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Supervolcanoes within an ancient volcanic province in Arabia Terra, Mars

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

The source of fine-grained, layered deposits[1,2] detected throughout the equatorial region of Mars[3] remains unresolved, though the deposits are linked to global sedimentary processes, climate change, and habitability of the surface[4]. A volcanic origin has been suggested on the basis of the stratigraphy, morphology and erosional characteristics of the deposits[5]. The case for a volcanic source is further strengthened by the spectroscopic detection of sulphates in many of these deposits[6] and detailed analyses of such rocks at the Meridiani Planum landing site, which revealed materials altered under water-limited, acidic conditions that were probably governed by volcanic outgassing[7]. Yet, although very fine-grained ash can be dispersed globally from a large explosive eruption on Mars[5,8], the currently known volcanic centres are unlikely to have been the sources for thick, low-latitude layered deposits in Arabia Terra[9].

The lack of identifiable volcanic sources that could have produced possible volcanogenic sediments in Meridiani Planum or in Gale crater is not a unique problem. In fact, 70% of the crust was resurfaced by basaltic volcanism, with a significant fraction emplaced from as yet unrecognized sources[10]. Thus, undetected volcanic source regions must exist within the ancient crust of Mars. Therefore, the following questions arise: first, is ancient volcanism poorly understood because higher Noachian erosion rates[11] obliterated evidence for source regions? Second, are ancient volcanoes highland volcanoes of fundamentally different character from the well-recognized, massive, Hesperian shield volcanoes[12,13]? We suggest that the answer to the second question is yes; we propose a new category of ancient volcanic construct that has escaped detection until now.

Volcanism is the thread binding nearly every aspect of Mars's geological evolution. The crust of the planet was built through magmatism and effusive volcanism[14], although an early phase of explosive volcanism might have emplaced a significant amount of fragmented material across the ancient crust[15]. Volatiles outgassed[16] from volcanoes controlled atmospheric chemistry[17] and strongly affected climate[18–20] throughout Martian history. The geochemistry and habitability of Martian soils and sedimentary rocks are ultimately controlled by the global sulphur cycle, which is fundamentally linked to volcanism[21]. It is therefore critical to understand all styles and phases of Martian volcanism and how they have affected the Martian climate through time.

Evidence for volcanism in Arabia Terra

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

The best example of a plains-style caldera complex is Eden patera, which is a large, irregularly shaped topographic depression (dimensions ~55 km northwest–southeast and 85 km southwest–northeast) located at 348.9° E, 33.6° N within Noachian–Hesperian ridged plains of probable volcanic origin. The complex, which reaches a maximum depth ~1.8 km below surrounding plains, includes at least three linked depressions (Fig. 2) bounded by arcuate scarps and associated with numerous faults and fractures. Although this feature has never been differentiated from impact craters in the region, it lacks any geological indicator of an impact origin, such as the presence of ejecta, an uplifted rim, nearly circular geometry or the presence of a central peak[22]. Its high ratio of depth to diameter is inconsistent with that of an ancient impact crater that has been modified by erosion[23]. We therefore rule out an impact origin for Eden patera.

We interpret Eden patera as a caldera complex on the basis of its similarity to terrestrial calderas[24] and its association with features that indicate formation by means of collapse and volcanism both within and outside the depression. The surrounding terrain comprises ridged plains typical of Hesperian basaltic volcanism on Mars[10]. Within the complex are fault-bounded blocks that display surfaces similar to the adjacent ridged plain lavas (Fig. 2a). These blocks are tilted towards the crater centre and are unrelated to headwall scarps that would

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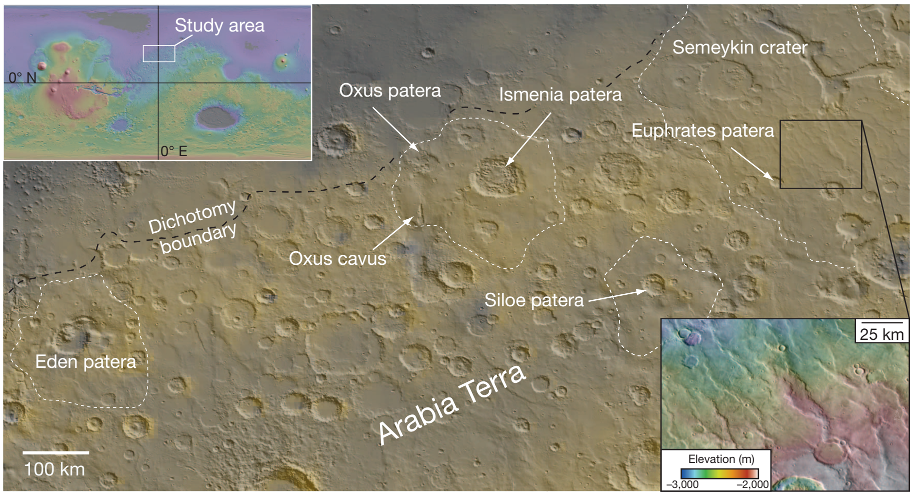

