

EMBARGOED BY NATURE

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1 Supervolcanoes within an ancient volcanic province in Arabia Terra, Mars2
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12 Summary:

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14 Several irregularly shaped craters located within Arabia Terra, Mars represent a**15 new type of highland volcanic construct and together constitute a previously****16 unrecognized martian igneous province. Similar to terrestrial supervolcanoes, these****17 low-relief paterae display a range of geomorphic features related to structural****18 collapse, effusive volcanism, and explosive eruptions. Extruded lavas contributed to****19 the formation of enigmatic highland ridged plains in Arabia Terra. Outgassed sulfur****20 and erupted fine-grained pyroclastics from these calderas likely fed the formation of****21 altered, layered sedimentary rocks and fretted terrain found throughout the****22 equatorial region. Discovery of a new type of volcanic construct in the Arabia****23 volcanic province fundamentally changes the picture of ancient volcanism and****24 climate evolution on Mars. Other eroded topographic basins in the ancient Martian****25 highlands that have been dismissed as degraded impact craters should be****26 reconsidered as possible volcanic constructs formed in an early phase of****27 widespread, disseminated magmatism on Mars.**

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31 The source of fine-grained, layered deposits^{1,2} detected throughout the equatorial
32 region of Mars³ remains unresolved, though the deposits are clearly linked to global
33 sedimentary processes, climate change, and habitability of the surface⁴. A volcanic origin
34 has been suggested based on the stratigraphy, morphology, and erosional characteristics of
35 the deposits⁵. The case for a volcanic source is further strengthened by spectroscopic
36 detection of sulfates in many of these deposits⁶ and detailed analyses of such rocks at the
37 Meridiani Planum landing site, which revealed materials altered under water-limited,
38 acidic conditions likely governed by volcanic outgassing⁷. Yet, while very fine-grained ash
39 can be dispersed globally from a large explosive eruption on Mars^{5,8}, the currently known
40 volcanic centers are unlikely to be the sources for thick, low-latitude layered deposits in
41 Arabia Terra⁹.

42 The lack of identifiable volcanic sources that could have produced possible
43 volcanogenic sediments in Meridiani Planum or in Gale Crater is not a unique problem. In
44 fact, seventy percent of the crust was resurfaced by basaltic volcanism, with a significant
45 fraction emplaced from yet unrecognized sources¹⁰. Thus, undetected volcanic source
46 regions must exist within the ancient crust of Mars. Therefore, the questions arise: 1) is
47 ancient volcanism poorly understood because higher Noachian erosion rates¹¹ obliterated
48 evidence for source regions and/or 2) are ancient volcanoes highland volcanoes of
49 fundamentally different character from the well recognized, massive, Hesperian shield
50 volcanoes^{12,13}? We suggest that the answer to the second question is yes; we propose a new
51 category of ancient volcanic construct that has until now escaped detection.

52 Volcanism is the thread binding nearly every aspect of Mars' geologic evolution. The
53 crust of the planet was built through magmatism and effusive volcanism¹⁴, though an early

54 phase of explosive volcanism might have emplaced a significant amount of fragmented
55 material across the ancient crust¹⁵. Volatiles outgassed¹⁶ from volcanoes have controlled
56 atmospheric chemistry¹⁷ and strongly affected climate¹⁸⁻²⁰ throughout martian history. The
57 geochemistry and habitability of martian soils and sedimentary rocks are ultimately
58 controlled by the global sulphur cycle, which is fundamentally linked to volcanism²¹. As
59 such, it is critical to understand all styles and phases of martian volcanism and how they
60 have affected the martian climate through time.

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62 **Evidence for volcanism in Arabia Terra**

63 We present evidence for a new category of ancient volcanic construct on Mars, ancient
64 supervolcanoes, which together could have produced vast amounts of lava and pyroclastic
65 materials throughout Arabia Terra and beyond. The features, which we call “plains style
66 caldera complexes,” are characterized by the presence of collapse features, low topographic
67 relief (lower than that of typical paterae), and association with plains-style lavas and
68 friable, layered deposits. Taken together, the features, each with explosive outputs likely in
69 excess of terrestrial supervolcanoes, constitute a previously unrecognized ancient volcanic
70 province in Arabia Terra (Figure 1).

