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Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1016/j.icarus.2017.01.005>

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1 **Late movement of basin-edge lobate scarps on Mercury**

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10 Keywords: Planetary; geology; Mercury; tectonics; model ages; lobate scarps; planetary volcanism.

11 **ABSTRACT**

12 Basin-edge lobate scarps are a sub-type of tectonic shortening structure on the surface of
13 Mercury that have formed at the edge of volcanic units that fill or partly fill impact basins.
14 We have performed a global survey of these features and find that they are widespread in
15 basins across the planet. We obtained model ages from crater size–frequency distribution
16 analysis for a subset of our surveyed basins, for both the smooth plains infill and for the last
17 resolvable tectonic activity on the associated basin-edge scarps. Our results indicate that
18 some of these lobate scarps were still accumulating strain in the late Mansurian
19 (approximately 1 Ga). From a photogeological assessment, we find that the orientations of
20 these basin-edge lobate scarps are similar to those reported for the global population of
21 lobate scarps in earlier studies, appearing to align ~north–south at low latitudes and ~east–
22 west at higher latitudes. However, reassessing these landforms’ orientation with artificially
23 illuminated topographic data does not allow us to rule out the effect of illumination bias.
24 We propose that these landforms, the result of crustal shortening in response to global
25 contraction, formed along the interface between the basin floor and the smooth plains unit,
26 which acted as a mechanical discontinuity along which shortening strains were
27 concentrated.

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33 **1. INTRODUCTION**

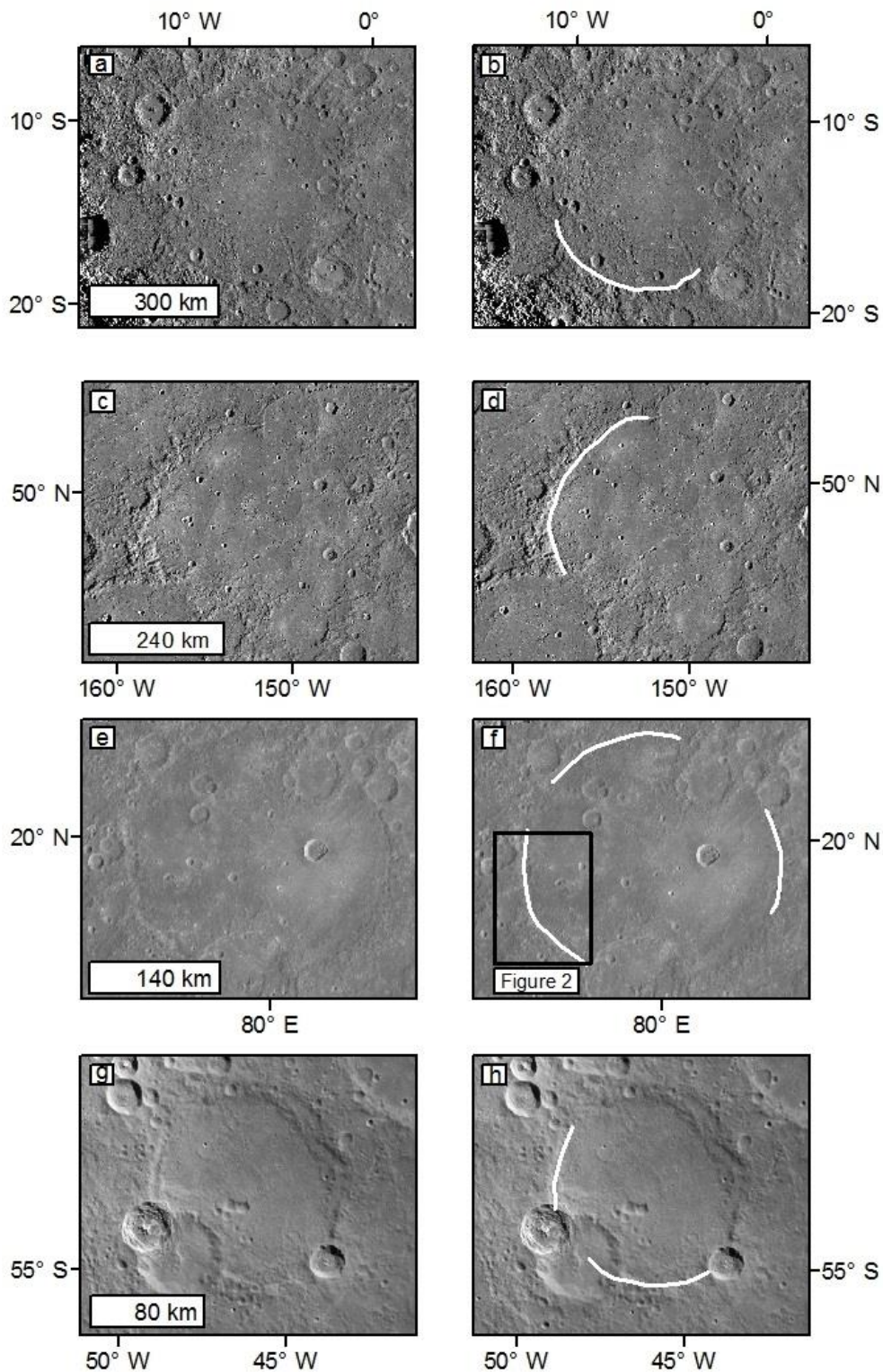
34 Data from the MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry, and
35 Ranging) mission flybys and orbital operations have confirmed that tectonic landforms, and
36 shortening structures in particular, are widespread on Mercury's surface (Byrne *et al.*, 2014).
37 Among the most frequently observed features are lobate scarps: curvilinear surface
38 deformations associated with thrust faults, with a steep front scarp and gently dipping back
39 scarp, and topographic relief of hundreds of metres to 1-3 km (Strom, Trask and Guest,
40 1975; Watters *et al.*, 2002; Solomon, 2011). The generally accepted formation mechanism
41 for the many shortening structures on Mercury, including lobate scarps, is that secular
42 interior cooling and attendant global contraction resulted in thrust faulting in the
43 lithosphere (Strom, Trask and Guest, 1975; Watters, 2004; Byrne *et al.*, 2014).

44 The distribution and orientation of Mercury's population of shortening structures were
45 detailed by Byrne *et al.* (2014). In this work we focus on a subset of lobate scarps found at
46 the edges of numerous impact basins (defined here as an impact crater >100 km in
47 diameter), and which can be hundreds of kilometres in length (Rothery and Massironi,
48 2013). The interiors of these basins are occupied by smooth plains deposits, which are
49 interpreted to be formed due to volcanic infilling; these plains have similar morphological
50 and spectral properties to those of the northern volcanic plains (Denevi *et al.*, 2013; Byrne
51 *et al.*, 2016). The majority of these basin-specific scarps (Byrne *et al.* 2014) are spatially
52 collocated with the edge of their corresponding basin. Four examples of this feature —
53 which we refer to in this study as “basin-edge scarps” —are illustrated in Figures 1 and 2; an
54 additional example associated with the impact basin Aneirin is shown in Figure 3. They share
55 the morphological features of lobate scarps described above, but follow the edge of the
56 volcanic infill. The vergence of the basin-edge scarps (the facing direction of the steep front
57 scarp, interpreted as the shorter of two limbs of an asymmetric anticline) is always away
58 from the centre of the basin.

59

60 Although these features bear a morphological similarity to the steep sides of thick, lobate
61 lava flows within these basins, we interpret these basin-edge scarps as tectonic in nature.

62 We take this view because basin-filling lavas generally onlap basin walls without discernible
63 relief, and because there are examples of impact craters in the basin fill that have been cut
64 by these scarps (shown in Section 5.2). Moreover, crater areal density measurements at
65 some sites show a resolvable difference in age between the basin fill and a corresponding
66 basin-edge scarp (see section 5.1).