Figure 1 | Geographic context of the northern Arabia Terra region. The dusty nature of Arabia Terra is shown in false-colour TES-derived albedo data draped over MOLA hillshade data; bright colours correspond to dusty surfaces. Recently named geographic features discussed in the text are labelled.

suggest a process similar to landslides. Graben associated with the interior fault blocks may have originally been linked with circumferential graben outside the complex related to older collapses or progressive formation through 'piecemeal', multicyclic evolution[24]. We interpret a mound ~700 m high (11 km north–south and 23 km east–west) within the complex to be a graben-related vent (Fig. 2b). Two sets of nearly continuous terraces are found ~100 and 150 m above the caldera floor. These terraces are strikingly similar to the 'black ledge' described during the Kīlauea Iki eruption in 1959 (ref. 25), indicating high stands of a drained lava lake[26]. A small mound (1 km across) several hundred metres high and located between the two terraces shows surface cracks similar to a tumulus[27]. Although tumuli clefts form during inflation, we suggest that these cracks formed as the lava lake drained and the sinking lake crust was draped onto caldera wall rocks.

The presence of volcanic features and significant faulting consistent with collapse leads us to conclude that these linked depressions represent a large caldera complex formed in the Late Noachian to Early Hesperian. A lacustrine origin for the terraces is unlikely due to the

