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1   **Prolonged eruptive history of a compound volcano on Mercury: volcanic and**

2   **tectonic implications**

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18   Abstract:

19   A 27 × 13 km 'rimless depression' 100 km inside the southwest rim of the Caloris

20   basin is revealed by high resolution orbital imaging under a variety of illuminations to

21   consist of at least nine overlapping volcanic vents, each individually up to 8 km in

22   diameter. It is thus a 'compound' volcano, indicative of localised migration of the site

23   of the active vent. The vent floors are at a least 1 km below their brinks, but lack the

24   flat shape characteristically produced by piston-like subsidence of a caldera floor or

25   by flooding of a crater bottom by a lava lake. They bear a closer resemblance to

26   volcanic craters sculpted by explosive eruptions and/or modified by collapse into void

27   spaces created by magma withdrawal back down into a conduit. This complex of

28   overlapping vents is at the summit of a subtle edifice at least 100 km across, with

29   flank slopes of about only 0.2 degrees, after correction for the regional slope. This is

30   consistent with previous interpretation as a locus of pyroclastic eruptions.

31   Construction of the edifice could have been contributed to by effusion of very low

32   viscosity lava, but high resolution images show that the vent-facing rim of a nearby

33   impact crater is not heavily embayed as previously supposed on the basis of lower

34   resolution fly-by imaging. Contrasts in morphology (sharpness versus blurredness of

35   the texture) and different densities of superposed sub-km impact craters inside each

36   vent are consistent with (but do not prove) substantial differences in the age of the

37   most recent activity at each vent. This suggests a long duration of episodic

38   magmagenesis at a restricted locus. The age range cannot be quantified, but could be

39   of the order of a billion years. If each vent was fed from the same point source,

40   geometric considerations suggest a source depth of at least 50 km. However, the

41   migration of the active vent may be partly controlled by a deep-seated fault that is

42   radial to the Caloris basin. Other rimless depressions in this part of the Caloris basin

43 fall on or close to radial lines, suggesting that elements of the Pantheon Fossae radial

44 fracture system that dominates the surface of the central portion of the Caloris basin

45 may continue at depth almost as far as the basin rim.

46

47 **1. Introduction**

48 The vent complex on which we focus here is located at 22.3° N, 146.2° E, situated

49 about 100 km inside the southwestern rim of Mercury's Caloris basin. It was

50 discovered in images returned during MESSENGER's first flyby in 2008 (Figure 1),

51 and described by Head et al. (2008) as a 'kidney-shaped depression' surrounded by a

52 relatively bright deposit with diffuse outer edges that they interpreted to be pyroclastic

53 deposits erupted from the vent area. They referred to it as a 'rimless depression', on

54 the grounds of lacking any trace of a rampart or elevated rim such as surrounds an

55 impact crater. In the then absence of altimetric data, Head et al. (2008) used indirect

56 evidence to infer that the overall structure is a 'broad, low shield volcano'. The

57 inferred pyroclastic deposit centred on the vent was listed as Red Spot 3 (RS-03) by

58 Blewett et al. (2009) in their preliminary analysis of colour trends, and investigated as

59 an example of evidence for unexpectedly high volatile content in the erupting magma

60 (3600-13,000 ppm) by Kerber et al. (2009). With a radius of 24 km, this is the 5th

61 most areally extensive candidate pyroclastic deposit documented during the three

62 MESSENGER flybys (Kerber et al. 2011).

63 As well as presenting several other examples of volcanic vents, Head et al. (2009)

64 suggested that the scalloped edges of the RS-03 rimless depression are a result of

65 'successive stages of inflation and collapse of the (magma) reservoir' leading to

66 'multiple intersecting depressions'. Here we take advantage of higher resolution

67 images and altimetric data acquired during MESSENGER's first three Mercury solar

68 days in orbit to provide a more complete account of this feature. Diverse ages of the

69 individual vents demonstrate a prolonged, or at least complicated, history of episodic

70 eruption involving migration of the locus of eruption to and fro by about 25 km. A

71 hitherto unrecognised vent extends the rimless depression further west than previously

72 realised, so it can no longer be aptly described as 'kidney-shaped'. We discuss first

73 this main vent complex, and then draw attention to its relationship to other rimless

74 depressions nearby. Because this feature has previously been classified as a 'rimless',

75 we use the term 'brink' rather than 'rim' to refer to the perimeter of the depression.

