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Dyke swarms record the plume stage evolution of the Atla Regio superplume on Venus

Hafida El Bilali[1], Richard E. Ernst[1✉], Kenneth L. Buchan[2] & James W. Head[3]

Atla Regio, Venus, is interpreted as a young major mantle plume centre, and we address whether it is at plume head or plume tail stage. Our approach uses graben-fissure lineaments, interpreted as the surface expression of dykes. Mapping > 40,000 such lineaments reveals giant radiating dyke swarms associated with major volcanic centres of Maat (>1500 km dyke swarm radius), Ozza (>2000 km), Ongwuti (>1100 km) and Unnamed montes (>1100 km), indicating that each is due to plume head magmatism rather than plume tail magmatism (maximum swarm length ~ 100 km). The size of an underlying flattened plume head is estimated by the radius where the swarm transitions from a radiating to linear pattern. All four centres and their plume heads group within the 1200 km radius of the Ozza Mons plume head, consistent with a single event. Atla Regio is at the plume head stage with coeval triple-junction rifting, which on Earth would typically precede attempted continental breakup.

[1] Department of Earth Sciences, Carleton University, Ottawa, ON, Canada. [2] Private Address, Ottawa, ON, Canada. [3] Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA. ✉email: Richard.Ernst@Carleton.ca

Given the absence of plate tectonics[1] (at least since ~1 Ga ago[2]), all volcanism on Venus is intraplate and the largest events are considered analogous to terrestrial Large Igneous Provinces (LIPs) generated by large mantle plumes[3–6]. We apply a terrestrial dyke swarm interpretation to assess whether one of the largest and youngest interpreted Venusian plume events, Atla Regio, is still at the plume head stage or has progressed to the plume tail stage. If at the plume head stage, then in a terrestrial plate-tectonics context, it could just be a few Myr away from an attempted continental breakup. However, if Atla Regio has already reached the plume tail stage, then (in a terrestrial context) the timing for any breakup transitioning into ocean crust spreading would likely be passed.

On Earth, an ascending mantle plume arriving at the base of the lithosphere can massively and partially melt and produce a LIP with a scale of at least 100,000 km^2 and in some cases millions of km^2 [7,8]. Seismic tomography and thermal modelling suggest that the plume conduit (stalk) is only about 100–200 km wide as it buoyantly ascends through the mantle, with the top (the head) of the plume growing during ascent, due to resistance from the overlying mantle[7]. For a plume originating in the lower mantle, the plume head is about 1000–1200 km in diameter when it reaches the base of the lithosphere. It rapidly spreads to produce a flattened plume head about 2000–2400 km in diameter[7,9]. The voluminous LIP volcanism associated with the plume head ('starting plume') stage can be of short duration, often only lasting a few million years. However, LIPs can also be of longer duration, especially when associated with rifting, with multiple magmatic pulses spanning up to several 10 s of Myr[8].

Beyond about 50 Myr the capacity for high-volume partial melting of the plume head diminishes as the plume head thermal anomaly cools (e.g.[9,10]). After this point 'plume tail' volcanism can continue via continued ascent and partial melting of the plume tail for a duration of up to at least 180 Myr (e.g. refs. [7,11,12]). The plume tail stage is associated with smaller volumes of partial melting and on Earth is typically recognised by a hot spot chain, as the lithospheric plate moves above the approximately stationary plume tail. The classic example is the >6000 km long Hawaiian-Emperor seamount (hot spot) chain that can be traced for at least 85 Myr across the moving Pacific plate; in this case, the inferred initial plume head event, an oceanic plateau, is interpreted to have been partly subducted in the Aleutian trench and partly obducted in Kamchatka, Russia[13,14].

On the other hand, if the plate is approximately stationary (as on Venus, which is currently a one-plate planet[1]), the entire volume of plume tail magmatism would be superimposed in one location[4]. A terrestrial example is the Iceland plateau, which can be interpreted as the accumulation in one spot (fixed on a spreading ridge) from the plume tail stage following the plume head stage that produced the 62–55 Ma North Atlantic LIP[15]. Although, the volcanism of the plume tail stage is characterised by low flux, the cumulative volume can be huge. In the case of Hawaii, the cumulative volume of the 85 Myr duration Hawaii-Emperor hot spot chain (not including any estimate of the subducted portion) is 750,000 km^3 (https://pubs.usgs.gov/gip/dynamic/Hawaiian.html). The volume of the Iceland plateau is approximately 1.6 Mkm^3 based on its E-W extent of 800 km, N-S extent of 500 km and 4000 m elevation above the seafloor[16]. Thus, the cumulative volume of plume tail magmatism can be of LIP scale, making it difficult to determine whether a volcanic centre represents a LIP (plume head event) or the accumulation (in one location) of protracted plume tail magmatism. In this contribution, we use mafic dyke swarm length (or lava flow length) as a simple proxy parameter for identifying whether a volcanic centre (on Venus or on Earth) is at the plume head or plume tail stage.