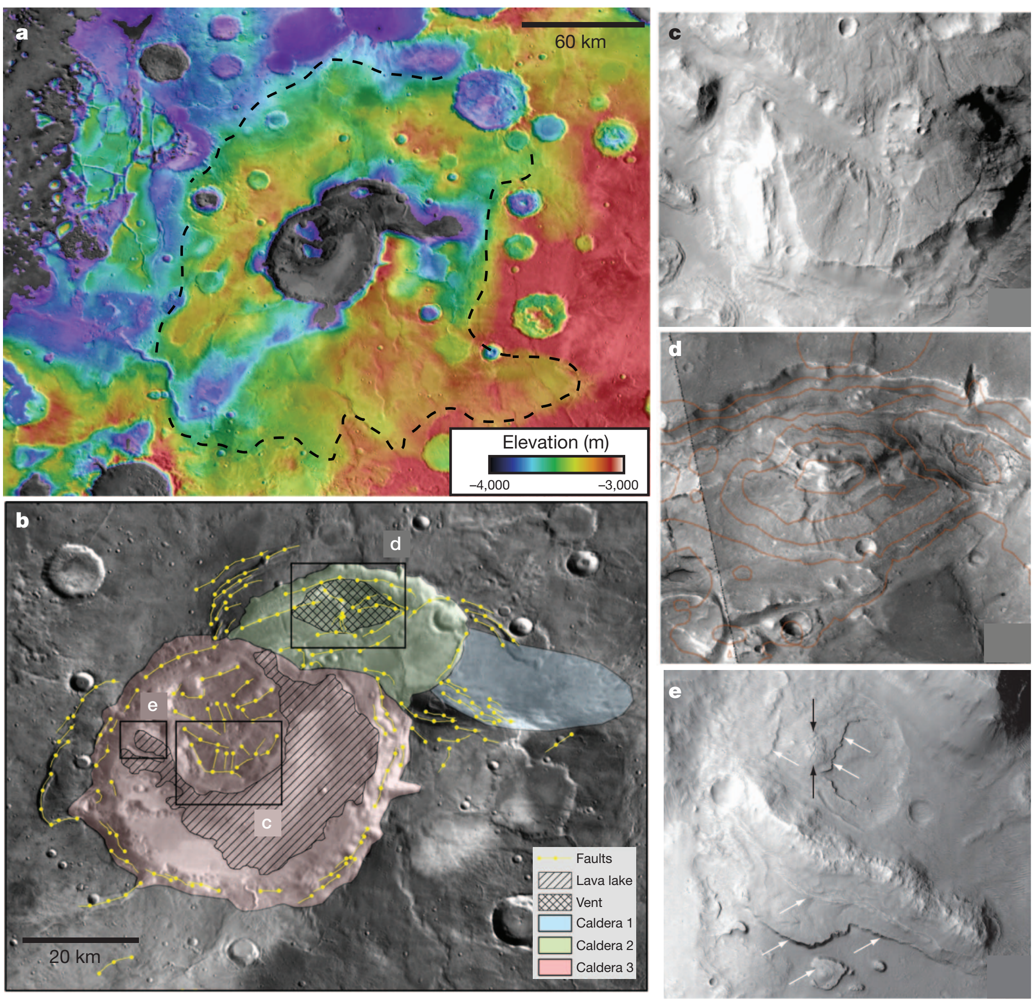

Figure 2 | The geology of Eden patera. **a**, MOLA topographic data are draped over THEMIS daytime infrared data, showing the morphology of Eden patera. **b**, Geological mapping reveals the presence of at least three calderas, indicated by coloured shading. **c**–**e**, Enlargements of the rectangles in **b**. The caldera contains evidence for fault blocks that preserve ridged plain lavas on the upper surface (**c**), a probable vent (**d**), and a series of terraces that mark lava high stands of a once active lava lake (white arrows) and cracked crust (black arrows) due to the draping of fragile crust onto pre-existing surfaces during lava lake drainage (**e**).

paucity of channels found in or around the depression that could be linked to aqueous surface processes. In addition, there is no apparent evidence for lacustrine sediments within the basin, and the depression is deeper than expected for a feature of this size that was partly filled by outside sediment. The sequential development of this feature (calderas 1–3 in Fig. 2) seems to have undergone a transition from surface sagging (caldera 1 in Fig. 2) to significant disruption of the crust and subsequent down-dropping of large surface blocks (calderas 2 and 3 in Fig. 2).

Several other features throughout the region have similar characteristics. Euphrates patera is an irregularly shaped depression that reaches 700 m in depth below the surrounding lava plains and contains several benches in the interior that might be explained by sequential episodes of collapse or lava-lake high stands (Fig. 3). The irregular, rhombohedral form of the depression might relate to shortening in the southwest–northeast direction. Fractured surface textures in the centre of the depression are morphologically similar to lava surfaces disrupted by collapse caused by the withdrawal of lava.

Other features in northern Arabia Terra contain evidence for collapse associated with volcanic activity. Siloe patera (6.6° E, 35.2° N) is a set of nested deep depressions that reach ~1,750 m below the surrounding plains (Fig. 3). Similar to Eden patera, the nested craters are characterized by steep-walled depressions linked by arcuate scarps and faults. The primary structure is linked to a subtle northeast–southwest-trending depression to the south that reaches ~700 m depth, which we interpret as evidence for sagging due to the migration of a magma body at depth. Although there is no evidence for impact ejecta around the structure, there is a single set of lobate flows emanating from the southwest portion of the depression rim, which may represent a single set of lava or pyroclastic flows reaching ~60 km from the rim. Irregular mounds of friable materials inside the nested craters are interpreted as pyroclastics from the volcano or as younger friable deposits of another origin.

Some other depressions in the region contain less well preserved evidence for volcanism, but in all cases they contain suites of features that are difficult to explain by other geological processes. Semeykin crater is a large scalloped depression surrounded by lava plains and friable deposits; it also contains mounds of friable materials in its interior and ridged plains along the exterior. A suite of features, Ismenia patera, Oxus patera and Oxus cavus, are located together near 0° E, 38.5° N. The two paterae have scalloped, breached rims composed of layered materials. Oxus cavus is an elongated depression within a broad mound 200–300 m high adjacent to a deep depression indicative of sagging or collapse. Although none of these structures individually contains as many pieces of evidence to clearly point to volcanism as are seen at Eden patera, all of the features contain some evidence for structural collapse, which is most likely to have occurred through magmatic activity (although other hypotheses are considered below).

Eden patera and Euphrates patera represent the strongest evidence for large calderas in Arabia Terra, on the basis of their association with features that are diagnostic of surface disruption and collapse coupled with evidence for effusive and explosive volcanism. Some of the other features with fewer diagnostic features might not all represent caldera formation, or they could have experienced a range of processes responsible for the current morphology. Nonetheless, the region does show strong evidence that several large depressions did not form as impact craters and are most easily explained as volcanic calderas.

The roles of ice and impact

Some depressions throughout Arabia Terra have previously been interpreted as thermokarst features[28,29]. There is no doubt that geological surfaces in and around the Arabia Terra region have been modified by ice[30], but we argue that it is unlikely that ice removal could have created the collapse features themselves. Scalloped depressions in the Utopia Planitia region of Mars bear a striking resemblance in size, shape and morphology to thermokarst features found on Earth[31,32]; both terrestrial and Martian types form depressions on the order of metres to tens of metres in depth[33,34] (Fig. 4). Thus, those well-accepted thermokarst features are orders of magnitude smaller than the collapse features discussed here, whereas the proposed volcanic