76   **2. Insights from orbit**

77 2.1   High-resolution imaging

78 The imaging system on MESSENGER is MDIS, the Mercury Dual Imaging System

79 (Hawkins et al., 2007). It consists of a monochrome narrow angle camera (NAC) and

80 a multispectral wide angle camera (WAC). The RS-03 vent complex was imaged

81 three times by targeted high-resolution NAC acquisitions during MESSENGER's first

82 three solar days orbit, and there are many WAC images that also show more detail

83 than the flyby images. We show in Figure 2a a WAC mosaic of the region and in

84 Figure 2b a map of the same area marking the RS-03 vent complex and five other

85 rimless depressions. An inset on the map assigns a letter to each vent within RS-03 for

86 ease of reference.

87 Spatial resolution in the NAC images is tremendously improved compared to the

88 flyby imaging, and the variety of solar illumination conditions allows many further

89 insights. All three NAC acquisitions were by off-nadir viewing (emission angles

90 between 30 and 46 degrees). Attributes of these images and one particularly useful

91   WAC image are listed in Table 1, and georectified mosaics centred on each are shown

92   in Figure 3.

93   The view in Figure 3a was acquired under conditions of solar illumination similar to

94   those in the flyby image (Figure 1), with the Sun high in the east. However, its

95   significantly higher resolution reveals very clearly some textural contrasts within the

96   vent complex that could not previously be recognised. The sides and floors of pits

97   occupying the east, north and west of the complex are smooth. These are A-E on

98   Figure 2b, although A is scarcely distinguishable (the brink of the depression seeming

99   to be at the western edge of B and C) and might not have been recognised if this had

100   been the only illumination available. We interpret each of A-E as hosting at least one

101   volcanic vent. In the centre of the complex is an area of much finer texture, whose

102   outline and internal morphology suggest that it contains at least four overlapping

103   vents (F-I on Figure 2b). Cross-cutting relationships demonstrate that these are

104   younger than their smoother-textured neighbours. The rough texture within vents F-I

105   suggests that they were active more recently than the smoother-textured vents. We

106   discuss the possible nature of this activity in section 4, where we argue that the

107   smoother-textured vents A-E were formerly much rougher, and that their contours

108   have become muted. Such smoothing is likely to occur over time by some

109   combination of mantling by younger pyroclastic deposits and regolith-forming

110   impacts.

111   The view in Figure 3b was acquired when the Sun was considerably lower and in the

112   west. This illumination accentuates the textural contrast between older and younger

113   vents, and there are shadows from which depths can be estimated. Moreover, the

114   favourable shading under this illumination direction reveals a westward extension of

115   the overall rimless depression that destroys its kidney-like shape. We interpret this as

116 another vent belonging to the complex (A on Figure 2b), and note that it contains

117 several sub-km sized impact craters on its floor, which are less common or absent in

118 the other vents. These craters exhibit a range of degradation states, from sharp to

119 muted, and so are almost certainly of different ages.

120 The floor area of vent A is too small for reliable statistics, but it is notable that the

121 crater-density there is not significantly different from that on nearby surfaces outside

122 the rimless depression, and there is no obvious increase in superposed crater density

123 with distance away from the brink. The fresher craters in particular are clustered and

124 are therefore likely to be secondaries, and so of little use for relative dating, especially

125 of areas so small as the interior of a vent (e.g., McEwen and Bierhaus, 2006).

126 However cross-cutting relationships also suggest that vent A is the oldest in the

127 complex, and it is plausible that vent A ceased activity not very long after the

128 formation of the adjacent plains, and did so significantly longer ago than other vents

129 in the complex. Comparative preservation state suggests that its immediate neighbour

130 to the southeast, vent B, may be the next-oldest.

131 The view in Figure 3c was acquired under the highest incidence angle (most grazing-

132 incidence sunlight) of the set. It misses the western vent, but the longer shadows and

133 different viewing geometry (spacecraft azimuth in Table 1) accentuate some features

134 of the central vents F-I that are less apparent in the other views.

135 Slopes that appeared foreshortened or elongated in the raw NAC images because of

136 the off-nadir viewing geometry remain distorted in the geo-rectified images.