71 The best example of a plains style caldera complex is Eden Patera, which is a large,
72 irregularly shaped topographic depression (~55 km by 85 km in diameter, NW-SE and SW-
73 NE respectively) located at 348.9 E, 33.6N within Noachian-Hesperian ridged plains of
74 likely volcanic origin. The complex, which reaches a maximum depth ~1.8 km below
75 surrounding plains, includes at least three linked depressions (Figure 2) bounded by
76 arcuate scarps and associated with numerous faults and fractures. Although this feature

77 has never been differentiated from impact craters in the region, it lacks any geologic
78 indicator of an impact origin, such as the presence of ejecta, an uplifted rim, nearly circular
79 geometry, or the presence of a central peak²². Its high depth-diameter ratio is inconsistent
80 with that of an ancient impact crater that has been modified by erosion²³. Thus, we rule out
81 an impact origin for Eden Patera.

82 We interpret Eden Patera as a caldera complex based on similarity to terrestrial
83 calderas²⁴ and its association with features that indicate formation via collapse and
84 volcanism both within and exterior to the depression. The surrounding terrain comprises
85 ridged plains typical of Hesperian basaltic volcanism on Mars¹⁰. Within the complex are
86 fault-bounded blocks that display surfaces similar to the adjacent ridged plain lavas (Figure
87 2a). These blocks are tilted towards the crater center and are unrelated to headwall scarps
88 that would suggest a process similar to landslides. Graben associated with the interior fault
89 blocks may have originally been linked with circumferential graben outside of the complex
90 related to older collapses or progressive formation through “piecemeal,” multicyclic
91 evolution²⁴. We interpret a ~ 700 m high mound (11x23 km N/S-EW respectively) within
92 the complex to be a graben-related vent (Figure 2b). Two sets of nearly continuous terraces
93 are found ~100 and 150 meters above the caldera floor. These terraces are strikingly
94 similar to the “black ledge” described during the Kilauea Iki eruption in 1959²⁵, indicating
95 high stands of a drained lava lake²⁶. A small mound (1 km across) several hundred meters
96 high and located between the two terraces displays surface cracks similar to a tumulus²⁷.
97 Although tumuli clefts form during inflation, we suggest that these cracks formed as the
98 lava lake drained and the sinking lake crust was draped onto caldera wall rocks.

99 The presence of volcanic features and significant faulting consistent with collapse
100 leads us to conclude that these linked depressions represent a large caldera complex
101 formed in the Late Noachian to Early Hesperian. A lacustrine origin for the terraces is
102 unlikely due to the paucity of channels found in or around the depression that could be
103 linked to aqueous surface processes. In addition, there is no apparent evidence for
104 lacustrine sediments within the basin and the depression is deeper than expected for a
105 feature of this size that was partially filled by outside sediment. The sequential
106 development of this feature (Calderas 1-3 in Figure 2) appears to have transitioned from
107 surface sagging (Caldera 1 in Figure 2), to significant disruption of the crust and
108 subsequent down-dropping of large surface blocks (Calderas 2,3 in Figure 2).

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110 Several other features throughout the region display similar characteristics.
111 Euphrates Patera is an irregularly shaped depression that reaches 700 meters depth below
112 the surrounding lava plains and contains several benches in the interior that might be
113 explained by sequential episodes of collapse or lava lake high stands. The irregular,
114 rhombohedral form of the depression might relate to shortening in the SW-NE direction.
115 Fractured surface textures in the center of the depression are morphologically similar to
116 lava surfaces disrupted by collapse caused by withdrawal of lava.