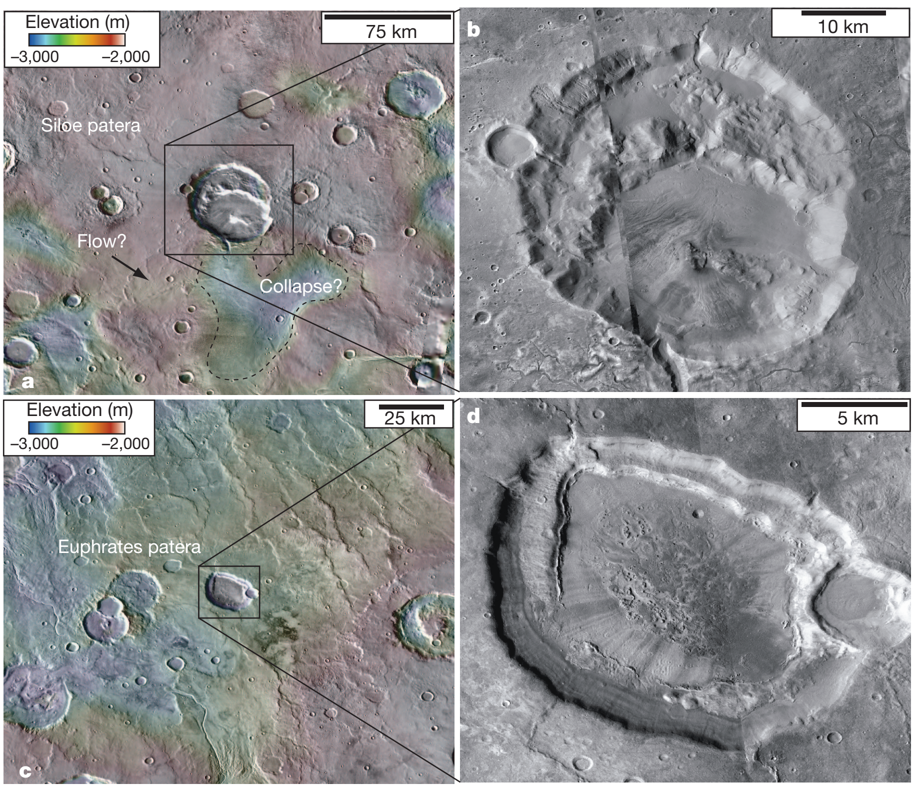

Figure 3 | The geology of Siloe and Euphrates paterae. MOLA data draped over CTX images show the morphologies of Siloe patera (**a**; rectangle enlarged in **b**) and Euphrates patera (**c**; rectangle enlarged in **d**).

structures in Arabia Terra are of the same scale and morphology as terrestrial supervolcanoes[35] (Fig. 4). If these proposed volcanic structures are in fact the result of thermokarst, then they are a new type of thermokarst beyond any that has been definitively recognized previously.

In addition, the large volume of the collapse features is a strong constraint on the possible origins. If they formed by collapse associated with the removal of subsurface ice, it necessarily implies that a significant volume of ice was removed from each location, quickly enough to cause the high strain rates required for faulting. However, none of the features is associated with outflow channels, which are typically cited as evidence for the rapid removal of surface or near-surface ice. Furthermore, the amount of ice that could have existed below such depressions can be constrained from quantitative models of Martian subsurface porosity[36]. For example, if Eden patera had been formed by the removal of subsurface ice, it would have been necessary for all of the available void space to be entirely saturated with ice to a depth of ~10 km (see Supplementary Information). We therefore conclude that, although ice and thermokarst processes could have been involved in the modification of the collapse features, it is unlikely to explain the origin of the collapse or the presence of the large depressions.

It is also possible that the depressions in Arabia Terra represent degraded impact craters. However, none of the features described above contain evidence for impact geology, such as the presence of ejecta, raised crater rims, central peaks or inverted stratigraphy. It is possible that erosion has removed such evidence, but the proposed calderas are found adjacent to ancient impact craters of similar size (and possibly similar age) that have preserved clear evidence for impact origins (Fig. 5). Furthermore, impact craters that have been degraded by erosion[37] have much lower depth-to-diameter ratios than those measured in the proposed calderas (Fig. 5). The relations between depth and diameter among the calderas are only consistent with depth-to-diameter ratios of impact craters that are only partly modified; such craters have preserved at least some critical aspects of impact geology.