137 Therefore we show as Figure 3d a geo-rectified WAC image in which the entire

138 interior of the vent complex is covered by a single WAC frame acquired with near-

139 nadir viewing geometry (emission angle 1.6 degrees) but with similar conditions of

140   solar illumination to two of the NAC images (Table 1). This shows the plan-view

141   shapes of the steep, young vents F-I with minimal distortion. It provides confirmation

142   of the western vent (A), and shadowing on the southeastern part of its floor hints at

143   structural complexity that may indicate at least one additional vent contained within

144   it.

145   The largest vents A, B and C are each about 9 km across, but may have been slightly

146   bigger before being cut across by younger vents. The average spacing between centres

147   of adjacent vents is 5.5 km (with a range from 3.9 km to 9.9 km). This may equate to

148   the average spacing between conduits, though it is conservatively large given that

149   vent A could in fact comprise more than one individual vent.

150   2.2   Topography

151   Because of its between-track spacing at these latitudes, Mercury Laser Altimeter

152   (MLA) gridded topography (Zuber et al., 2012) has a spatial resolution that is too

153   coarse to test the inference made by Head et al. (2008) that the RS-03 vent complex is

154   at the summit of a feature that is 'domelike in nature'. Moreover, the volcanically-

155   flooded floor of the Caloris basin has been warped by the imposition of long

156   wavelength topography (Oberst et al., 2010; Zuber et al., 2012) on a scale of several

157   hundreds of km, as well as being distorted more locally by wrinkle ridges.

158   Fortunately, the 400 m along-track spacing of MLA data points is adequate to reveal

159   smaller-scale topography in the along-track direction. Three MLA tracks cross the

160   centre of our region of interest (Figure 4). One of these crosses the RS-03 vent

161   complex, and the other two graze its northeastern brink. Data from the vent-crossing

162   track provide a good measurement of the depth of the northernmost vent (D),

163   bottoming out before ground returns are lost, showing its floor to be 1.0 km below the

164 northern brink. There are no usable MLA returns inside the rest of the vent complex

165 (the track crosses vents G and H), but reliable data show the southern brink to be

166 more than 0.2 km higher than the northern brink. This may in part be because a minor

167 wrinkle ridge (WR2 on Figure 4) intersects the brink of the complex near here.

168 Although the slope down into the vent from the brink looks steep on the profile in

169 Figure 4, the scale is vertically exaggerated. In fact, the average slope from the brink

170 to the deepest point is only about 9º. Vent D measures 7.7 km by 5.1 km, and using

171 the mean value as its diameter, we find a depth/diameter ratio of 0.16.

172 It is clear from visual appearance on the images (Figure 3) and on the MLA profile of

173 vent D (Figure 4) that the vents within this complex are not flat-floored, but have

174 bowl-shaped or V-shaped profiles. The within-vent shadows cast at high solar

175 incidence angle (Figure 3b and c) allow depths of several of the vents to be measured.

176 These are minimum depths, because in most cases the shadow terminus is likely to be

177 part-way up the opposite, Sun-facing, wall rather than coinciding with the vent

178 bottom. We obtain minimum depths in the range 0.6-1.7 km for all shadowed vents in

179 Figure 3b and c. Some depths are below an internal septum (between C and H, and

180 between H and I) rather than below the external brink of the complex, so that the

181 depth below the brink is likely to be somewhat greater.

182 At first sight, no MLA profile shows obvious evidence of the vent complex being at

183 the summit of a volcanic edifice. Topography outside the vents is dominated by

184 wrinkle ridges and impact craters. However, there is an along-profile regional slope of

185 about 0.4º downwards towards the north. De-trending of the profiles to remove the

186 regional slope (Figure 5) reveals an along-track slope of about 0.21º downwards to the

187 north from the northern brink of the vent complex and about 0.07º downwards to the

188 south from its southern brink. If the regional tilt post-dates volcanic activity as

189 deduced on various grounds by Zuber et al. (2012), this represents the original flank

190 slopes on either side of the vent complex. Original slopes could be symmetrical at

191 0.14º on either flank if we have slightly overestimated the regional slope, which could

192 easily be the case given the complications arising from the wrinkle ridge adjacent to

193 the north. However, slopes are clearly very gentle, irrespective of whether or not they

194 are symmetrical on either side. Such a flank gradient is considerably less steep than

195 for the majority of low basaltic shields on Mars, where for example Hauber et al.