117 Other features in northern Arabia Terra contain evidence for collapse associated with
118 volcanic activity. Siloe Patera (6.6E, 35.2N) is a set of nested, deep depressions that reach
119 ~1750 m below the surrounding plains. Similar to Eden Patera, the nested craters are
120 characterized by steep-walled depressions linked by arcuate scarps and faults. The primary
121 structure is linked to a subtle NE-SW trending depression to the south that reaches ~700 m

122 depth, which we interpret as evidence for sagging due to migration of a magma body at
123 depth. While there is no evidence for impact ejecta around the structure, there is a single
124 set of lobate flows emanating from the SW portion of the depression rim, which may
125 represent a single set of lava or pyroclastic flows reaching ~60 km from the rim. Irregular
126 mounds of friable materials inside the nested craters are interpreted as pyroclastics from
127 the volcano or younger friable deposits of another origin.

128 Some other depressions in the region contain less well preserved evidence for
129 volcanism, but in all cases contain suites of features that are difficult to explain by other
130 geological processes. Semeykin Crater is a large, scalloped depression surrounded by lava
131 plains and friable deposits, which also contains mounds of friable materials in its interior
132 and ridged plains along the exterior. A suite of features, Ismenia Patera, Oxus Patera, and
133 Oxus cavus are located together near 0E, 38.5 N. The two paterae exhibit scalloped,
134 breached rims composed of layered materials. Oxus Cavus is an elongated depression
135 within a broad mound 200-300 m high adjacent to a deep depression indicative of
136 sagging/collapse. While none of these structures individually contains as many pieces of
137 evidence to clearly point to volcanism as seen at Eden Patera, all of the features contain
138 some evidence for structural collapse, which is most likely to have occurred through
139 magmatic activity (though other hypotheses are considered below).

140 Eden Patera and Euphrates Patera represent the strongest evidence for large calderas
141 in Arabia Terra based on their association with features that are diagnostic of surface
142 disruption and collapse coupled with evidence for effusive and explosive volcanism. Some
143 of the other features that display fewer diagnostic features might not all represent caldera
144 formation, or could have experienced a range of processes responsible for the current

145 morphology. Nonetheless, the region does display strong evidence that several large
146 depressions did not form as impact craters, and are most easily explained as volcanic
147 calderas.

148 **The roles of ice and impact**

149 Some depressions throughout Arabia Terra have been previously interpreted as
150 thermokarst features^{28,29}. There is no doubt that geologic surfaces in and around the Arabia
151 Terra region have been modified by ice³⁰, but we argue that it is unlikely that ice-removal
152 could have created the collapse features themselves. Scalloped depressions in the Utopia
153 Planitia region of Mars bear a striking resemblance in size, shape and morphology to
154 thermokarst features found on Earth^{31,32}; both terrestrial and martian types form
155 depressions on the order of meters to 10s of meters in depth^{33,34} (Figure 4). Thus, those
156 well-accepted thermokarst features are orders of magnitude smaller than the collapse
157 features discussed here, whereas the proposed volcanic structures in Arabia Terra are of
158 the same scale and morphology as terrestrial supervolcanoes³⁵ (Figure 4). If these
159 proposed volcanic structures are in fact the result of thermokarst, then they are a new type
160 of thermokarst beyond any that has been definitively recognized previously.

161 In addition, the large volume of the collapse features is a strong constraint on the
162 possible origins. If they formed by collapse associated with removal of subsurface ice, it
163 necessarily implies that a significant volume of ice was removed from each location, quickly
164 enough to cause the high strain rates required for faulting. However, none of the features is
165 associated with outflow channels, which are typically cited as evidence for rapid removal of
166 surface or near-surface ice. Furthermore, the amount of ice that could have existed below
167 such depressions can be constrained from quantitative models of martian subsurface

168 porosity³⁶. For example, in order for Eden Patera to have formed from removal of
169 subsurface ice, it would have required that all of the available void space was entirely
170 saturated with ice to a depth of ~10 km (see Supplementary Materials). In summary, we
171 conclude that, while ice and thermokarst processes could have played a role in the
172 modification of the collapse features, it is unlikely to explain the origin of the collapse or
173 the presence of the large depressions.