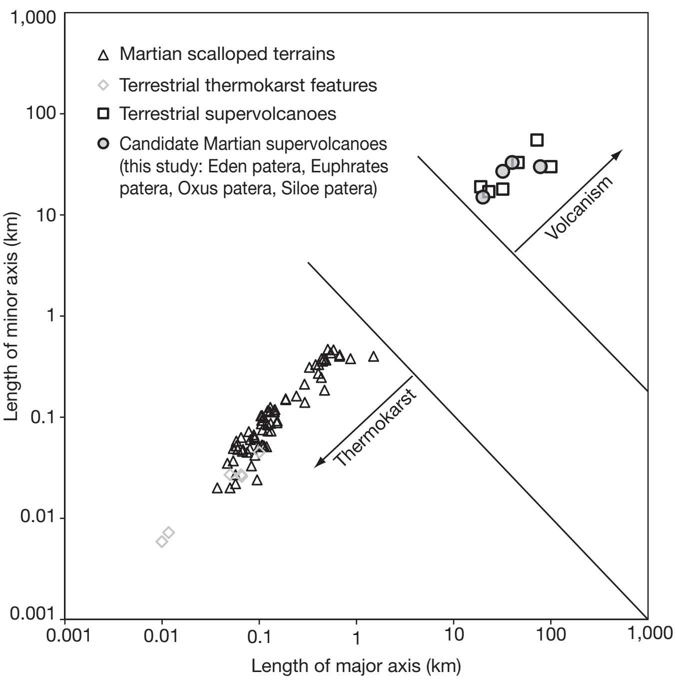

Figure 4 | Comparison of thermokarst features, terrestrial supervolcanoes and the putative supervolcanoes on Mars. A plot of the dimensions of typical terrestrial and Martian thermokarst features shows that they have roughly similar sizes[32,34]. The proposed calderas in Arabia Terra have similar dimensions to those of terrestrial supervolcanoes, which together are orders of magnitude larger than known thermokarst features.

A new category of Martian volcanic construct

Taken together, these features constitute a new category of Martian volcano that can be described as plains-style caldera complexes, of which Eden patera is the type example. Eden patera is not associated with a major edifice. Each of the Martian low-slope paterae recognized previously[12,13] shows a major edifice related to repeated volcanic deposition of explosive and effusive products. Thus, Eden patera seems to be a new class of Martian volcanic feature, formed through a combination of magma withdraw, subsurface magma migration (caldera 1) and/or major explosive episodes that would have distributed ash regionally or globally such that they did not accumulate near the vent (calderas 2 and 3). These geomorphic features are most analogous to those of a terrestrial supervolcano.

On Earth a supervolcano is defined as a volcano that can produce at least 1,000 km^3 of volcanic materials in an eruption. On Mars it is generally not possible to link a single volcanic deposit to a particular eruption event. However, erupted volumes can be constrained from the volume of void space observed in the caldera itself, if that collapse

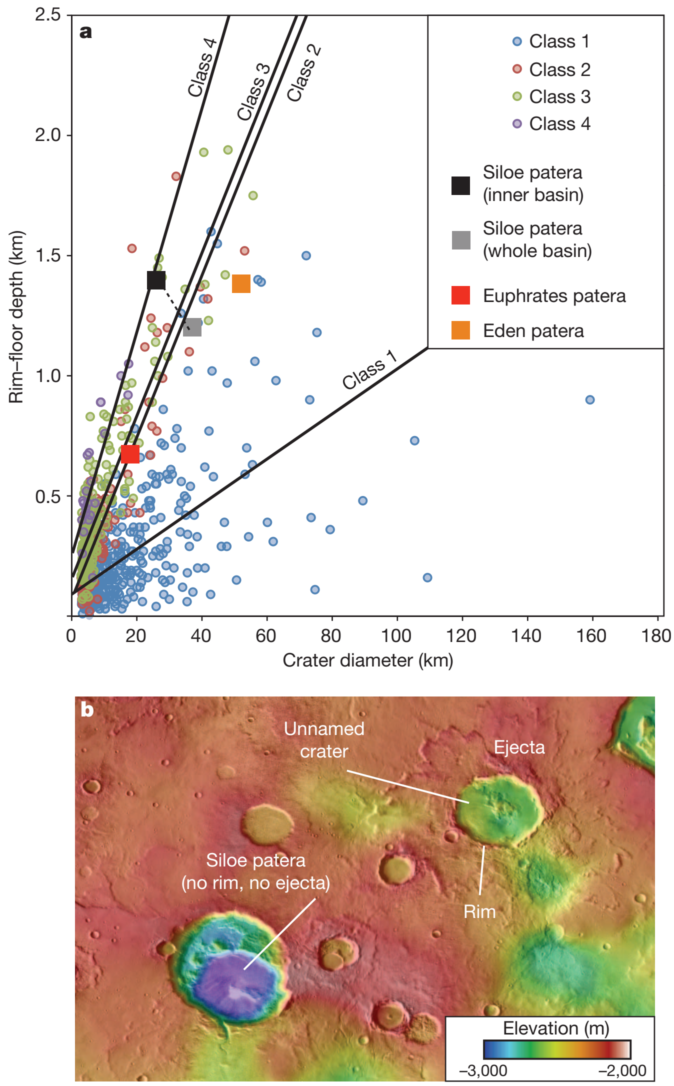

Figure 5 | Comparison of the depth-to-diameter ratios of possible Martian supervolcanoes with those of known impact craters. **a**, Plot of crater measurements for all of the craters within the area of Fig. 1 with diameters of 1 km or more that have previously been categorized according to their level of preservation[37]. Class 1 craters are the most degraded and class 4 are the least degraded (essentially pristine). The proposed supervolcanoes plot along trendlines associated with moderately modified craters that preserved impact morphologies. **b**, However, the calderas clearly do not contain morphological evidence for impact processes as seen in adjacent craters of similar size.