67 *Figure 1: Examples of four basins in which the volcanic infill is part-bounded by one or more lobate*
 68 *scarps. Figure 1 (a) and (b): Sanai (490 km diameter); (c) and (d): Shakespeare (399 km diameter); (e)*
 69 *and (f): Hafiz (280 km diameter); (g) and (h): Shevchenko (143 km diameter).*
 70 *White lines on (b), (d), (f) and (h) delineate resolvable lobate scarps where basin-fill is thrust towards*
 71 *or over the basin rim. The black rectangle on (f) denotes the area shown in greater detail in Figure 2.*

72 Images are from the MESSENGER MDIS global monochrome base map, which has a resolution of 250
73 m/px (available: http://messenger.jhuapl.edu/the_mission/mosaics.html).

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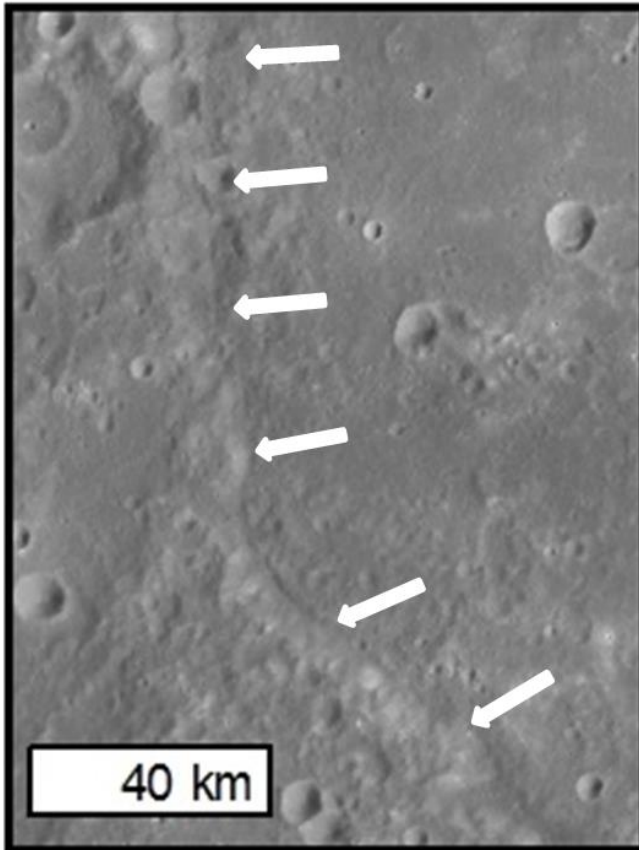
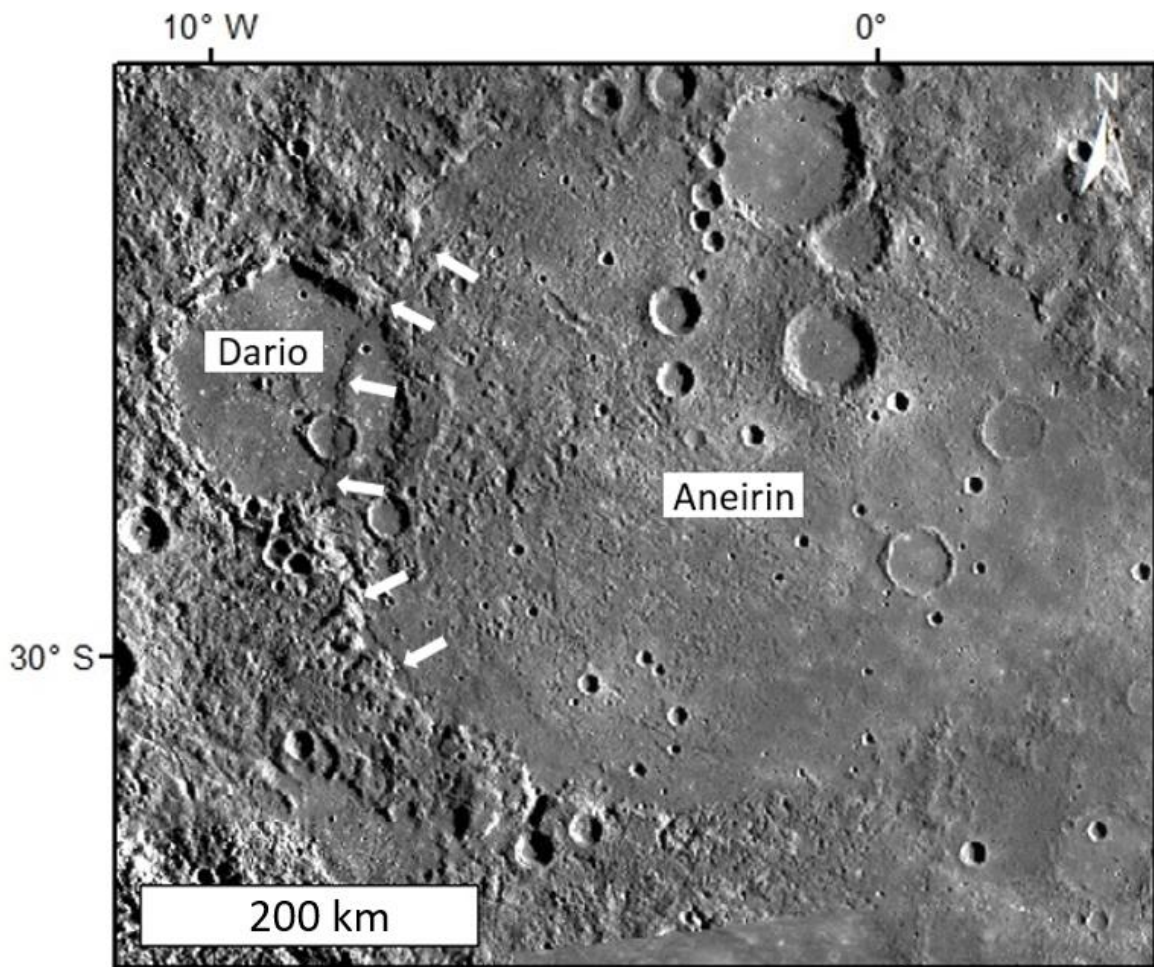


Figure 2: A closer view of a section of the basin-edge scarp of Hafiz basin (as outlined by the back rectangle in Figure 1(f)). The white arrows indicate the basin-edge lobate scarp, and the approximate vergence (i.e. direction of tectonic displacement of the hanging wall).

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90

91 We conducted a global survey to document the occurrence of scarps at the edges of basin
92 fills. We investigate the distribution of this type of scarp with photogeological mapping, and
93 of both the relative and absolute timing of volcanic infill and scarp formation, using crater
94 size–frequency distribution measurements.



95

96 *Figure 3: Aneirin basin, and associated basin-edge scarp (indicated by white arrows, which also*
97 *indicate approximate vergence). The basin-edge scarp of Aneirin cuts through the rim and volcanic*
98 *infill of the neighbouring younger basin Dario as well as through a still later, unnamed crater inside*
99 *Dario. Two “ghost craters” can be seen in the east of the smooth plains unit of Aneirin.*

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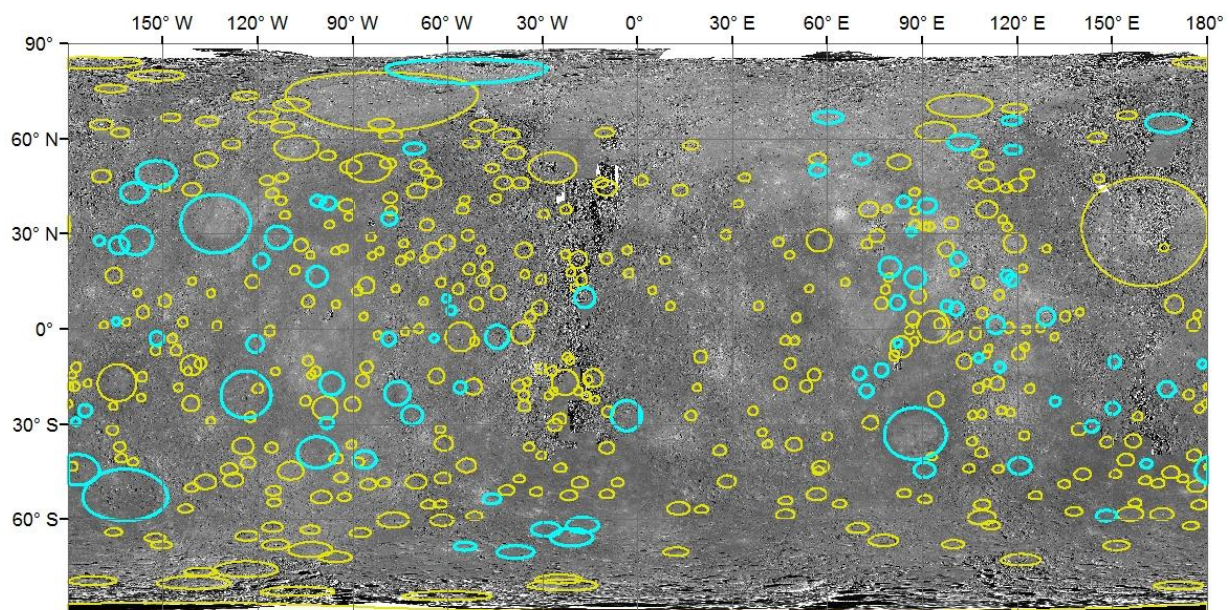
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107 **2. GLOBAL OCCURENCE OF BASIN-EDGE LOBATE SCARPS**