196 (2009) report a range of 0.3-4.7º on the upper flanks of 24 examples in the Tempe

197 province.

198 2.3   Nearby related vents

199 Travelling southwest from the brink of the RS-03 complex, the first feature of note is

200 a curved line of four or five overlapping craters, each roughly circular and 5-10 km in

201 diameter. Head et al. (2008, 2009) mapped this group as an irregularly shaped

202 depression and regarded it as of likely volcanic origin. This is prominent in Figure 6

203 and is the feature labelled 1 on Figure 2b. These craters lack obvious rims and we

204 agree that they are possibly, though not necessarily, of volcanic rather than impact

205 origin, as are two similar depressions to their southwest (2 and 3 on Figure 2b) that

206 were also mapped by Head et al. (2008, 2009) and which lack circular sub-structures.

207 Of less equivocal volcanic origin is the shallow 20×10 km, roughly rectangular,

208 rimless depression with finely-scalloped walls that is immediately adjacent (4 on

209 Figure 2b). This is the centre of a candidate pyroclastic deposit, with a 'pyroclastic'

210 spectral signature, listed as RS-03 SW by Kerber et al. (2011). The easternmost pit on

211 its floor can be seen to contain high-albedo material similar to that found associated

212 with areas of hollow-formation (Blewett et al., 2011, 2013), which we have found

213   (Thomas et al., 2013) to be widely associated with rimless depressions elsewhere on

214   Mercury. There seem to be at least four vents within 'feature 4', of which the deepest,

215   and perhaps youngest, are at either end.

216   We draw special attention to a newly-identified 19×13 km rimless depression that

217   lies 120 km to the northeast of the RS-03 vent, which is labelled 5 on Figure 2b. A

218   fortuitously well-placed and low-noise MLA track crosses this feature, as illustrated

219   in Figure 7. It passes very close to what appears to be the deepest part of the

220   easternmost vent within the 'feature 5' complex, and the profile (Figure 7b) shows it

221   to have sloping sides and a narrow bottom. The steepness is exaggerated in Figure 7b,

222   and in fact the slope from the northern brink to the deepest point is an average of 7°

223   (and steeper near the top), whereas the opposite slope as 17°. The deepest point on the

224   profile is about 1.3 km below the brink. Given that the profile may not cross the

225   deepest point in the vent, a minimum depth/diameter ratio is 0.13.

226   After de-trending to remove the regional slope (Figure 7c), the outward slope

227   downward to the north from the northern brink can be seen to be about 0.30 km in 50

228   km, while the outward downward slope to the south from the southern brink is about

229   0.22 km in 50 km. The flank slopes are thus about 0.34° on the north and 0.25° on the

230   south. This is marginally steeper than the flank slopes of the RS-03 complex, but less

231   steep than the majority of low basaltic shields on Mars (Hauber et al. 2009).

232   'Feature 5' has no surrounding spectral anomaly in WAC colour, and lacks any other

233   evidence of pyroclastic activity, but is otherwise similar to feature 4, including being

234   apparently deepest at either end.

235   Targeted NAC images of 'feature 5' acquired in June and July 2013 became available

236   on the MESSENGER website while this paper was under review (see Supplementary

237 Material), and provided the basis for the internal boundaries between the vents within

238 it shown in Figure 2. Stereoscopic viewing confirms that the MLA track in Figure 7

239 passes close to the deepest point of the easternmost vent. There is no topographically

240 rough area analogous to vents F-I within the RS-03 complex within feature 5, and the

241 whole floor is liberally peppered by sub-1 km impact craters.

242   ## 3. Tectonic implications

243 There is a radial fracture system named Pantheon Fossae at the middle of the Caloris

244 basin (Murchie et al., 2008), and the extension of a line drawn through the long axis

245 of the RS-03 vent complex leads towards the centre of the pattern, as illustrated in

246 Figure 8. 'Feature 4' (which, as already noted, has a surrounding pyroclastic deposit)

247 lies exactly on this line, and 'feature 5' lies close to it.

