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 3.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLat"))
      dev.off()

}
```

B3 – R Code to Analyze Rim Segments of Different Degradation Subgroups in 30° by 30° bins

```
# Adding necessary libraries
library(writexl)
library(boot)
library(MASS)
library(CircStats)
library(circular)
# Importing the data file of the all rim segments of Mercury.
mercurycraters <- read.table(file = "Quad_All.txt", sep = ";",
header=TRUE)
# Extracting the straight rim segments (segments longer than 10 km).
mercury_Craters <- mercurycraters[mercurycraters$Sph_Len>10000, ]
# Reducing data variance of azimuth between 0 to 180.
mercury_Craters$End_Az <- ifelse (mercury_Craters$End_Az>180,
mercury_Craters$End_Az - 180, mercury_Craters$End_Az)
# Getting the data in which CRATER_CLASS is 1 and 2.
deg1 <- mercury_Craters[mercury_Craters$CRATER_CLA==1 |
mercury_Craters$CRATER_CLA==2, ]
# Getting the data in which CRATER_CLASS is 3.
deg2 <- mercury_Craters[mercury_Craters$CRATER_CLA==3, ]
# Getting the data in which CRATER_CLASS is 4 and 5.
deg3 <- mercury_Craters[mercury_Craters$CRATER_CLA==4 |
mercury_Craters$CRATER_CLA==5, ]

###############  FOR DEGRADATION SUBGROUP 1  ###############
# Define the list for the bins.
binList <- list()
# jj defines the total bin number.
jj = 0
# Group the bins in the interval of [-180,180] on the x axis with the
step size of 30.
for (xx in -5:6)
{
# Group the bins in the interval of [-90,90] on the y axis with the
step size of 30.
      for(yy in -2:3)
      {
            jj = jj + 1
            # Extract the bin inside related interval.
            tempBin <- deg1[deg1$Sph_Mid_X > xx*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y >  yy*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]
            # Add the bin to the list.
            binList[[jj]] = tempBin

      }

}
# Save all the bins in individual excel files.
```

```
for (hh in 1:jj)
{
      tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Bins/Deg1/', toString(hh), '.xlsx')

      #Use writexl package
      write_xlsx(binList[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jj)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binList[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binList[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] = binList[[binIndex]][rowIndex,
endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] = binList[[binIndex]][rowIndex,
endAzCol] + 180
            }
      }
      # Draw and save the rose diagram.
      # Transforming data into circular form.
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_roseDeg1.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 3.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "Weighted Deg1"))
      dev.off()

}

###############  FOR DEGRADATION SUBGROUP 2  ###############
# Define the list for the bins.
binList <- list()
```

```
# jj defines the total bin number.
jj = 0
# Group the bins in the interval of [-180,180] on the x axis with the
step size of 30.
for (xx in -5:6)
{
# Group the bins in the interval of [-90,90] on the y axis with the
step size of 30.
      for(yy in -2:3)
      {
            jj = jj + 1
            # Extract the bin inside related interval.
            tempBin <- deg2[deg2$Sph_Mid_X > xx*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y >  yy*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]
            # Add the bin to the list.
            binList[[jj]] = tempBin

      }

}
# Save all the bins in individual excel files.
for (hh in 1:jj)
{
      tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Bins/Deg2/', toString(hh), '.xlsx')

      #Use writexl package
      write_xlsx(binList[[hh]], tempFileName)
}


# Define the column numbers for length and azimuth.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jj)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binList[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binList[[binIndex]][rowIndex,
sphLenCol])
            {
```

```
                counter = counter + 1
                azimuthVector[counter] = binList[[binIndex]][rowIndex, 
endAzCol]
                counter = counter + 1
                azimuthVector[counter] = binList[[binIndex]][rowIndex, 
endAzCol] + 180
            }
        }
        # Draw and save the rose diagram.
        # Transforming data into circular form.
        circAzimuth <- circular(azimuthVector, type="directions", 
units="degrees", template="geographics", rotation="clock")
        dev.new()
        pdf(file=paste(toString(binIndex),"_roseDeg2.pdf"))
        rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop 
= 2, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "Weighted Deg2"))
        dev.off()