108 To investigate how common basin-edge scarps are on Mercury, we carried out a global
109 survey with the MESSENGER Dual Imaging Systems (MDIS) (Hawkins *et al.*, 2007) global
110 mosaic (average resolution 250m/pixel). We used the Fassett *et al.* 2012 database of basins
111 >100 km in diameter, adding basins not included in that study. We then identified all
112 discernible basin-edge lobate scarps within that aggregate population of >100 km diameter
113 basins. Visual examination of each basin in a global database of basins based upon the
114 database of Figure 4 shows the global database of basins examined in this study, all of which
115 have been volcanically filled, and distinguishes those that show evidence for lobate scarps
116 along at least part of the margin of their fill from those that do not. Our survey indicates
117 that basins without basin-edge lobate scarps, have comparable diameters to, and are found
118 in proximity with, those where such scarps are present, indicating that factors other than
119 basin-location and basin-size are involved.

120



121

122 *Figure 4: Our photogeological survey results. Basins outlined in yellow have no identifiable lobate*
123 *scarps at the periphery of their volcanic fills, whereas those outlined in blue have a lobate scarp on*
124 *some part of the margins of their fill.*

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128 4.0 ORIENTATION AND FACING DIRECTIONS

129 Analysis of shortening structures on Mercury can provide and insight into the global
130 processes responsible for their formation (e.g. Strom et al. 1975, Melosh and McKinnon,
131 1988, Watters et al., 2009, Byrne et al., 2014). One process proposed to have influenced the
132 tectonic evolution of Mercury is tidal despinning; under this scenario, the decrease in
133 rotation period, leads to the relaxation of an equatorial tidal bulge (Melosh & Dzurisin
134 1978; Melosh & McKinnon 1988; Dombard & Hauck 2008; Watters et al. 2015). Despinning
135 has been predicted to form a diagnostic pattern of tectonic features: preferential north–
136 south alignments of shortening structures at low latitudes, and east–west orientations of
137 normal faults at high latitudes (Melosh & McKinnon 1988; Dombard & Hauck 2008; Beuthe
138 2010).

139

140 However, should despinning have operated in combination with global contraction due to
141 secular cooling, which is known to have been extensive on Mercury (Byrne *et al.*, 2014),
142 models have suggested either that north–south aligned thrust faults would be the dominant
143 tectonic structure present (Pechmann and Melosh, 1979; Beuthe, 2010). Alternatively,
144 models that employ a more realistic value for rock strength indicate that north–south-
145 aligned thrust faults would dominantly form at low latitudes with thrust faults with no
146 preferred orientation would preferentially form at higher latitudes (Klimczak, Byrne and
147 Solomon, 2015).

148

149 Previous efforts to investigate whether Mercury’s lobate scarps display any preferential
150 trend in orientation (e.g., Watters et al. 2009; Di Achille et al. 2012; Byrne et al. 2014)
151 yielded inconclusive results on account of unvarying illumination geometry on the surface
152 resulting in observational bias (Cordell and Strom, 1977). However, Watters et al. (2015)
153 claimed to have identified a definitive orientation preference of structures independent of
154 illumination conditions, with ~north–south orientations (either west- or east-facing) for
155 shortening structures at low latitudes, and ~east–west orientations (either north- or south-
156 facing) at higher latitudes. These results imply that a combination of despinning and global
157 contraction continued until well after the end of the late heavy bombardment of Mercury
158 (Watters *et al.*, 2015), which is thought to have ended by around 3.6–3.9 Ga (Marchi et al.

159 2013).

160

161 Both the orientations and facing direction of the basin-edge lobate scarps we surveyed in
162 this work are shown in Figures 5–7. The data plotted are the frequency of occurrence of
163 lobate scarps per 1° segment of basin circumference (where 0°, i.e., due north, is indicated
164 by a black arrow). For example, Figure 5 indicates a preference for ~east- and ~west-facing
165 directions, and thus a preponderance of ~north–south strikes, for the lobate scarps in our
166 global survey, and in particular a preference for west-facing over east-facing scarps. Note
167 that although this method allows both scarp orientation and facing direction to be
168 displayed, it does not indicate the length of each constituent scarp; for example, scarps that
169 subtend 45° of arc along the circumference of a 100 km-diameter basin and of a 500 km-
170 diameter basin would have necessarily different lengths, but would contribute equally to a
171 plot of this nature.

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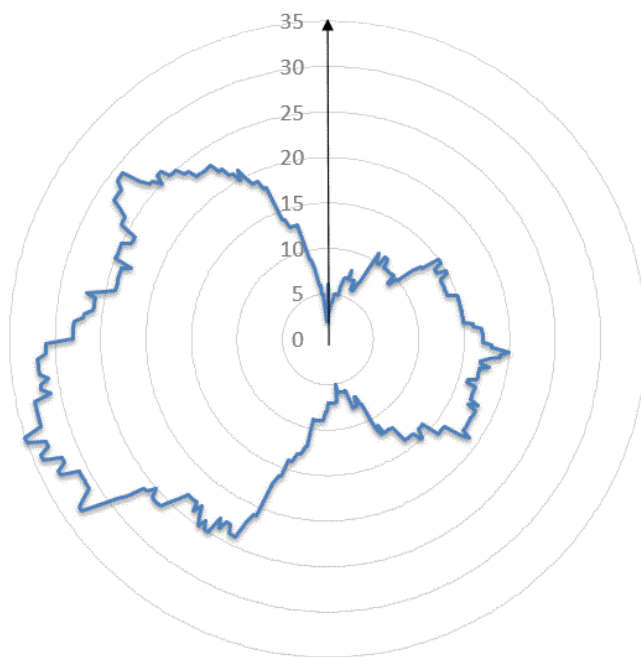


Figure 5: A radial plot displaying the facing directions of the global population of basin-edge scarps (n = 142). The black arrow denotes north; the radial axis indicates frequency of lobate scarp facing direction occurrence (per degree of bearing). This plot indicates a north–south alignment of scarps, which are more commonly west-facing than east-facing.

186

187

188 To test whether or not our results are subject to the same illumination bias suspected in
189 earlier studies, we resurveyed those basin-edge scarps present on shaded-relief models of
190 selected portions of Mercury’s surface created from digital terrain models (DTMs). Preusker
191 et al. (2011) produced these DTMs with stereo images from MESSENGER’s flybys of

192 Mercury, and we created shaded-relief models with artificial lighting directions (method as
193 referred to in the supplementary material of Watters et al (2015)). Briefly, we used the
194 Hillshade tool in the Spatial Analyst Toolbox of ArcGIS 10.1 to create two hillshade models
195 with illumination azimuths of 090° and 000°, respectively. The hillshade model with the
196 illumination azimuth of 090° is approximately similar to that of the global monochrome
197 mosaic we carried out our survey on (Section 2), while the illumination azimuth of 000° is
198 perpendicular to the natural illumination in that mosaic (and in all low-Sun images except at
199 polar latitudes).