is assumed to have occurred as a result of the removal of magma during eruptive events. Focusing on a subset of these features including Eden patera, Oxus cavus, Semeyken crater and Ismenia patera, the average depression volume is more than 3,300 km^3. This volume at each site could have been produced by the removal of a comparable amount of dense-rock-equivalent material. Assuming an average density of 2,800 $kg\,m^{-3}$ of the magma and an estimated density of 2,000 $kg\,m^{-3}$ for erupted lava or 1,300 $kg\,m^{-3}$ for tephra, it is possible to estimate the amount of erupted material from each source. The average minimum erupted volume could be more than 4,600–7,200 km^3 for each of these caldera complexes. Although this estimate cannot be linked to a single eruption event, nor can we differentiate void space created by explosive ejection from that created by magmatic subsidence, these features are unlike other known Martian volcanoes and it is likely that they fall in the category of terrestrial supervolcano, on the basis of both geomorphology and eruptive potential.

The question remains: Why would large calderas associated with explosive volcanism occur in northern Arabia Terra? One possibility is that volatile-rich crust was subducted beneath Arabia Terra during an ancient episode of plate tectonics[38]. However, although the presence of northwest–southeast-trending scarps related to thrust faulting in northern Arabia Terra related to southwest–northeast compression might seem consistent with such an interpretation, the estimated displacement on such faults is small and does not support the model of an active plate margin[28,39]. It is more likely that the dichotomy boundary evolved as a result of crustal thinning associated with endogenic processes[39]. The crust within Arabia Terra is relatively thin and more similar to thicknesses modelled for the northern lowlands than for the southern highlands[40]. Even so, we consider an origin due to subduction to be an open question that merits further consideration.

We suggest that a combination of regional extension and thermal erosion of the lower crust in the Late Noachian to Early Hesperian led to a rapid ascent of magma in the northern Arabia Terra region. It is not necessary that the magmas were of higher viscosity (more silicic) or had higher volatile content than other Martian magmas. The lower gravity and atmospheric pressure on Mars lead to bubble nucleation at greater depths and greater gas expansion in comparison with Earth[41]. As a result, pyroclastic eruptions would be more commonly associated with basaltic volcanoes on Mars than on Earth, particularly if the magma rapidly ascended and erupted and was not stored in degassing magma chambers for long periods, as is thought to occur at younger, large shield volcanoes[42]. In fact, it is possible that explosive volcanism was more prevalent globally on early Mars because the ancient crust was thinner, leading to less devolatilization of magmas during ascent. The result may have been the deposition of vast quantities of tephra early in Mars's history.

Links to global geology

Explosive eruptions of fine-grained materials might be linked to the formation of fretted terrains that also occur in northern Arabia Terra, the origin of which represents one of the major outstanding mysteries in Mars science[29] (Fig. 6). Youthful ice-related processes may have modified the fretted terrains, but the sediment of which they are composed was probably deposited in the Noachian to Early Hesperian[43]. These voluminous, fine-grained sediments may be tephra deposits from explosive volcanic activity in northern Arabia Terra. In fact, layered terrains throughout Arabia Terra might consist of tephra deposits, but previous work has suggested that the source region was the Tharsis province[5]. A much simpler explanation is that plains-style calderas produced these sediments locally[44] (Fig. 6).

Our understanding of volcanism[45] on Mars continues to evolve as numerous, small (tens of kilometres in diameter) and dispersed volcanic centres are recognized throughout the Tharsis region[46–49], and degraded, ancient volcanic centres are recognized in the southern highlands[12,13]. Major volcanic constructs are now recognized in several distinct provinces throughout the Martian surface, although with a paucity of features previously identified between Tharsis and Syrtis Major (Fig. 4). The features identified here constitute a major volcanic province in Arabia Terra, which fills a void in a large fraction of the surface where volcanoes are expected to have occurred but have never been recognized.