}

###############  FOR DEGRADATION SUBGROUP 3  ###############
# Define the list for the bins.
binList <- list()

# jj defines the total bin number.
jj = 0
# Group the bins in the interval of [-180,180] on the x axis with the 
step size of 30.
for (xx in -5:6)
{
# Group the bins in the interval of [-90,90] on the y axis with the 
step size of 30.
        for(yy in -2:3)
        {
            jj = jj + 1
            # Extract the bin inside related interval.
            tempBin <- deg3[deg3$Sph_Mid_X > xx*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y >  yy*30 - 30, ]
            tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]
            # Add the bin to the list.
            binList[[jj]] = tempBin

        }

}
# Save all the bins in individual excel files.
for (hh in 1:jj)
{
        tempFileName = paste('~/Desktop/MercuryR/Straight Rim 
Segments/Bins/Deg3/', toString(hh), '.xlsx')
```

```
      #Use writexl package
      write_xlsx(binList[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jj)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binList[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binList[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] = binList[[binIndex]][rowIndex,
endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] = binList[[binIndex]][rowIndex,
endAzCol] + 180
            }
      }
      # Draw and save the rose diagram.
      # Transforming data into circular form.
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_roseDeg3.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 2, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "Weighted Deg3"))
      dev.off()

}
```

B2 – R Code to Analyze Rim Segments of Different Degradation Subgroups in Longitudinal and Latitudinal Bands of Bins

```
# Adding necessary libraries
library(writexl)
library(boot)
library(MASS)
library(CircStats)
library(circular)
# Importing the data file of the all rim segments of Mercury.
mercurycraters <- read.table(file = "Quad_All.txt", sep = ";",
header=TRUE)
# Extracting the straight rim segments (segments longer than 10 km).
mercury_Craters <- mercurycraters[mercurycraters$Sph_Len>10000, ]
# Reducing data variance of azimuth between 0 to 180.
mercury_Craters$End_Az <- ifelse (mercury_Craters$End_Az>180,
mercury_Craters$End_Az - 180, mercury_Craters$End_Az)
# Getting the data in which CRATER_CLASS is 1 and 2.
deg1 <- mercury_Craters[mercury_Craters$CRATER_CLA==1 |
mercury_Craters$CRATER_CLA==2, ]
# Getting the data in which CRATER_CLASS is 3.
deg2 <- mercury_Craters[mercury_Craters$CRATER_CLA==3, ]
# Getting the data in which CRATER_CLASS is 4 and 5.
deg3 <- mercury_Craters[mercury_Craters$CRATER_CLA==4 |
mercury_Craters$CRATER_CLA==5, ]

###############  FOR DEGRADATION SUBGROUP 1  ###############
# Define the list for the longitudinal bins.
binListLong <- list()

# jj defines the total bin number for longitude.
jjLong = 0
# Group the bins in the interval of [-180,180] on the x axis with the
step size of 30.
for (xx in -5:6)
{
      jjLong = jjLong + 1
      # Extract the bin inside related interval.
      tempBin <- deg1[deg1$Sph_Mid_X > xx*30 - 30, ]
      tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]

      # Add the bin to the list.
      binListLong[[jjLong]] = tempBin
}

# Define the list for the latitudinal bins.
binListLat <- list()
# jj defines the total bin number for latitude.
jjLat = 0
# Group the bins in the interval of [-90,90] on the y axis with the
step size of 30.
```

```
for (yy in -2:3)
{
      jjLat = jjLat + 1
      # Extract the bin inside related interval.
      tempBin <- deg1[deg1$Sph_Mid_Y >  yy*30 - 30, ]
      tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]