Atla Regio is part of the extensive BAT (Beta-Atla-Themis) region with the youngest volcanism and rifting on Venus[4,17–23]. Atla Regio represents a major concentration of large volcanic centres and related coronae that are associated with topographic and geoid highs, gravity lows and a radiating rift system (Fig. 1), all classic signatures of terrestrial LIPs associated with currently active large mantle plumes that originated in the deep mantle[7,8,11] (Fig. 1). Available modelling of the Venusian mantle suggests it can also support mantle plumes[17,24,25].

Major volcanic centres belonging to Atla Regio include Maat Mons (9 km elevation, with reference to mean planetary radius), the highest volcano on Venus[26,27], Ozza Mons (7.5 km elevation), Ongwuti Mons (8.5 km elevation), and an unnamed mons (7.5 km elevation), which will be referred to in this study as 'Unnamed Mons'. Major lava flows, at least 1200 km long, are associated with the volcanic features. For instance, Ningyo fluctus is a major flow field 1200 km long[28]. A remarkable four-armed 'triple-junction' rift system radiates from Ozza Mons (Fig. 1). It features the 8000 km long ENE-trending Hecate Chasma which connects with Beta Regio[29–31], the 10,000 km long SE-trending Parga Chasma which connects with Themis Regio[29,31,32], the 7500 km long SW-trending Dali-Diana Chasma which connects with Thetis Regio[33] and the 2500 km long N-trending Ganiki (Ganis) Chasma[34,35].

However, the characteristics and timing of Atla Regio volcanism are not well understood, with the most detailed regional mapping conducted at a scale of about 1:2.5 M[26]. More detailed mapping at a scale of about 1:500,000 is in progress[27,36]. An important question is the level of present-day volcanic activity. One insight is from the Ganiki Chasma, north of Atla Regio, where the Venus Express mission revealed transient thermal anomalies interpreted to represent the extrusion of lava flows[34,35]. Also, based on emissivity data from NASA's Magellan mission, ref. [37] concluded that some of the lava flows at Maat Mons may be geologically recent. Herrick and Hensley[38] recently proposed ongoing volcanic activity at Matt Mons based on differences observed in Magellan images taken eight months apart.

Results and discussion

Dyke swarms and magmatic centres of Atla Regio. While there have been regional and some detailed studies on the volcanism and rifting associated with Atla Regio[18,19,22,26], the dyke swarm component has not been previously considered, except at a reconnaissance scale[39,40]. Comparable LIP magmatism on Earth consists of major volcanism in the form of shield and plateau basalts, and a plumbing system that includes giant radiating (up to 3000 km in radius) and circumferential dyke swarms (up to 1800 km in diameter) (e.g. refs. [5,41,42]). Given the absence of extensive surface erosion on Venus (at least back to the time of formation of tessera terrain, the stratigraphically oldest unit in the global geological record[22]), dyke swarms on Venus are unlikely to be exposed on the surface. Rather they are interpreted to be expressed as sets of long narrow grabens and fissures (and also pit chains) that overlie blind dykes (not reaching the surface) that were, for the most part, laterally emplaced (e.g. refs. [39,43]). Although such grabens above dykes are rarely observed on Earth due to extensive erosion, they have been documented in a number of dyke swarms[44,45]. There have been several detailed studies of graben systems (herein, we use graben system as a short form for graben-fissure system) interpreted in the context of dykes in multiple regions of Venus (e.g. refs. [29,46–48]) and other planetary bodies[41,49,50]. Such grabens are interpreted to overlie dykes on the basis of specific criteria: (a) the grabens extend beyond any central domal uplift (and are therefore not purely tectonic