The origin of altered, fine-grained, layered, clay-bearing and sulphate-bearing sediments throughout the equatorial region of Mars has yet to be explained. A local volcanic source could explain the presence of clastic materials composing these deposits and could serve as a significant source of volcanogenic sulphur that might have led to acidic alteration at the surface and strongly perturbed the Martian climate, sending it into periods of significant warming[18] or substantial cooling[19]. We suggest that fine-grained deposits at the Meridiani Planum and Gale crater landing sites, as well as friable deposits in the equatorial region of Mars, might ultimately have originated from volcanic sources in Arabia Terra. Further mapping of plains-style caldera complexes might reveal additional ancient volcanic source regions distributed throughout the Martian highlands. Deciphering the nature of an early

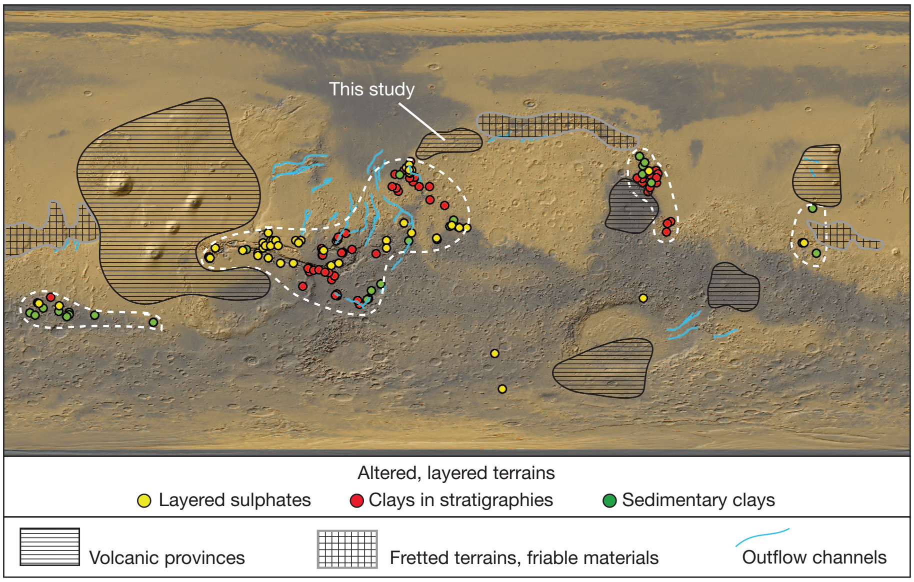

Figure 6 | Links to global geology. The distribution of major volcanic provinces on Mars in relation to friable and fretted terrain, layered sulphates[17] and layered clay-bearing terrains[50].

phase of widespread, disseminated, explosive volcanism will be critical to revealing the climate history and past habitability of Mars.

METHODS SUMMARY

The primary data sets used to evaluate the geomorphology of topographic depressions in the Arabia Terra region were gridded elevation data from the Mars Orbiter Laser Altimeter (MOLA) and a global mosaic of daytime infrared images from the Thermal Emission Imaging System (THEMIS). Additional data products included high-resolution images and digital topographic data from the High Resolution Stereo Camera (HRSC) aboard the Mars Express spacecraft, high-resolution images from the High Resolution Imaging Science Experiment (HiRISE) and Mars Context Imager (CTX) aboard the Mars Reconnaissance Orbiter, and the Mars Orbiter Camera (MOC) aboard the Mars Global Surveyor spacecraft. These data products are available within the publicly available Java Mission-planning and Analysis for Remote Sensing (JMARS) software produced by Arizona State University (available at http://jmars.mars.asu.edu). Image-based geological mapping was performed after geo-registering these data products within a geographic information system (GIS). Data from the Thermal Emission Spectrometer (TES) were used to evaluate dust cover and albedo.

Full Methods and any associated references are available in the online version of the paper.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.R.M. (michalski@psi.edu).

METHODS

Identification of volcanic features. Most well-recognized volcanic edifices on Mars occur as central vent structures within topographically elevated terrain built through sustained volcanism around the vent. Pavonis Mons (Supplementary Fig. 1) is an example of typical shield-style volcanism on Mars. Note that Pavonis Mons contains evidence for collapse and crustal sagging owing to removal or migration of magma. The central caldera is a steep-sided, nearly circular crater that formed during the latest stage of volcanic activity. However, that caldera is nested within a larger set of ring-fractures that suggest more extensive collapse or additional collapse events. Complex calderas are common on the Earth and Mars, and occur as a result of collapse associated with magma withdrawal, owing to migration of magma at depth, removal of magma during eruptions, or both. Tyrrhenus Mons (Supplementary Fig. 1b) is an ancient volcano of different character on Mars. It also is defined by a topographic rise with ring fractures. However, the flanks of Tyrhennus Mons have a much lower profile than Pavonis Mons and are composed of fingering, eroded, layered materials thought to indicate the presence of pyroclastic materials. Tyrrhena patera (the main caldera) might be the final location of the central vent, but the caldera is breached and eroded, and there is evidence for secondary calderas on the volcano. The plains-style caldera complexes that we have identified in northern Arabia Terra bear characteristics similar to each of these volcanoes, yet some other characteristics that are fundamentally different. Most notably, the calderas in Arabia Terra do not occur on topographically elevated volcanic constructs, which is probably one reason why they have never previously been identified as volcanoes despite abundant evidence for volcanic processes.