      # Add the bin to the list.
      binListLat[[jjLat]] = tempBin
}



# Save all the bins in individual excel files for longitudes
for (hh in 1:jjLong)
{
      tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Longitude Bins/Deg1/', toString(hh), '_Long.xlsx')

      #Use writexl package
      write_xlsx(binListLong[[hh]], tempFileName)
}

# Save all the bins in individual excel files for latitudes.
for (hh in 1:jjLat)
{
      tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Latitude Bins/Deg1/', toString(hh), '_Lat.xlsx')

      #Use writexl package
      write_xlsx(binListLat[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth for longitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLong)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLong[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binListLong[[binIndex]][rowIndex,
sphLenCol])
            {
```

```
                counter = counter + 1
                azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol]
                counter = counter + 1
                azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol] + 180
          }
      }
      # Draw and save the rose diagram for longitudinal bands.
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLong.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 2.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLong1"))
      dev.off()

}

# Define the column numbers for length and azimuth for latitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLat)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLat[[binIndex]]))
      {
          print(rowIndex)
          # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
          for (lenIndex in 1:binListLat[[binIndex]][rowIndex,
sphLenCol])
          {
                counter = counter + 1
                azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol]
                counter = counter + 1
                azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol] + 180
          }
      }
      # Draw and save the rose diagram for latitudinal bands.
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLat.pdf"))
```

```
	rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop = 2.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -0.1, main=paste(toString(binIndex), "WeightedLat1"))
	dev.off()

}

###############  FOR DEGRADATION SUBGROUP 2  ###############
# Define the list for the longitudinal bins.
binListLong <- list()

# jj defines the total bin number for longitude.
jjLong = 0
# Group the bins in the interval of [-180,180] on the x axis with the step size of 30.
for (xx in -5:6)
{
	jjLong = jjLong + 1
	# Extract the bin inside related interval.
	tempBin <- deg2[deg2$Sph_Mid_X > xx*30 - 30, ]
	tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]

	# Add the bin to the list.
	binListLong[[jjLong]] = tempBin
}

# Define the list for the latitudinal bins.
binListLat <- list()
# jj defines the total bin number for latitude.
jjLat = 0
# Group the bins in the interval of [-90,90] on the y axis with the step size of 30.
for (yy in -2:3)
{
	jjLat = jjLat + 1
	# Extract the bin inside related interval.
	tempBin <- deg2[deg2$Sph_Mid_Y >  yy*30 - 30, ]
	tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]

	# Add the bin to the list.
	binListLat[[jjLat]] = tempBin
}



# Save all the bins in individual excel files for longitudes
for (hh in 1:jjLong)
{
	tempFileName = paste('~/Desktop/MercuryR/Straight Rim Segments/Longitude Bins/Deg2/', toString(hh), '_Long.xlsx')

	#Use writexl package
```

```
      write_xlsx(binListLong[[hh]], tempFileName)
}

# Save all the bins in individual excel files for latitudes.
for (hh in 1:jjLat)
{
      tempFileName = paste('~/Desktop/Desktop - Işık MacBook
Pro/MercuryR/Straight Rim Segments/Latitude Bins/Deg2/', toString(hh),
'_Lat.xlsx')

      #Use writexl package
      write_xlsx(binListLat[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth for longitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLong)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLong[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binListLong[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol] + 180
            }
      }
      # Draw and save the rose diagram for longitudinal bands.
      setwd('~/Desktop/MercuryR/Straight Rim Segments/Weighted
Rose/Deg2 Rose/Long')
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLong.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 2.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLong2"))
      dev.off()
```

```
}

# Define the column numbers for length and azimuth for latitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLat)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLat[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binListLat[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol] + 180
            }
      }
      # Draw and save the rose diagram for latitudinal bands.
      setwd('~/Desktop/MercuryR/Straight Rim Segments/Weighted
Rose/Deg2 Rose/Lat')
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLat.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 2.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLat2"))
      dev.off()