200

201 We found that the preferential orientation results from the radial plots with artificial
202 illumination differed from the results shown in Figure 5. Two examples are shown in Figures
203 6 and 7 which also show that changing the illumination azimuth resulted in a change of
204 observed preference for facing direction of our surveyed scarps.

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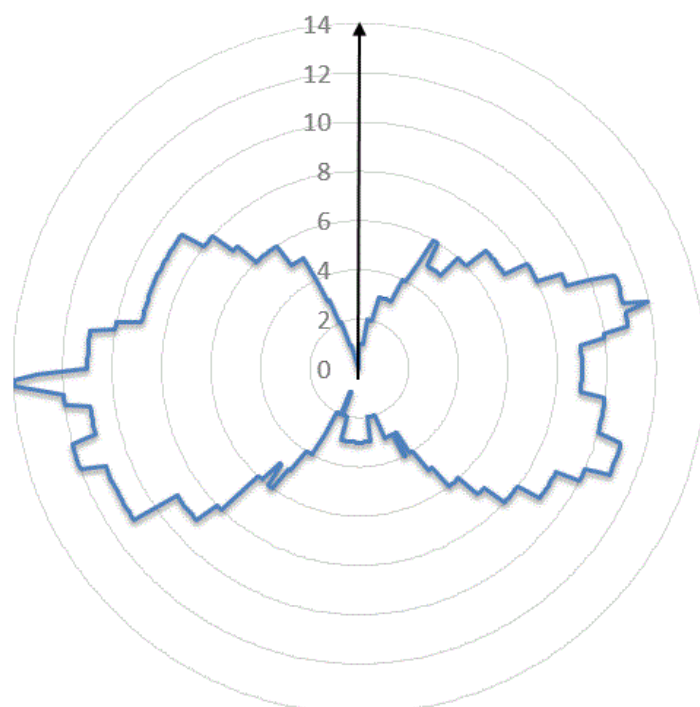
206 Because of this apparent dependence of scarp facing direction (and thus strike) on solar
207 illumination angle, we are unable to discount the influence of illumination geometry on our
208 global survey and scarp orientation results (Figure 5), despite the features involved being
209 several hundred km in length and being relatively easy to identify (as they are, by definition,
210 on the edge of impact basins). Thus, we cannot be certain that basin-edge lobate scarps are
211 preferentially oriented north–south on Mercury.

212

213

214 *Figure 6: Radial plot of facing*
215 *directions produced from hillshade*
216 *models artificially illuminated from*
217 *the east (n = 40). The scarps show*
218 *strong preferences for east- or*
219 *west-facing directions. Note that*
220 *the total frequency is lower than the*
221 *global plot (Figure 5) as the DTM we*
222 *used covers only a portion of the*
223 *surface.*

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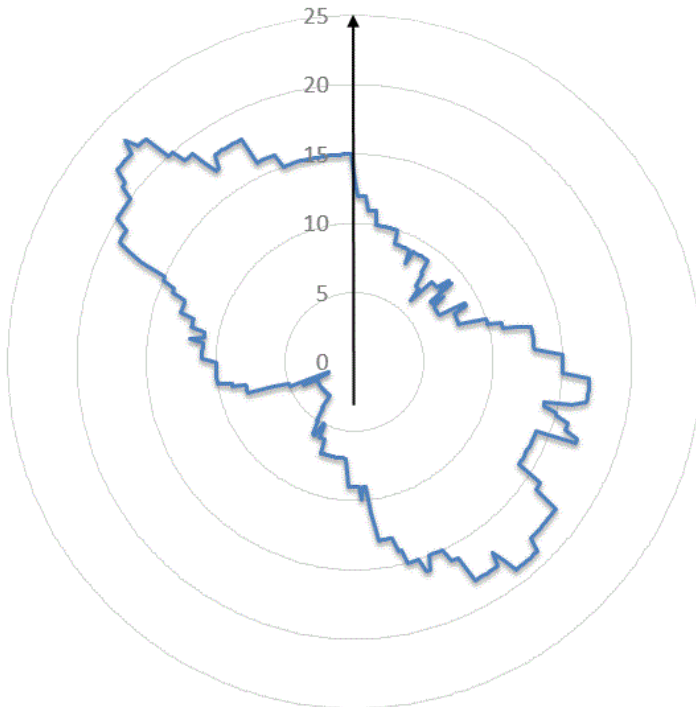


Figure 7: Radial plot of facing directions produced when hillshade model (as used for Figure 6) was artificially illuminated from the north ($n = 56$), yielding preferential scarp facing directions to the northwest and southeast.

241

242 That caveat aside, like Byrne et al. (2014) and Watters et al. (2015), we observe a preference
243 globally for ~north–south orientations of basin-edge lobate scarps (Figure 5), and specifically
244 ~north–south orientations at low latitudes and ~east–west orientations at high latitudes.
245 Byrne et al. (2014) examined the orientation of the global population of shortening
246 structures on Mercury and found them to have ~north–south orientations at low latitudes,
247 and a northeast–southwest trend at higher northern latitudes, but no preferred orientations
248 at high southern latitudes. Our observations agree with this first finding, but not the third
249 (we have not examined the variation of apparent trends with latitude in this study so are
250 unable to comment on the second finding). Klimczak et al. (2015) tested end-member
251 scenarios under which despinning ended prior to the onset of global contraction, or where
252 despinning was still operating when contraction began, and compared their model
253 predictions against the observations of Byrne et al. (2014). Klimczak et al. (2015) concluded,
254 as did Watters et al. (2015), that observational evidence supports a scenario under which
255 despinning was still underway when global contraction began.

256

257 **5.0 RELATIVE AND ABSOLUTE AGES**

258 **5.1 N NUMBERS AND MODEL CRATER RETENTION AGES**

259 To investigate the timing of smooth plains emplacement within basins, and the timing of
260 subsequent basin-edge lobate scarp formation, we conducted a size-frequency distribution
261 (SFD) analysis of a number of smooth plains surfaces both for basins with and without a
262 basin-edge lobate scarp. When identifying craters to produce SFDs for the surface of our
263 selected volcanic fills, we used the highest available resolution MDIS images (which have an
264 average resolution of 50 m/pixel) that cover the count areas. We processed the images with
265 USGS ISIS3 software before importing them into the ArcGIS environment. We determined
266 crater SFDs for these units with CraterTools (Kneissl, van Gasselt and Neukum, 2011) within
267 ArcGIS, digitising primary craters >1 km in diameter. Secondary craters (as identified by
268 clustering, chains and herringbone patterns) were excluded from the counts, although their
269 corresponding areas (accounting for between 0 and 1% of the count areas) were left in. We
270 do not believe removing these areas would have had any impact on our model ages,
271 particularly since we quote them to only two significant figures. The inclusion of craters as
272 small as 1 km in diameter makes it highly likely that secondary craters have been included,
273 despite our efforts to avoid them. However, without including craters down to 1 km in
274 diameter the SFD statistics would have been too unreliable (due to too few craters being
275 included in the counts) to draw any conclusions from.

276 We selected a subset of eight impact basins >100 km in diameter that have basin-edge
277 lobate scarps for our model age analysis. Note that these eight samples represent
278 approximately 10% of the total population of basin-edge scarps (n = 78), as identified in our
279 survey (see section 2). For comparison, we also determined SFDs for the volcanic fill of eight
280 basins >100 km in diameter that do not have basin-edge scarps. We did so to investigate
281 whether the smooth plains within basins with basin-edge scarps are, in general, older,
282 younger, or comparable in absolute age with the smooth plains within those basins that lack
283 such scarps.

284

285 To enable direct comparison between the relative ages of the smooth plains units in Table 2,
286 we calculated the cumulative number of craters equal to or greater than 10 km and 20 km in

287 diameter ($N(10)$ and $N(20)$ respectively) (Arvidson et al. 1979). The smaller the number of
288 superposed craters, the younger the surface is likely to be.