174 It is also possible that the depressions in Arabia Terra represent degraded impact
175 craters. However none of the features described above contain evidence for impact
176 geology, such as the presence of ejecta, raised crater rims, central peaks, or inverted
177 stratigraphy. It is possible that erosion has removed such evidence. However, the proposed
178 calderas are found adjacent to ancient impact craters of similar size (and possibly similar
179 age) that have preserved clear evidence for impact origins (Figure 5). Furthermore, impact
180 craters that have been degraded by erosion³⁷ exhibit much lower depth-diameter ratios
181 than those measured in the proposed calderas (Figure 5). The depth-diameter
182 relationships among the calderas are only consistent with depth-diameter ratios of impact
183 craters that are only partially modified; such craters have preserved at least some critical
184 aspects of impact geology.

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186 **A new category of Martian volcanic construct**

187 Taken together, these features constitute a new category of martian volcano that can
188 be described as plains style caldera complexes, of which Eden Patera is the type-example.
189 Eden Patera is not associated with a major edifice. Each of the martian low-slope
190 Paterae^{12,13} displays a major edifice related to repeated volcanic deposition of explosive

191 and effusive products. As such, Eden Patera appears to be a new class of martian volcanic
192 feature, formed through a combination of magma withdraw, subsurface magma migration
193 (Caldera 1) and/or major explosive episodes that would have distributed ash regionally or
194 globally such that they did not accumulate near the vent (Caldera 2,3). These geomorphic
195 features are most analogous to those of a terrestrial supervolcano.

196 On Earth, a supervolcano is defined as a volcano that can produce $\geq 1000 \text{ km}^3$ of
197 volcanic materials in an eruption. On Mars, it is generally not possible to link a single
198 volcanic deposit to particular eruption event. However, erupted volumes can be
199 constrained from the volume of void space observed in the caldera itself, if that collapse is
200 assumed to have occurred due to removal of magma during eruptive events. Focusing on a
201 subset of these features including Eden Patera, Oxus Cavus, Semeyken Crater, and Ismenia
202 Patera, the average depression volume is $>3300 \text{ km}^3$. This volume at each site could have
203 been produced by the removal of a comparable amount of dense-rock-equivalent material.
204 Assuming an average density of 2800 kg/m^3 of the magma and an estimated density of
205 2000 kg/m^3 for erupted lava or 1300 kg/m^3 for tephra, it is possible to estimate the
206 amount of erupted material from each source. The average minimum erupted volume could
207 be $>4600\text{-}7200 \text{ km}^3$ for each of these caldera complexes. While this estimate cannot be
208 linked to a single eruption event, nor can we differentiate void space created via explosive
209 ejection and magmatic subsidence, these features are unlike other known martian
210 volcanoes and it is likely that they fall in the category of terrestrial supervolcano, based on
211 both geomorphology and eruptive potential.

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213 The question remains: why would large calderas associated with explosive volcanism
214 occur in northern Arabia Terra? One possibility is that volatile-rich crust was subducted
215 beneath Arabia Terra during an ancient episode of plate tectonics³⁸. However, while the
216 presence of NW-SE-trending scarps related to thrust faulting in northern Arabia Terra
217 related to SW-NE compression might seem consistent with such an interpretation, the
218 estimated displacement on such faults is small and does not support the model of an active
219 plate margin^{28,39}. More likely, the dichotomy boundary evolved due to crustal thinning
220 associated with endogenic processes³⁹. The crust within Arabia Terra is relatively thin and
221 more similar to thicknesses modeled for the northern lowlands than the southern
222 highlands⁴⁰. Even so, we consider an origin due to subduction to be an open question that
223 merits further consideration.

224 We suggest that a combination of regional extension and thermal erosion of the lower
225 crust in the Late Noachian-Early Hesperian led to rapid ascent of magma in the northern
226 Arabia Terra region. It is not necessary that the magmas were higher viscosity (more
227 silicic) or had higher volatile content than other martian magmas. The lower gravity and
228 atmospheric pressure on Mars lead to bubble nucleation at greater depths and greater gas
229 expansion compared to Earth⁴¹. As a result, pyroclastic eruptions would be more
230 commonly associated with basaltic volcanoes on Mars than on Earth, particularly if the
231 magma rapidly ascends and erupts, and is not stored in degassing magma chambers for
232 long periods of time, as is thought to occur at younger, large shield volcanoes⁴². In fact, it is
233 possible that explosive volcanism was more prevalent on early Mars because the ancient
234 crust was thinner, leading to less devolatilization of magmas during ascent. The result may
235 have been the deposition of vast quantities of tephra early in Mars' history.