248 Head et al. (2009) note additional rimless depressions, many with associated

249 candidate pyroclastic deposits, close inside the Caloris rim between 200 and 700 km

250 southeast of RS-03. The closest group of these includes a vent surrounded by

251 candidate pyroclastic deposit RS-03 SE of Kerber et al. (2011). These fall within the

252 area of Figure 8 and are identified on the inset map. Four rimless depressions in this

253 group, including the one centred within candidate pyroclastic deposit RS-03 SE, fall

254 along a second line radial to Caloris.

255 The Pantheon Fossae radial fractures can be traced outwards to about 55% of the

256 basin radius, where they are replaced by circumferential fractures, whereas the

257 tectonic pattern beyond 70% of the radius is dominated by randomly-oriented ridges

258 attributable to contraction (Byrne et al., 2013). Our two lines extending the vent

259 alignment inwards are parallel to the first clear surficial radial fractures that they

260 encounter (i.e., those most distal from the basin center), which lends weight to their

261 inferred association. Within about 150 km of the basin centre the 'radial' fractures in

262 this part of the pattern bend gradually to the right by about 10°, and because of this

263 our two lines meet a few tens of km north of where the fracture pattern converges.

264 The consensus interpretation of Pantheon Fossae is that it is they are grabens,

265 representing radial extension. Basilevsky et al. (2011) claim that these radial grabens

266 are the oldest tectonic element in Caloris, whereas Watters et al. (2009) and Byrne et

267 al. (2013a) consider that extensional features in Caloris post-date the contractional

268 ridges. Head et al. (2008) suggested that the Pantheon Fossae grabens overlie dykes,

269 although other interpretations are possible, such as fracturing in response to the

270 impact that formed Apollodorus crater (Freed et al., 2009), which is suspiciously

271 close to the centre of the pattern.

272 The fact that the RS-03 vent complex is radially elongated suggests that its magma

273 supply rose up a radial fracture. The occurrence of the associated vents very close to

274 the same line suggest that this fracture could be at least 160 km long, and may even

275 extend all the way from the centre of the basin, which would make it more than 800

276 km long. A similar argument can be made for the alignment of rimless depressions

277 that includes candidate pyroclastic deposit RS-03 SE (Figure 8). If this interpretation

278 is correct, it could mean that, in the outer 45% of Caloris, radial extensional tectonism

279 occurred at depth but never propagated to the surface with sufficient strain to form

280 grabens. Alternatively, radial extensional tectonism could pre-date a more recent

281 regional volcanic resurfacing event in the outer part of Caloris, which buried any

282 surface expressions of radial tectonics that had occurred before cessation of vent

283 activity. In the latter case, given that compressional tectonism is apparent on surfaces

284 in the outer region of Caloris, it would lend weight to the argument by Basilevsky et

285 al. (2011) that radial extension pre-dates other tectonic events.

286 The Caloris Basin has several other candidate vents round much of its circumference,

287 but all are close to the edge of the basin. Our 'Feature 5', about 220 km from the basin

288 rim, is the furthest inwards from the rim that we have identified. Thicker basin-filling

289 lavas towards the centre of the basin (Byrne et al., 2013b) may have acted as a cap to

290 prevent vent-forming eruptions. Alternatively there may be additional structural

291 control on magma ascent by circumferential fractures close to the basin rim, similar to

292 that suggested to explain the locations of large shield volcanoes peripheral to some

293 deeply-flooded lunar impact basins (Spudis et al, 2013). A case could be made that

294 the alignment of the four most distal candidate vents in the Figure 8 inset is controlled

295 by such a circumferential fracture.

296 **4. Eruptive history**

297 4.1   The RS-03 vent complex

298 The locus of volcanic activity in the RS-03 vent complex has evidently migrated over

299 time, with the most recent activity being near the centre. The most appropriate term to

300 describe an edifice hosting such a vent complex is 'compound volcano', defined by

301 Davidson and de Silva (2000) as a 'volcanic massif formed from coalesced products

302 of multiple, closely spaced, vents.' This is not to be confused with 'composite

303 volcano' (or composite cone), which denotes construction by alternating lava and

304 pyroclastic materials that may be erupted from a single vent. Figure 9 shows

305 compound volcanoes on Earth with a similar vent-migration history to RS-03,

306 although there are differences in the mode of caldera/crater formation.