289

290

With basin-edge scarps						Without basin-edge scarps				
Name	Count Area km ²	N(10) (conf. int.)	N(20) (conf. int.)	Fill (conf. int.) Ga	Scarp (conf. int.) Ga	Name	Count Area km ²	N(10) (conf. int.)	N(20) (conf. int.)	Fill (conf. int.) Ga
Aneirin	7.5x10 ⁴	93 (±35)	27 (±19)	2.2 (±0.3)	0.6 (±0.1)	Mendelson	4.4x10 ⁴	45 (±32)	23 (±23)	1.8 (±0.2)
Beethoven	1.6x10 ⁴	88 (±23)	31 (±14)	3.5 (±0.1)	1.0 (±0.1)	Hugo	1.3x10 ³	155 (±109)	N/A	3.7 (±0.1)
Hafiz	2.1x10 ⁵	242 (±108)	97 (±69)	2.9 (±0.5)	<i>1.0 (±0.1)</i>	Khansa	4.6x10 ³	N/A	N/A	0.9 (±0.1)
Shakespeare	7.0x10 ⁴	72 (±32)	29 (±20)	2.9 (±0.1)	1.0 (±0.1)	Copland	2.4x10 ³	N/A	N/A	1.7 (±0.4)
Shevchenko	6.1x10 ³	N/A	N/A	1.5 (±0.2)	1.1 (±0.1)	Unnamed[166°S, 25°W]	4.0x10 ³	N/A	N/A	3.4 (±0.1)
Unnamed[40°S, 70°W]	7.5x10 ⁴	239 (±57)	76 (±32)	3.9 (±0.1)	1.1 (±0.1)	Unnamed[154°N, 67°E]	3.8x10 ³	261 (±261)	N/A	2.7 (±0.2)
Unnamed[91°N, 38°E]	1.8x10 ⁴	N/A	N/A	3.9 (±0.1)	1.1 (±0.1)	Unnamed[69°S, 0°E]	8.0x10 ³	126 (±126)	N/A	2.4 (±0.3)
Unnamed[150°N, 10°W]	1.4x10 ⁴	138 (±97)	N/A	3.0 (±0.3)	1.1 (±0.1)	Unnamed[13°S, 22°W]	4.2x10 ³	416 (±315)	N/A	2.6 (±0.4)

291 Table 2: Count areas and N(10) and N(20) numbers for a subset of basins with and without basin-edge scarps. Confidence intervals (conf. int.) are ± one standard deviation, derived as the square root of the number
292 of craters counted, divided by the area over which the count was made, per million square km. Basins where the crater SFD did not include any craters of diameter greater than 10 km or 20 km are indicated by N/A.
293 Columns titled 'Fill (conf. int.)' and 'Scarp (conf. int.)' list our model ages, produced using the Marchi production function (Marchi et al. 2009). Italics indicate poor fits to the data, in which cases the cratering age is
294 highly uncertain as the crater production function does not represent the shape of the cumulative SFD. The unnamed basins are distinguished by the coordinates of their centre points in decimal degrees.

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Denevi et al. (2013) published N(10) and N(20) values for the smooth plains within Beethoven basin, one of the basins we examine in this work. They obtained an N(10) value of 82 ± 19 and an N(20) value of 32 ± 12 for this unit; we obtained N(10) and N(20) values of 88 ± 23 and 31 ± 14 , respectively, for these smooth plains units, in good agreement with the Denevi et al. (2013) values.

Area	N(10) (error)	N(20) (error)
Intercrater plains ¹	217 (± 14)	94 (± 9)
Caloris interior plains ¹	80 (± 7)	26 (± 4)
Smooth plains south of Rachmaninoff ¹	58 (± 13)	17 (± 7)
Northern smooth plains (NSP) ²	51 (± 8) – 81 (± 9)	16 (± 5) – 30 (± 5)
Northern Heavily Catered Terrain (NHCT) ²	184 (± 14) – 256 (± 14)	74 (± 9) – 122 (± 14)

302 *Table 3: N(10) and N(20) values published by previous authors. References: ¹Denevi et al. (2013),*
303 *²Ostrach et al. (2015).*

304

305 N(10) and N(20) values cannot be used to estimate the last tectonic activity of basin-edge
306 scarps, because N values correspond to the aerial density of impact craters, and provide no
307 absolute age data. To compare the approximate timing of emplacement of the smooth
308 plains units with the age of cessation of resolvable activity on their associated basin-edge
309 scarp, we applied the model production function of Marchi et al. (2009), Massironi et al.
310 (2009), and Marchi et al. (2013) to the crater SFD and buffered SFD data.

311 To derive relative and absolute model ages on the lobate scarps, which are linear features
312 rather than surface units, we applied the buffered count method (Fassett and Head, 2008),
313 following the example of Giacomini et al. (2015) in applying it to tectonic features.

314 In this approach, craters that superpose the lobate scarp are counted, except those cut by a
315 clear trace of the scarp —for example, the ~20 km diameter unnamed crater inside Dario in

316 Figure 3 would not be included because the basin-edge scarp of Aneirin cuts straight across
317 it. For a subset of eight of the basin-edge lobate scarps we identified in the survey, we then
318 calculated the feature width (W) by measuring the distance between the base of the front
319 scarp and the base of the back slope (as identified by the break in slope, manifested in
320 image data as a change in shading). Since the lobate scarps also vary in width along their
321 length we took 20–30 measurements at regular intervals and used the mean of these as the
322 value for W for each scarp. For each crater, we measured the diameter (D) and created a
323 buffer around the scarp at a distance S_{Buffer} (using ArcGIS 10.1). The areas of these buffers
324 were then used in the crater statistics calculations, and were calculated as follows:

325

$$326 \quad S_{Buffer} = 1.5 D + 0.5 W \quad (1)$$

327

328 Since the buffered method was not initially designed to be used on tectonic features, the
329 following points should be borne in mind:

- 330 - The method includes craters that are not directly superposed onto the structure of
331 interest (although their ejecta is superposed onto the structure).
- 332 - Faults are frequently composed of segments on which discrete slip events can occur,
333 and so obtaining a single model age for the cessation of activity along the aggregate
334 structure is an oversimplification.
- 335 - The count areas involved in linear features (as described above) are necessarily
336 small, which can result in large errors from small-number statistics.

337 It is important to note that this buffered method provides an estimate for the age of
338 cessation of resolvable activity on the scarp. Due to likely fault reactivation, it is not possible
339 to use this method to determine the time at which faulting began.

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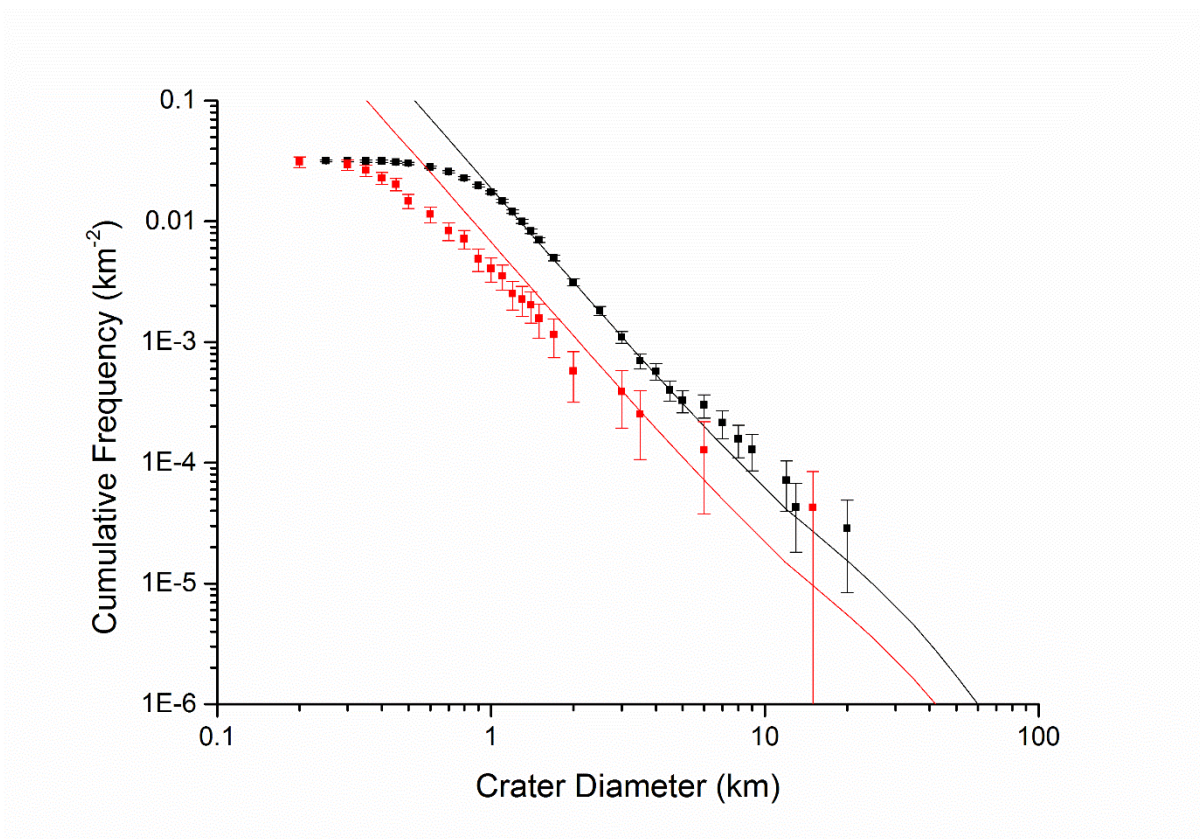
341 Marchi et al. (2013) defined the terms “hard rock” and “cohesive soil” to characterise two
342 end-member target properties, the choice of which changes the applicable production
343 function. Here, we followed the example of Giacomini et al. (2015) in regarding the former
344 term to mean unfractured rock and the latter to denote rock with reduced strength due to
345 fracturing. The Marchi et al. (2009) MPF also accommodated rheological layering of the