236

237 **Links to global geology**

238 Explosive eruptions of fine-grained materials might be linked to the formation of
239 fretted terrains that also occur in northern Arabia Terra, the origin of which represents one
240 of the major outstanding mysteries in Mars science²⁹ (Figure 6). Youthful ice-related
241 processes may have modified the fretted terrains, but the sediment of which they are
242 composed was likely deposited in the Noachian-Early Hesperian⁴³. These voluminous, fine-
243 grained sediments may be tephra deposits from explosive volcanic activity in northern
244 Arabia Terra. In fact, layered terrains throughout Arabia Terra might consist of tephra
245 deposits, but previous work has suggested the source region was the Tharsis province⁵. A
246 much simpler explanation is that plains style calderas produced these sediments locally⁴⁴
247 (Figure 6).

248 Our understanding of volcanism⁴⁵ on Mars continues to evolve as numerous, small
249 (10s km diameter) and dispersed volcanic centers are recognized throughout the Tharsis
250 region⁴⁶⁻⁴⁹ and degraded, ancient volcanic centers are recognized in the southern
251 highlands^{12,13}. Major volcanic provinces are now recognized in several distinct provinces
252 throughout the martian surface, though with a paucity of features previously identified
253 between Tharsis and Syrtis Major (Figure 4). The features identified here constitute a
254 major volcanic province in Arabia Terra, which fills a void in a large fraction of the surface
255 where volcanoes are expected to occur, but have never been recognized.

256 The origin of altered, fine-grained, layered, clay- and sulfate-bearing sediments
257 throughout the equatorial region of Mars has yet to be explained. A local volcanic source
258 could explain the presence of clastic materials composing these deposits, and serve as a

259 significant source of volcanogenic sulfur that could have led to acidic alteration at the
260 surface and strongly perturbed the martian climate, sending it into periods of significant
261 warming¹⁸ or substantial cooling¹⁹. We suggest that fine-grained deposits at the Meridiani
262 Planum and Gale Crater landing sites, as well as friable deposits in the equatorial region of
263 Mars, might ultimately have originated from volcanic sources in Arabia Terra. Further
264 mapping of plains style caldera complexes might reveal additional ancient volcanic source
265 regions distributed throughout the martian highlands. Deciphering the nature of an early
266 phase of widespread, disseminated, explosive volcanism will be critical to revealing Mars
267 climate history and past habitability.

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270 **Methods Summary**

271 The primary datasets used to evaluate the geomorphology of topographic depressions in
272 the Arabia Terra region were gridded elevation data from the Mars Orbiter Laser Altimeter
273 (MOLA) and a global mosaic of daytime infrared images from the Thermal Emission
274 Imaging System (THEMIS). Additional data products included high-resolution images and
275 digital topographic data from the High Resolution Stereo Camera (HRSC) aboard the Mars
276 Express spacecraft, high-resolution images from the High Resolution Imaging Science
277 Experiment (HiRISE) and Mars Context Imager (CTX) aboard the Mars Reconnaissance
278 Orbiter, and the Mars Orbiter Camera (MOC) aboard the Mars Global Surveyor spacecraft.
279 These data products are available within the publicly available Java Mission-planning and
280 Analysis for Remote Sensing (JMARS) software produced by Arizona State University
281 (available at <http://jmars.mars.asu.edu>). Image-based geologic mapping was carried out

282 after geo-registering these data products within a geographic information system (GIS).
283 Data from the Thermal Emission Spectrometer (TES) were used to evaluate dust cover and
284 albedo.

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427

428 Author Contributions

429 J.R.M. performed the initial observations, processed image and topographic data, and wrote
430 most of the manuscript. J.E.B. wrote portions of the manuscript, performed geologic
431 mapping, and processed imaging and topographic data. Both authors synthesized the
432 results, developed the ideas, and edited the paper.