307 Given that the vents within the RS-03 complex are not flat-floored, but have bowl-

308 shaped or V-shaped profiles, this is a significant contrast with the nested and

309 overlapping calderas on Mars. Those have flat floors and steep, sometimes terraced,

310 walls. Their depressed floors are widely held to result from piston-like subsidence

along ring-faults above shallow, deflated magma chambers (e.g., Wilson et al., 2001;

Crumpler et al., 2013). In contrast, we suggest that each vent in the RS-03 complex,

or at least the younger ones whose forms are essentially unmodified, owes its shape to

a combination of explosive excavation of the crater and collapse of the walls of an

evacuated conduit, which would at first deepen the main crater floor. Terrestrial

examples include the active crater on Telica volcano, Nicaragua (Figure 10).

We deduce a sequence of vent activity at RS-03 on the grounds of cross-cutting

relationships, sharpness versus blurredness of internal texture, and consistent relative

densities of impact craters, as follows (using the vent-identification letters in Figure

2b). Note that this is the sequence of the *most recent* activity at each vent, and does

not necessarily reflect the order in which each vent first became active. There may

also have been older vents within the perimeter of the complex that have become

completely obscured by younger vents. The oldest is A, followed by B then C. D and

E are of similar age to each other, and we can find no evidence to decide on the C, D,

E sequence. Texture and cross-cutting relationships show that F, G, H and I are the

youngest, with their likeliest sequence following the order of lettering.

There is no morphological evidence of lava flows sourced from the vent complex, and

shading on the low-Sun WAC image (Figure 3d) largely disproves the contention of

Head et al. (2008) that the eastern rim of the nearby 25 km impact crater has been

'heavily embayed' by eruption products from the RS-03 vent complex. The eastern

and northeastern portions of this impact crater rim are shaded/shadowed as would

normally be expected, and the rim of this crater appears to be higher than the brink of

the RS-03 vent complex. The east to south portion of the impact crater rim has a less

clear topographic signature. This could be due to a combination of the influence of

335   Wrinkle Ridge 2 (Figure 4), which curves towards it, and products erupted from

336   rimless depressions 1 and 4 (Figure 2b).

337   The very gentle flank slopes of the RS-03 vent complex are consistent with low-

338   viscosity lavas of the kinds proposed for Mercury on photogeological (Byrne et al.,

339   2013a) and X-ray spectroscopic (Weider et al, 2012) grounds. However, they could

340   also be due largely or even entirely to pyroclastic deposits erupted from each vent.

341   There is actually no evidence that juvenile material played a significant role in the

342   vent-forming pyroclastic events, which could have been essentially vulcanian, driven

343   by volatile escape from subsurface magma but in which the solid eruption products

344   were largely or solely fragments of pre-existing rock. In such a situation the

345   characteristic colour of the candidate pyroclastic products could reflect pre-eruptive

346   subsurface alteration of wall-rock in the presence of hot volatiles rather than the

347   properties of shards of juvenile magma or volcanic glass.

348   RS-03 cuts across and so post-dates the wrinkle ridge that intersect its. Given the

349   altimetric evidence that wrinkle ridges are topographically more prominent than the

350   very low shield hosting the vent, we would not expect them to be significantly buried

351   by eruption products.

352   We suggest therefore that vent complex RS-03 has a dominantly pyroclastic,

353   explosive, eruptive history, and that it is a structure superimposed on, and therefore

354   post-dating, the Caloris interior plains lavas and their wrinkle ridges. Crater statistics

355   show that Caloris interior plains either post-date the late heavy bombardment (Fassett

356   et al., 2009) or occurred mainly towards the end then possibly continued for 'an

357   undetermined interval' (Strom et al., 2011). The youngest plains surfaces are

358   nevertheless ancient, probably in the region of 3 billion years old. The similarity in

359   sub-1 km size impact crater density on the floor of vent A and on nearby plains is not

360   reliable evidence of similar age because many craters in this small size range are

361   likely to be secondaries (Strom et al., 2011). The smooth and crater-free floors of

362   vents D and E (D has one crater, and E has none) are consistent with these being

363   considerably, conceivably billions of years, younger than the floor of vent A, but do

364   not prove this contention. As an alternative to significant age differences, impact

365   craters on the floors of D and E could have become buried by pyroclastic deposits

366   erupted from vents F-I, but the radial decrease in deposit thickness would need to be

367   surprisingly great for the floors of vents A and B to have escaped a similar fate.