346 target material, if observations of the surface or crater SFD data support the possibility of
347 crustal layering (Marchi *et al.*, 2011; Ferrari *et al.*, 2015). To facilitate comparison between
348 data obtained for the basins in Table 2, we consistently applied the following parameters:
349 hard rock scaling (tensile strength: 2×10^8 dyne cm^{-2}) with no rheological layering and with
350 predominantly Near-Earth Object population of impactors.

351

352 Along with our areal crater density values, we present our model age results in Table 2;
353 plots for the volcanic infill of Shakespeare basin, and associated basin-edge scarp, using the
354 Marchi *et al.* (2009) MPF are shown in Figure 8. Plots for the other results in Table 2 are
355 given as supplementary material. The errors in Table 2 result from the process of fitting a
356 production function to the cumulative SFD data only and do not include methodological
357 errors involved in crater SFD analysis (such as those set out above).

358



359

360 *Figure 8: Marchi production function model age plots for the volcanic fill (black) and basin-edge scarp*
361 *(red) of Shakespeare.*

362 The absolute model ages derived by consistent application of the Marchi *et al.* (2009) MPF
363 (Table 2) for the volcanic infills in the basins of this study with basin-edge scarps suggest a

364 range of model ages for this last volcanic activity between 1.5 and 3.9 Ga. For the basins
365 without basin-edge scarps, we obtained absolute model ages ranging from 0.9 Ga to 3.7 Ga.
366 The sample size is small —eight basins with basin-edge scarps and eight basins without such
367 structures— but our data indicate a range of ages for smooth plains units, whether or not
368 they have basin-edge scarps. Our N(10) and N(20) values for Aneirin and Beethoven are the
369 same, within error, to values recently found by Byrne et al. (2016). Byrne et al. (2016)
370 derived an N(10) value for Aneirin of 72 ± 20 (our value: 93 ± 35), an N(20) value of 22 ± 11
371 (our value: 27 ± 19), and for Beethoven an N(10) value of 92 ± 22 (our value: 88 ± 23) and an
372 N(20) value of 31 ± 13 (our value: 31 ± 14). Our absolute model ages for the smooth plains
373 units of these two basins differ, however, from those of Byrne et al. (2016), who applied a
374 different MPF (that of Le Feuvre & Wieczorek (2011)) and obtained absolute model ages of
375 $\sim 3.7/3.8$ Ga for both smooth plains units using porous scaling. When they used non-porous
376 scaling, Byrne et al. (2016) obtained ages of ~ 2.2 Ga (Aneirin) and 2.7 Ga (Beethoven) which
377 are comparable to our absolute ages but the errors for the non-porous scaling fits were of
378 the order of several billion years.

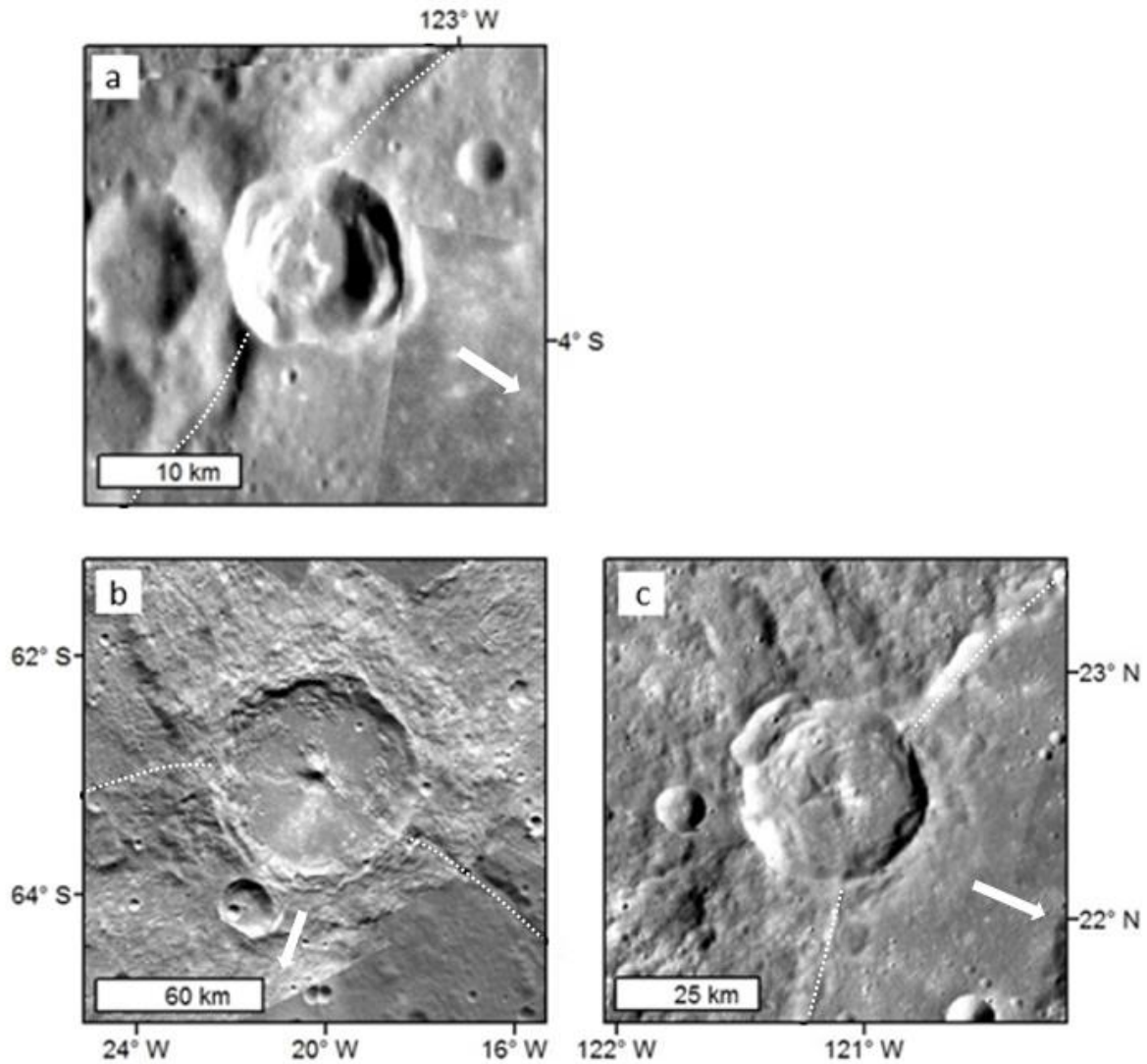
379 Comparison between the model ages for the tectonic landforms and the smooth plains
380 indicates that the application of the buffered method to linear tectonic features, as opposed
381 to the Martian valley floors for which it was designed, produces results consistent with the
382 stratigraphic observation that the last tectonic activity on the basin-edge scarps post-dates
383 the emplacement of the most recent volcanic infill. This comparison is also consistent with
384 new evidence of recent tectonic activity in the form of detection of small scale and
385 necessarily young thrust scarps during MESSENGER's end-of-mission low altitude campaign
386 (Watters et al., 2016).