433

434 **Figure 1: Geographic context of the northern Arabia Terra region.** The dusty nature of
435 Arabia Terra is shown in false color TES-derived albedo data draped over MOLA hillshade
436 data, where bright colors correspond to dusty surfaces. Recently named geographic
437 features discussed in the text are labeled.

438

439 **Figure 2: The geology of Eden Patera.** MOLA topographic data are draped over THEMIS
440 daytime IR data to the top left showing the morphology of Eden Patera. Geologic mapping
441 reveals the presence of at least three calderas, highlighted at the bottom left. The caldera
442 contains evidence for fault blocks that preserve ridged plain lavas on the upper surface (A),
443 a likely vent (B), and a series of terraces that mark lava high stands of a once active lava
444 lake (white arrows) and cracked crust (black arrows) due to the draping of fragile crust
445 onto preexisting surfaces during lava lake drainage (c).

446

447 **Figure 3: The geology of Siloe and Euphrates Paterae.** MOLA data draped over CTX
448 images show the morphology of Siloe (a-b) and Euphrates (c-d) Paterae.

449

450 **Figure 4: Comparison of thermokarst features, terrestrial supervolcanoes and the**
451 **putative supervolcanoes on Mars.** A plot of the dimensions of typical terrestrial and
452 Martian thermokarst features shows that they have approximately similar sizes^{32,34}. The
453 proposed calderas in Arabia Terra have similar dimensions to terrestrial supervolcanoes,
454 which together are orders of magnitude larger than known thermokarst features.

455

456 **Figure 5: Comparison of the depth-diameter ratios of possible Martian**
457 **supervolcanoes to those of known impact craters.** A plot of crater measurements for all
458 of the craters within the area of Figure 1 of this manuscript with diameters ≥ 1 km that have
459 been categorized according to their level of preservation³⁷ (a). Class 1 craters are the most
460 degraded and Class 4 are the least (essentially pristine). The proposed supervolcanoes plot
461 along trendlines associated with moderately modified craters that preserved impact
462 morphologies. Yet, the calderas clearly do not contain morphological evidence for impact
463 processes as seen in adjacent craters of similar size (b).

464

465 **Figure 6: Links to global geology.** The distribution of major volcanic provinces on Mars is
466 shown in relation to friable and fretted terrain, layered sulfates¹⁷, and layered clay-bearing
467 terrains⁵⁰.

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471

472 **Methods**

473 Most well recognized volcanic edifices on Mars occur as central vent structures within
474 topographically elevated terrain built through sustained volcanism around the vent.
475 Pavonis Mons (Supplementary Figure 1) is an example of typical shield-style volcanism on
476 Mars. Note that Pavonis Mons contains evidence for collapse and crustal sagging due to
477 removal/migration of magma. The central caldera is a steep-sided, nearly circular crater
478 that formed during the latest stage of volcanic activity. However, that caldera is nested

479 within a larger set of ring-fractures that suggest more extensive collapse or additional
480 collapse events. Complex calderas are common on the Earth and Mars, and occur due to
481 collapse associated with magma withdrawal, due to migration of magma at depth, removal
482 of magma during eruptions, or both. Tyrrhenus Mons (Figure S1b) is an ancient volcano on
483 Mars of different character. It also is defined by a topographic rise with ring fractures.
484 However, the flanks of Tyrrhenus Mons display a much lower profile than Pavonis Mons
485 and are composed of fingering, eroded, layered materials thought to indicate the presence
486 of pyroclastic materials. Tyrrhena Patera (the main caldera) might be the final location of
487 the central vent, but the caldera is breached and eroded, and there is evidence for
488 secondary calderas on the volcano. The plains style caldera complexes we have identified in
489 northern Arabia Terra bear characteristics similar to each of these volcanoes, yet some
490 other characteristics that are fundamentally different. Most notably, the calderas in Arabia
491 Terra do not occur on topographically elevated volcanic constructs, which is likely one
492 reason why they have never been identified as volcanoes previously despite abundant
493 evidence for volcanic processes.