368   The younger vents, F-I, are smaller than A-E, perhaps reflecting waning eruptive

369   power over time. Their interiors preserve fine-scale texture that has been lost in the

370   older vents, where it could have been mantled by pyroclastic deposits erupted from

371   the younger vents, or become degraded and mantled by regolith-forming processes.

372   Langevin (1997) estimates that on Mercury 5-10 m of regolith should form over 3-4

373   billion years. The preserved internal morphology of vents F-I does not necessarily

374   represent their state as it was after their last eruption; it could equally likely be a result

375   of the crumbling of conduit walls following magma withdrawal and the collapse of

376   associated caverns. As remarked above, there are no signs of piston-like subsidence

377   along caldera ring-faults.

378   There are many uncertainties in both absolute age and relative ages. An eruptive

379   lifetime in excess of a billion years at RS-03 is possible, but is poorly constrained. We

380   do not address here the issue of how episodic magmagenesis could have been

381   sustained for such a long period. However, we note that if RS-03 was fed from below

382   from a fixed source, the 25 km spread of the vents suggests that a source depth in

383   excess of 50 km given near-vertical magma or gas ascent.

384   4.2   The associated vents

385   Features 4 and 5 (Figure 2b) are perhaps more similar to the RS-03 vent complex than

386   features 1-3. Feature 4 is the centre of a candidate pyroclastic deposit, and so is very

387   likely to be a site of explosive eruptions like RS-03, whereas 1-3 could be essentially

388   collapse features lacking any erupted products (Gillis-Davis, 2009). There are

389   insufficient grounds to regard any of them as 'parasitic' or 'subsidiary' vents (fed by

390   inclined conduits branching off a vertical conduit to a main vent) as opposed to others

391   being 'central' volcanoes. The alignment of the whole suite suggests that it overlies a

392   fracture that is radial to the Caloris basin. There is no definitive evidence of the

393   relative ages, but the internal smoothness of 'feature 5' suggests that it is older than

394   'feature 4', and this is consistent with the spectral signature of any pyroclastic deposit

395   that once surrounded 'feature 5' having been lost.

396   **5**   **Conclusions**

397   We interpret the rimless depression centred within the candidate pyroclastic deposit

398   RS-03 as the overlapping vents of a compound volcano, from which eruptions have

399   been dominantly, perhaps exclusively, explosive. The vent complex is at the summit

400   of a subtle edifice whose flanks slope at less than a quarter of a degree. Rimless

401   depressions 40 km to the southwest and 120 km to the northeast (4 and 5 on Figure 2)

402   may be similar in origin to the RS-03 vent complex. The long axis of the RS-03 vent

403   complex is aligned radially to the Caloris basin, and there is a similar radial alignment

404   within a group of candidate vents to the southeast. Both examples may lie above

405   buried radial fractures that extend much further from the basin centre than the radial

406   fractures that are visible at the surface.

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517

518 Table 1: MESSENGER MDIS NAC and WAC orbital images used in this study.

Image ID	Solar incidence angle / degrees	Solar azimuth / degrees	Emission angle / degrees	Spacecraft azimuth / degrees	Raw pixel size / metres
EN0215894570M	39.6	133.6	45.5	333.9	28.6
EN0220591242M	74.5	264.8	41.0	359.9	20.7
EN0220850481M	83.7	267.8	30.1	179.0	19.5
EW0220764090G	79.7	266.0	1.6	351.9	125.1

520

521 Figure 1 MESSENGER flyby 1 'discovery' image, as used in Head et al. (2008). The

522 "kidney-shaped" volcanic depression is in the upper centre, a 25 km circular impact

523 crater lies to its west, and several smaller putative volcanic craters lie to the

524 southwest.

525

526 Figure 2 (a) Regional mosaic of WAC images mapped to a sinusoidal projection

527 centred on the RS-03 vent complex. (b) Sketch map of the area shown in (a), based on

528 NAC and WAC images. The main vent complex (RS-03) is shown with a heavy black

529 outline. Other rimless depressions hosting possible vents are outlined with a finer

530 black boundary, and numbered 1-5. Septa marking the divides between individual

531 vents marked by fine grey lines. Impact craters are shown with a grey fill. The inset

532 shows the main vent complex enlarged, and with letters to identify each vent. The

533 original description as 'kidney shaped' (Head et al., 2008) was based on the outline

534 around vents B-I only, because vent A was not apparent in the flyby image (Figure 1).