}

###############  FOR DEGRADATION SUBGROUP 3  ###############
# Define the list for the longitudinal bins.
binListLong <- list()

# jj defines the total bin number for longitude.
jjLong = 0
# Group the bins in the interval of [-180,180] on the x axis with the
step size of 30.
```

```
for (xx in -5:6)
{
	jjLong = jjLong + 1
	# Extract the bin inside related interval.
	tempBin <- deg3[deg3$Sph_Mid_X > xx*30 - 30, ]
	tempBin <- tempBin[tempBin$Sph_Mid_X <= xx*30, ]

	# Add the bin to the list.
	binListLong[[jjLong]] = tempBin
}

# Define the list for the latitudinal bins.
binListLat <- list()
# jj defines the total bin number for latitude.
jjLat = 0
# Group the bins in the interval of [-90,90] on the y axis with the
step size of 30.
for (yy in -2:3)
{
	jjLat = jjLat + 1
	# Extract the bin inside related interval.
	tempBin <- deg3[deg3$Sph_Mid_Y >  yy*30 - 30, ]
	tempBin <- tempBin[tempBin$Sph_Mid_Y <= yy*30, ]

	# Add the bin to the list.
	binListLat[[jjLat]] = tempBin
}



# Save all the bins in individual excel files for longitudes
for (hh in 1:jjLong)
{
	tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Longitude Bins/Deg3/', toString(hh), '_Long.xlsx')

	#Use writexl package
	write_xlsx(binListLong[[hh]], tempFileName)
}

# Save all the bins in individual excel files for latitudes.
for (hh in 1:jjLat)
{
	tempFileName = paste('~/Desktop/MercuryR/Straight Rim
Segments/Latitude Bins/Deg3/', toString(hh), '_Lat.xlsx')

	#Use writexl package
	write_xlsx(binListLat[[hh]], tempFileName)
}

# Define the column numbers for length and azimuth for longitudes.
sphLenCol = 11
```

```
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLong)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLong[[binIndex]]))
      {
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binListLong[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] =
binListLong[[binIndex]][rowIndex, endAzCol] + 180
            }
      }
      # Draw and save the rose diagrams for longitudinal bands.
      setwd('~/Desktop/MercuryR/Straight Rim Segments/Weighted
Rose/Deg3 Rose/Long')
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLong.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 2.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLong3"))
      dev.off()

}

# Define the column numbers for length and azimuth for latitudes.
sphLenCol = 11
endAzCol = 14
# For every bin in the list;
for (binIndex in 1:jjLat)
{

      azimuthVector <- c()
      counter = 0
      # Add the azimuth value (and +180) of every srs in the related
bin.
      for (rowIndex in 1:nrow(binListLat[[binIndex]]))
      {
```

```
            print(rowIndex)
            # Add the azimuth value (and +180) of every srs by the
number (meter) of its length.
            for (lenIndex in 1:binListLat[[binIndex]][rowIndex,
sphLenCol])
            {
                  counter = counter + 1
                  azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol]
                  counter = counter + 1
                  azimuthVector[counter] =
binListLat[[binIndex]][rowIndex, endAzCol] + 180
            }
      }
      # Draw and save the rose diagram latitudinal bands.
      setwd('~/Desktop/MercuryR/Straight Rim Segments/Weighted
Rose/Deg3 Rose/Lat')
      circAzimuth <- circular(azimuthVector, type="directions",
units="degrees", template="geographics", rotation="clock")
      dev.new()
      pdf(file=paste(toString(binIndex),"_rosediagramLat.pdf"))
      rose.diag(circAzimuth, pch=16, cex=1, axes=TRUE, shrink = 1, prop
= 2.5, bins=36, upper=TRUE, ticks=TRUE, units="degrees", tcl.text = -
0.1, main=paste(toString(binIndex), "WeightedLat3"))
      dev.off()

}
```