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

Supplementary Fig. 2 shows the morphology of all seven features discussed in the text. Of these, Eden patera and Euphrates patera bear the strongest evidence for ancient volcanism. The others probably formed through collapse, although the link to volcanism is less clear in the other cases.

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

To estimate the amount of collapse that has occurred, we mapped the features in a GIS environment and used MOLA elevation data to calculate the volume of each depression. The volume calculations are straightforward but depend on several assumptions. First we describe the technical process, and then the assumptions.

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

Examples of the volume calculations are shown in Supplementary Fig. 3. Note that the fit of an elevation plane to each site is imperfect. One assumption we make is that topography has not changed since the formation of the depressions. This is clearly not so, but it is a limitation on our approach. There is clear evidence that the entire region has been tilted towards the north since the formation of these features. In addition, several of the calderas described in this work show evidence that they were breached, which means that there is not an obvious closed depression at most structures. Therefore, delineation of a single closed depression grossly underestimates the actual volume of the structure because the calderas are typically breached at some elevation along the rim. Last, younger impact craters have been superimposed on each site, which further complicates the effort to define a single elevation contour related exclusively to the caldera collapse itself. Given these challenges, we have made every effort to perform the volume calculations with the most conservative approach possible, to avoid overestimating the volume of each depression. We have therefore chosen elevations that in each case are below the rim of the depression, to provide the best estimate of a closed depression with the knowledge that this decision results in an underestimate of the total caldera volume.

There are errors associated with these analyses, both in the direction of artificially increasing the volume estimates and in the direction of artificially decreasing them. One of the major errors resulting in underestimation of the volume calculations is related to the fill deposits within the depressions themselves. Those materials were probably sourced from the caldera in each case, but their topographic setting now is still considered part of the underlying terrain. In other words, there is no way to identify the true caldera floor because friable fill deposits bury the floor in most cases. We are calculating volumes of the void space that exists above modern topographic depression in each case. Our calculations therefore actually correspond to the volume of the caldera that has not been filled by friable materials, lavas or colluvial deposits.

There are two sources of error that lead to overestimation of volumes. The first is related to the erosional breaching of rims of the depression. In fitting a plane to the best estimate of the closed depression, there is still some additional volume added by calculating void space above the plains surrounding the breached depression. However, we made every effort to avoid this bias as much as possible, and the errors that did occur are likely to have been small. Another bias includes the calculation of void space within superimposed impact craters that have interior depressions rivalling the depth of the caldera itself (see Supplementary Fig. 4). However, these errors are again extremely small and do not change the calculated volumes appreciably.

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

To test this hypothesis we used the volume calculations described above to constrain how much ice must have been removed to produce the collapse by removal of ice from the subsurface. Models describing the amount and distribution of subsurface ice on Mars have been produced[36]. These calculations include models of subsurface porosity as a function of depth. Using those models of porosity, we can then calculate the amount of pore space that could potentially have been filled with ice beneath a given feature. In other words, is there enough pore space available that, even if entirely filled with subsurface ice, would result in the collapse volume of the depression if all of that ice were removed?

The best test case is Eden patera. Here, $\sim$4,000 km^3 of void space exists. If that space was created by means of collapse that was related to removal of ice, it stands to reason that the ice must have been present essentially beneath the feature itself. If the ice was widely distributed in area, its removal would probably have produced multiple small collapse pits (if any at all) or regional subsidence. We therefore focus on the area of the depression itself. In the case of Eden patera, this area is roughly equal to 5,000 km^2.

Supplementary Figure 4 shows the decay of porosity with depth on Mars and the cumulative volume of void space beneath an area of 5,000 km^2 beneath Eden patera. Pore space decays to near zero by a depth of $\sim$10 km. If all of the void space to this depth were completely filled with ice, it would result in a total volume of $\sim$4,000 km^3—roughly equal to the volume of collapse at Eden patera. Therefore, the calculations, to first order, suggest that the volume of collapse at Eden patera could potentially be explained theoretically by the removal of subsurface ice. However, we suggest that the calculations present a compelling case that ice was not solely responsible for the formation of the collapse at Eden patera because they imply that all of the void space became filled with ice to a great depth and then all of that ice was somehow removed from the subsurface without leaving any traces of fluvial features (that is, outflow channels) that could be related to catastrophic melting.

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

Assuming that the void space within calderas relates directly to the removal of magma during eruptions, we can produce some simple scaling calculations to estimate how much material may have been erupted. By assuming a dense rock equivalent (DSE) of caldera volume equal to a typical mafic magma with density of 2,800 $kg\,m^{-3}$, we can then scale the DSE for a lava density of 2,000 $kg\,m^{-3}$ or a tephra of density 1,000-1,500 $kg\,m^{-3}$. Using these scaling factors and the volume calculations described above, we calculated the estimated minimum erupted volumes described in the text.