535 Boundaries between vents within vent complex 5 were drawn on the basis of targeted

536 NAC images that became available while this paper was in review; see

537 Supplementary Material.

538

539 Figure 3: Mosaics of NAC(a-c) and WAC (d) images of the RS-03 vent area,

540 including the individual frames listed in table 1. These are mapped to the same

541 sinusoidal projection as Figure 2. The frame including all or most of the vent in each

542 case is: (a) EN0215894570M, (b) EN0220591242M, (c) EN0220850481M, (d)

543 EW0220764090G

544

545 Figure 4 MLA profiles crossing or passing near to the RS-03 vent complex. All

546 useable (non-noise trigger channels) shot points are shown. WR1 is a major wrinkle

547 ridge and WR2 is a less prominent wrinkle ridge. The portions of each altimetry

548 profile affected by the wrinkle ridges are marked accordingly.Note the gap in datain

549 the vent-crossing line.

550

551 Figure 5 (a) MLA profile 1104071527 (see Figure 3) indicating the region unaffected

552 by wrinkle ridges used to define the regional slope. (b) De-trended to reveal the flank

553 slopes of the edifice, on the assumption that the regional tilt was imposed after edifice

554 growth. The wrinkle ridge at the north (left) end is a more signficant topographic

555 feature than the RS-03 volcanic edifice, which occurs at 80-160 km along the track .

556   This profile is tangential to the brink of the rimless depression, and so does not show

557   the vents.

558

559   Figure 6: WAC mosaic (sinusoidal projection) showing the RS-03 vent complex in

560   context with its southwestern neighbours.

561

562   Figure 7 (a) MDIS9 mosaic showing the location of MLA track 1104070323 that

563   crosses rimless depression 5 (Figure 2b). (b) The MLA profile indicating the region

564   unaffected by wrinkle ridges used to define the regional slope. (c) The wrinkle-ridge

565   free portion of (b) de-trended to reveal the flank slopes of the edifice.

566

567   Figure 8 Sinusoidal projection of part of the MDIS9 mosaic. The two dashed lines are

568   geodesic lines (curved on this map projection) parallel to the vent alignments and

569   consistent with the distal part of Pantheon Fossae radial graben system. The line

570   trending approximately WSW passes through the long axis of the RS-03 vent and is

571   close to all other vents identified in Figure 2b. The line trending approximately SW

572   passes along a group of four candidate vents within the boxed area. Inset: sketch map

573   of the boxed area. Candidate vents have black outlines, impact craters are shown with

574   a grey fill, as in Figure 2b. The northeasternmost of the candidate vents in the inset

575   (arrowed) is centred within candidate pyroclastic deposit RS-03 SE of Kerber et al.

576   (2011).

577   Figure 9 Compound volcanoes on Earth. (a) Volcan Lascar, Chile. Overlapping

578   volcanic craters top an andesitic composite cone volcano that rises more than 2 km

579   above its base. The currently active vent, a site of repeated lava dome growth and

580   collapse, punctuated by explosive eruptions (Gardeweg et al. 1998) is near the centre

581   of the complex. Image is 7 km wide. (b) Volcan Masaya, Nicaragua. Overlapping and

582   nested volcanic craters on a basaltic shield near the centre of a much larger caldera.

583   Present-day activity is gas emission and occasional strombolian explosions at the deep

584   vent on the floor of the crater in the centre left (Rymer et al., 1998). Image is 3 km

585   across. Source: Google Earth.

586

587   Figure 10 Volcan Telica, Nicaragua. When photographed in 2000 it was an open-vent

588   degassing volcano, but formerly a site of explosive and effusive eruption of basaltic

589   andesite. The crater lacks a flat floor, and has steep interior slopes leading down to an

590   open vent. Cessation of eruptive activity and further collapse could result in a vent

591   profile similar to that seen in the youngest SW Caloris vents. Internal and external

592   slopes here are steeper than on Mercury. The crater measures approximately 560 m

593   rim to rim at right-angles to the line of sight.