387 Our results also indicate that the interval between the smooth plains emplacement and the
388 last discernible movement on the associated basin-edge lobate scarp usually exceeds 1 Ga.
389 The absolute model ages for the last resolvable slip on the basin-edge lobate scarps are
390 clustered around approximately 1 Ga (with a range of 0.6 to 1.1 Ga). Giacomini et al. (2015)
391 suggested that activity on small scarp segments or small individual scarps continued,
392 perhaps even to the present, having found that buffer-derived model ages for a ~ 2000 km-
393 long thrust system (composed of multiple lobate scarps 100 – 350 km in length), the
394 “Blossom thrust system”, indicated that these structures were most active prior to 3.5 Ga

395 (Model ages in this case were produced under the assumption of a layered target with
396 cohesive soil on top of hard rock, which we note is likely to produce generally older results
397 than the uniform hard rock composition of the target body in the model ages we present).
398 Our results suggest that activity continued on the subset of lobate scarps that we
399 investigate here until considerably more recently than 3.5 Ga.

400 **5.2 Verification of the Mansurian age of basin-edge scarps**

401 Because the MPF model ages for the basin-edge scarps in Table 2 extend well into the
402 Mansurian, we examined these structures in more detail with high-resolution MDIS images.
403 Our aim was to determine whether any craters cross-cut by the lobate scarps appear
404 themselves to be Mansurian in age, in order to provide additional evidence to support our
405 inference that the formation of basin-edge scarps was indeed still occurring during the
406 Mansurian (Table 1). The Mansurian epoch is now considered to extend from 1.9–0.3 Ga
407 (Banks et al. 2016). Using the established method for estimating age of Hermean craters on
408 the basis of their degradation state (Spudis and Guest, 1988), we searched for the presence
409 of morphologically crisp rims, visible terracing within a given crater, a visible central peak,
410 and a visible ejecta blanket (with or without rays) . Using the global MDIS mosaic basemap
411 we identified three craters that match the above morphological requirements and that are
412 crosscut by basin-edge scarps. We then examined these craters with higher resolution
413 (average 50 m/pixel) MDIS images (Figures 9a–c).



414
 415 *Figure 9 (a–c): Three examples of craters, assessed to have formed during the Mansurian on the*
 416 *basis of degradation state, which are cut and deformed by basin-edge scarps. The white dotted lines*
 417 *indicate the basin-edge scarp (delineated only outside the cross-cut craters to avoid obscuring detail),*
 418 *and the white arrows indicate the direction to the centre of the volcanically infilled basin in each*
 419 *case. The volcanically infilled basins in each case are: (a) Unnamed (centre coordinates: 04°S,*
 420 *123°W), 14 km diameter (images: EN1051949290M and EN0257562458M), (b) Pushkin (the crater*
 421 *that has been cut through by the basin-edge lobate scarp is Tsurayuki, 83 km diameter) (images:*
 422 *EN1066019121M, EN1066078737M and EN1066019149M), and (c) Durer, 31 km diameter (images:*
 423 *EN0211806621M, EN0227048749M and EN0211806621M).*

424

425 In the case of Figure 9a, the unnamed crater centred at 04°S, 123°W, there are subtle
 426 morphological indications that the scarp affects at least the northern rim, but the evidence
 427 for tectonic deformation here is equivocal. However, the craters in Figures 9b and c are

428 definitely cut by their proximal basin-edge lobate scarps, as the trace of the scarp can be
429 seen on both the crater floor and in the crater wall.

430 Our observations of craters we assess as Mansurian on the basis of their morphology that
431 are cross-cut by basin-edge lobate scarps supports our model ages results (Table 2), since
432 they also indicate tectonic activity was occurring along these structures after the
433 emplacement of the volcanic infill (in the Mansurian or possibly Kuiperian epoch).

434

435 **6. DISCUSSION**

436 **6.1 PROPOSED FORMATION MECHANISM**

437 Upon the basis of the location and morphology of the basin-edge lobate scarps, we propose
438 the following formation sequence (depicted in Figure 10):

- 439 1. An impact event creates a basin.
- 440 2. Regolith accumulates on the basin floor.
- 441 3. This basin is subsequently flooded by basaltic lavas that solidify to form a “smooth
442 plains” unit (Strom, Trask and Guest, 1975; Denevi *et al.*, 2013). The interface
443 between the basin floor and the base of the smooth plains unit may represent a
444 mechanical discontinuity, especially if there had been time for an appreciable
445 thickness of regolith to develop prior to flooding. The expectation is that regolith
446 growth on Mercury is faster than on the Moon, since the median impact velocity at
447 Mercury is approximately double that at the Moon (because Mercury is deeper in
448 the Sun’s gravity well (Langevin, 1997)). The observation of “ghost craters” visible
449 within some of the smooth plains units (for example, Aneirin shown in Figure 3)
450 indicates that a substantial period of time elapsed between basin creation and the
451 most recent episode of volcanic plains emplacement in at least some cases (cf. Byrne
452 *et al.* 2016).
- 453 4. As Mercury’s crust shortens due to global contraction, fault nucleation occurs along
454 the mechanically weak interface, and propagates along it before breaching the
455 surface at the edge of the basin infill. The mechanically weak interface is at shallow
456 crustal levels, where fault nucleation is most favourable within a stress field driving

457 global contraction (Klimczak, 2015). A detachment fault, along which the overlying
458 material slides, forms along the interface.

459 5. The smooth plains unit moves along the detachment fault, essentially as a hanging
460 wall block, forming an arcuate lobate scarp (or scarps, since we observed examples
461 where a basin-edge scarp has formed at opposite edges of the same volcanically
462 filled basin) at the basin margin that approximately follows the inner edge of the
463 original impact basin rim and, with increased amounts of shortening strains, over-
464 thrusts it.

465 The mechanism we propose is comparable, although smaller in scale, to the basal
466 décollement proposed by Rothery & Massironi (2010) beneath Beagle Rupes. Mechanical
467 discontinuities within the crust of Mercury that have been suggested by Byrne et al. (2014)
468 and hypothesised to be a contributing factor in the formation of Discovery and Adventure-
469 Resolution Rupes (Watters et al. 2001). We observe that basin-edge scarps' vergence is
470 always outwards facing, and that the scarps themselves follow the interior rim of the
471 original basin without extending beyond it (except in examples where the smooth plains
472 unit has overthrust the original rim). The mechanism we propose here accounts for these
473 observations. When crustal shortening is localised along the interface between the basin
474 floor and the base of the smooth plain infill (with a buried layer of regolith at some depth
475 possibly also contributing, as discussed in point 3, above), that interface could constitute a
476 detachment surface that would act as a stress guide into which thrust faults would be
477 channelled (Zoback, Townend and Grollmund, 2002). The smooth plains unit within the
478 original basin is not fractured in this scenario, but instead is forced upwards along the
479 detachment fault towards the rim of the original impact basin.