494 The International Astronomical Union (IAU) formally named six features (five
495 paterae and one cavus) located in northern Arabia Terra in 2012. These features have not
496 been discussed by their proper names in previous literature. As discussed in the main text,
497 these features, as well as Semeykin Crater (which was previously named) have
498 morphological characteristics that are entirely inconsistent with impact origins. They are
499 not the only depressions in Arabia Terra with enigmatic origins, but they are the subset of
500 features on which this paper is focused.

501 Supplementary Figure 2 shows the morphology of all seven features discussed in
502 the text. Of these, Eden Patera and Euphrates Patera bear the strongest evidence for
503 ancient volcanism. The others likely formed through collapse, though the link to volcanism
504 is less clear in the other cases.

505

506 *Calculation of volumes:*

507 One of the goals of this work is to constrain the amount of collapse that occurred at
508 each of the putative caldera complexes. Estimates of collapse volume are important for
509 placing minimum constraints on the amount of magma involved in ancient igneous
510 processes at each site, and for testing alternative hypotheses for the origins of these
511 features (*e.g.* pseudokarst, described below).

512 In order to estimate the amount of collapse that has occurred, we mapped the
513 features in a GIS environment and used MOLA elevation data to calculate the volume of
514 each depression. The volume calculations are straightforward, but are dependent on a
515 number of assumptions. First we describe the technical process, then the assumptions.

516 For each site, gridded MOLA data were contoured and draped onto MOLA hillshade
517 and THEMIS daytime IR data. The contoured data help to delineate the maximum
518 topographic level of the depression at each feature. We then converted gridded MOLA
519 elevation data to triangulated irregular networks (TINs) at each site. The TINs provide a
520 combined quantitative measure of surface elevation and area. Then, for each site, we fit a
521 plane to the maximum allowable elevation corresponding to the closest approximation to a
522 closed depression. Then, we calculated the volume of void space beneath the plane, within
523 the caldera at each site.

524 Examples of the volume calculations are shown in Supplementary Figure 3. Note
525 that the fit of an elevation plane to each site is imperfect. One assumption we make is that
526 topography has not changed since the formation of the depressions. This is clearly not the
527 case, but it is a limitation on our approach. There is clear evidence that the entire region
528 has been tilted toward the north since the formation of these features. In addition, several
529 of the calderas described in this work display evidence that they were breached, which
530 means that there is not an obvious closed depression at most structures. Or, delineation of
531 a single closed depression grossly underestimates the actual volume of the structure
532 because the calderas are typically breached at some elevation along the rim. Lastly,
533 younger impact craters have been superimposed on each site, which further complicates
534 the effort to define a single elevation contour related exclusively to the caldera collapse
535 itself. Given these challenges, we have made every effort carry out the volume calculations
536 in the most conservative approach possible, so as to avoid overestimating the volume of
537 each depression. As such, we have chosen elevations that in each case are below the rim of
538 the depression in order to provide the best estimate of a closed-depression with the
539 knowledge that this decision results in an underestimation of the total caldera volume.

540 There are errors associated with these analyses, both in the direction of artificially
541 increasing the volume estimates and in the direction of artificially decreasing the estimates.
542 One of the major errors resulting in underestimation of the volume calculations is related
543 to the fill deposits within the depressions themselves. Those materials were likely sourced
544 from the caldera in each case, but their topographic setting now is still considered part of
545 the underlying terrain. In other words, there is no way to identify the true caldera floor
546 because friable fill deposits in most cases bury the floor. We are calculating volumes of the

547 void space that exists above modern topographic depression in each case. Therefore, our
548 calculations actually correspond to the volume of the caldera that has not been filled by
549 friable materials, lavas, or colluvial deposits.

550 There are two sources of error that lead to overestimation of volumes. The first is
551 related to the erosional breaching of rims of the depression. In fitting a plane to the best
552 estimate of the closed depression, there is still some additional volume added by
553 calculating void space above the plains surrounding the breached depression. However, we
554 made every effort to avoid this bias as much as possible, and the errors that did occur are
555 likely to be small. Secondly, another bias includes calculation of void space within
556 superimposed impact craters that have interior depressions rivaling the depth of the
557 caldera itself (see Supplementary Figure 4). However, these errors are again extremely
558 small and don't change the calculated volumes appreciably. Supplementary Table 1 reports
559 the calculated minimum volumes for depressions discussed in the text.

