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Prolonged eruptive history of a compound volcano on Mercury: volcanic and tectonic implications

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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 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 Keywords: Mercury, volcanism, compound volcano, Caloris basin, MESSENGER

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 9° . 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 0.4° downwards towards the north. De-trending of the profiles to remove the
186 regional slope (Figure 5) reveals an along-track slope of about 0.21° downwards to the
187 north from the northern brink of the vent complex and about 0.07° 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 0.14° 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 $0.3\text{-}4.7^\circ$ 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 is 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 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

311 along ring-faults above shallow, deflated magma chambers (e.g., Wilson et al., 2001;
312 Crumpler et al., 2013). In contrast, we suggest that each vent in the RS-03 complex,
313 or at least the younger ones whose forms are essentially unmodified, owes its shape to
314 a combination of explosive excavation of the crater and collapse of the walls of an
315 evacuated conduit, which would at first deepen the main crater floor. Terrestrial
316 examples include the active crater on Telica volcano, Nicaragua (Figure 10).

317 We deduce a sequence of vent activity at RS-03 on the grounds of cross-cutting
318 relationships, sharpness versus blurredness of internal texture, and consistent relative
319 densities of impact craters, as follows (using the vent-identification letters in Figure
320 2b). Note that this is the sequence of the *most recent* activity at each vent, and does
321 not necessarily reflect the order in which each vent first became active. There may
322 also have been older vents within the perimeter of the complex that have become
323 completely obscured by younger vents. The oldest is A, followed by B then C. D and
324 E are of similar age to each other, and we can find no evidence to decide on the C, D,
325 E sequence. Texture and cross-cutting relationships show that F, G, H and I are the
326 youngest, with their likeliest sequence following the order of lettering.

327 There is no morphological evidence of lava flows sourced from the vent complex, and
328 shading on the low-Sun WAC image (Figure 3d) largely disproves the contention of
329 Head et al. (2008) that the eastern rim of the nearby 25 km impact crater has been
330 ‘heavily embayed’ by eruption products from the RS-03 vent complex. The eastern
331 and northeastern portions of this impact crater rim are shaded/shadowed as would
332 normally be expected, and the rim of this crater appears to be higher than the brink of
333 the RS-03 vent complex. The east to south portion of the impact crater rim has a less
334 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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413

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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 data in
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 significant 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.