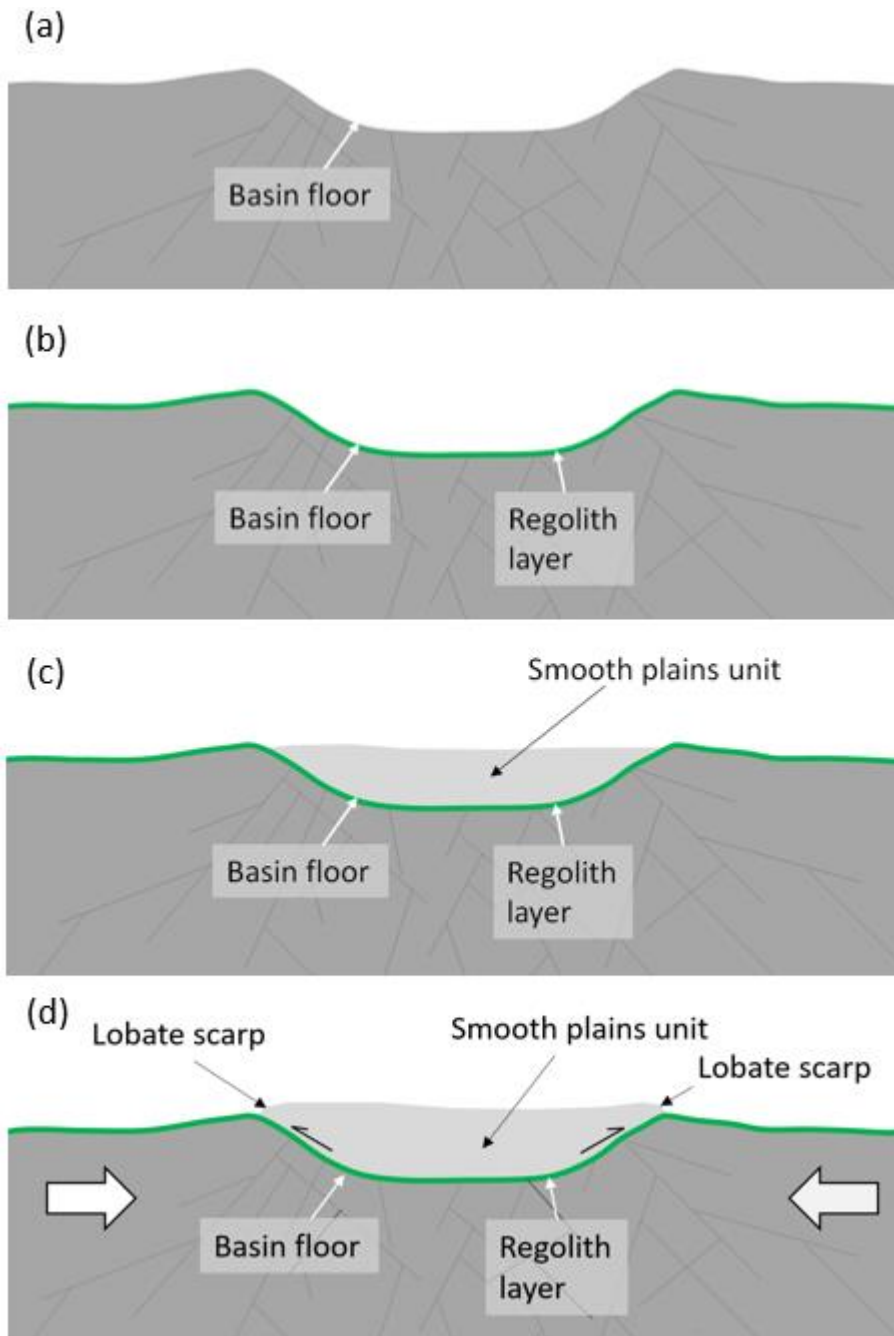


Figure 10: Cartoon depicting the basin-edge lobate scarp formation mechanism that we propose here. (a) The formation of an impact basin results in fracturing of the crust below and surrounding the impact basin (indicated by fine black lines). (b) A layer of regolith forms through continued impact bombardment (shown in green). (c) The basin is infilled by lava. (d) The large white arrows indicate direction of maximum compressive stresses in the lithosphere; as the crust is shortened, a fault (or faults) nucleate along the plane of weakness, resulting in movement along the interface

507

508 between the basin floor and the base of the smooth plains unit. The example above depicts a basin with two
 509 lobate scarps (in this cross-sectional diagram: left and right). The cartoons are not to scale.

510

511 6.2 TIMING AND LOCATIONS OF FORMATION

512 Volcanic activity on a very large scale (for example the northern volcanic plains and Caloris
 513 Plainitia) ended on Mercury by around 3.5 Ga (Byrne et al. 2016) with only smaller-scale
 514 volcanic flooding continuing thereafter (Prockter et al., 2010; Marchi et al., 2011; Byrne et

515 *al.*, 2016). Our results indicate that volcanism of sufficient scale to cover basin floors of
516 approximate areas of $8 \times 10^4 \text{ km}^2$ (for basins with a diameter of 100 km) and above
517 continued until at least approximately 1.5 Ga. Our youngest example (according to the
518 model ages we calculated: see Table 2) with a basin-edge scarp is Shevchenko ($1.5 \pm 0.2 \text{ Ga}$),
519 and our youngest example without a basin-edge scarp is Khansa ($0.9 \pm 0.1 \text{ Ga}$). These results
520 are consistent with the findings of Marchi *et al.* (2011), who derived ages younger than ~ 1.0
521 Ga for the smooth plains fill of two basins (Raditladi and Rachmaninoff), though it is likely
522 the fill in at least one of those cases is impact melt rather than volcanic lavas (Blair *et al.*,
523 2013). The ascent of magma is assisted by the fracturing created by impacts (Melosh, 2011;
524 Klimczak, 2015; Byrne *et al.*, 2016) potentially accounting for how relatively large volcanic
525 plains formed so late in Mercury's history despite ongoing global contraction.

526 The model ages we determined for the basin-edge lobate scarps lie between 0.6 and 1.1 Ga
527 and they average to approximately 1 Ga (see Table 2). Under a scenario in which sufficient
528 time elapsed between basin formation and volcanic infilling for a regolith to form on the
529 original basin floor, then the presence of this regolith layer could constitute a detachment
530 surface (Zoback, Townend and Grollmund, 2002). However, although model age difference
531 between basin formation and the youngest lava infill can sometimes be resolved (Marchi *et al.*
532 *al.*, 2011; Ferrari *et al.*, 2015) it is not possible to determine the interval between the basin-
533 forming impact and emplacement of the first volcanic fill, and therefore it is not possible to
534 determine whether or not there was time for a sufficient thickness of regolith to form.
535 However, we have observed several instances of ghost craters, such as those visible in
536 Figure 3. The presence of these landforms suggests a significant time interval during which
537 regolith could form, contributing themselves to the growth of regolith by way of their ejecta
538 blankets.

539

540 **7. CONCLUSIONS**

541 Our results suggest that:

- 542 - Effusive volcanism of sufficient volume to extend across the floors of basins 100 km
543 in diameter or greater continued until at least early Mansurian (approximately 1.5

544 Ga), possibly assisted by impact fracturing that allowed this relatively late ascent of
545 magma to the surface despite Mercury's history of sustained global contraction.

- 546 - The use of the buffered method on tectonic features produces results consistent
547 with the observed stratigraphy (Byrne *et al.*, 2016).
- 548 - Resolvable deformation accommodated by basin-edge lobate scarps appears to have
549 ceased between ~1.1 Ga and ~0.6 Ga, in the mid-to-late Mansurian, at least as
550 determined with our crater areal density surveys and our model ages.
- 551 - We suggest that the interface between the original basin floor and the base of the
552 smooth plains units acts as a mechanical discontinuity along which detachment
553 faulting could have occurred.

554

555 With regard to the orientation of basin-related lobate scarps we note that the results of our
556 global survey are to first order, consistent with those of Watters *et al.* (2015) and Byrne *et*
557 *al.* (2014), since we also observe a preference for north–south orientations at low latitudes
558 and east–west at higher latitudes. However, our conclusions differ from those of Watters *et*
559 *al.* (2015) since we found that the orientation/facing direction plots for structures in those
560 same areas do not consistently show these preferences when the illumination direction is
561 artificially varied. This strongly indicates to us that lighting bias cannot be ruled out when a
562 north–south preference in orientation is detected on the surface of Mercury, as has been
563 proposed by Byrne *et al.* (2014) and Klimczak *et al.* (2015).

564

565

566 **Acknowledgements:** We thank Paul Byrne and Christian Klimczak for undertaking substantial reviews of this
567 manuscript. Additional thanks due to Thomas Barrett for his assistance creating figures used in the manuscript
568 and supplementary material. This work was funded by a Science and Technology Facilities Council (STFC)
569 studentship to ERF, STFC grants (ST/L000776/1) to MA and (ST/N0039X/1 and ST/M002101/1) to DAR.

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