560

561 *Could the depressions have formed by pseudokarst?*

562 Mars is in many ways a periglacial planet. Permafrost is likely to be (and have been)
563 much more widespread and geologically important at the global scale on Mars than on
564 Earth. Catastrophically melted subsurface ice has been postulated as a likely source for
565 water that carved immense outflow channels on the surface. It has also implicated in the
566 formation of terrains bearing periglacial features such as fields of pitted terrain, as seen in
567 some parts of the Elysium basin. The possibility that the collapse features described in this
568 work could have formed from removal of subsurface ice there bears consideration.

569 In order to test this hypothesis, we have used the volume calculations described
570 above to constrain how much ice must have been removed in order to produce the collapse
571 by removal of ice from the subsurface. Clifford et al.³⁶ produced models describing the
572 amount and distribution of subsurface ice on Mars. These calculations include models of
573 subsurface porosity as a function of depth. Using those models of porosity, we can then
574 calculate the amount of pore space that could have potentially been filled with ice beneath
575 a given feature. In other words, is there enough pore space available that, even if entirely
576 filled with subsurface ice, would result in the collapse volume of the depression if all of that
577 ice was removed?

578 The best test case is Eden Patera. Here, $\sim 4000 \text{ km}^3$ of void space exists. If that space
579 was created via collapse that was related to removal of ice, it stands to reason that the ice
580 must have been present essentially beneath the feature itself. If the ice was widely
581 distributed in area, its removal would have likely produced multiple small collapse pits (if
582 any at all) or regional subsidence. Therefore, we focus on the area of the depression itself.
583 In the case of Eden Patera, this area is approximately equal to 5000 km^2 .

584 Supplementary Figure 4 shows the decay of porosity with depth on Mars and the
585 cumulative volume of void space beneath an area of 5000 km^2 beneath Eden Patera. Pore
586 space decays to near zero by a depth of $\sim 10 \text{ km}$. If all of the void space to this depth was
587 100% filled with ice, it would result in a total volume of $\sim 4000 \text{ km}^3$ – roughly equal to the
588 volume of collapse at Eden Patera. Therefore, the calculations, to first order, suggest that
589 the volume of collapse at Eden Patera could potentially theoretically be explained by the
590 removal of subsurface ice. However, we suggest that the calculations present a compelling
591 case that ice was not solely responsible for the formation of the collapse at Eden Patera

592 because they imply that all of the void space became filled with ice to a great depth and
593 then all of that ice was somehow removed from the subsurface without leaving any traces
594 of fluvial features (*i.e.* outflow channels) that could be related to catastrophic melting.

595 These volume estimates provide some constraints on the amount of material that
596 was erupted from plains style caldera complexes in the northern Arabia Terra region. The
597 volumes of the depressions represent, in the strictest sense, the amount of void space
598 produced by a combination of structural collapse and eruption of lavas and/or pyroclastics.
599 Structural collapse could occur due to withdrawal of magma, or migration of a magma
600 chamber at depth, and therefore, the voids do not necessarily relate directly to erupted
601 volumes. However, explosive eruptions often continue to fragment magma within the
602 volcano's conduit and the final caldera volume can also be an underestimate of an
603 eruption's total volume. Therefore, these calculations provide some guidance on the scale
604 of the eruptive potential of the Arabia volcanic province.

605 Assuming that the void space within calderas relates directly to the removal of
606 magma during eruptions, we can produce some simple scaling calculations to estimate how
607 much material may have been erupted. By assuming a dense-rock-equivalent (DSE) of
608 caldera volume equal to a typical mafic magma with density of 2800 kg/m³, we can then
609 scale the DSE for a lava density of 2000 kg/m³ or a tephra of density 1000-1500 kg/m³.
610 Using these scaling factors and the volume calculations described above, we calculated the
611 estimated minimum erupted volumes described in the text.

612