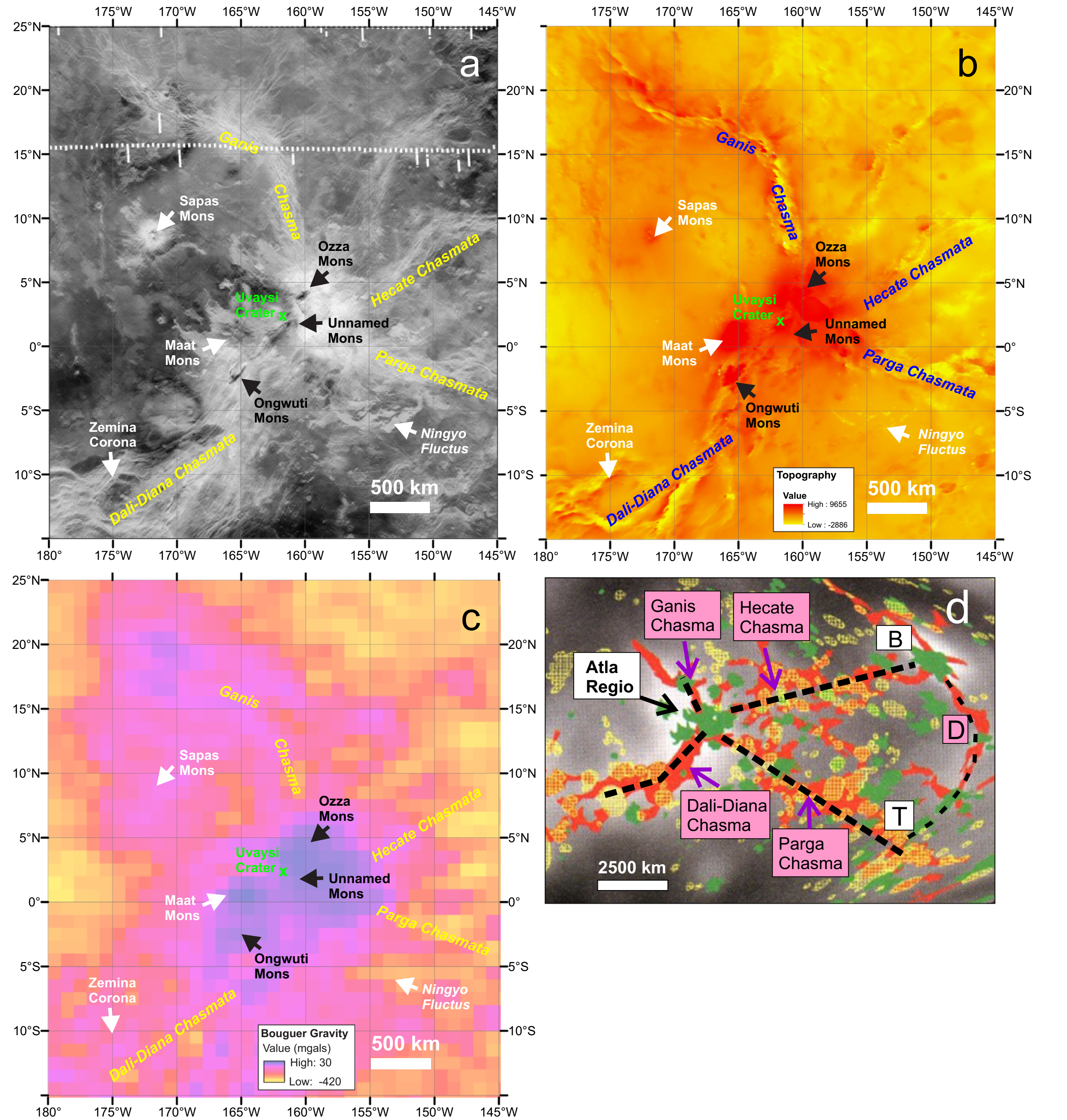

Fig. 1 Atla Regio study area. a NASA Magellan SAR (synthetic aperture radar) image annotated with features discussed in the text. **b** Magellan topography data. **c** Bouguer gravity data[76] with negative anomaly spatially associated with the four main centres of Atla Regio (pixel size 100 km, but with resolution size ranging from 170-540 km[17,76]. **d** location of Atla Regio and associated triple-junction rift arms in BAT (Beta-Atla-Themis) region. B Beta Regio, T Themis Regio, D Devana Chasma. Basemap, after[77], in sinusoidal projection of Venus with rift zones (chasmata) in red, large volcanoes in green and coronae in yellow, and superimposed on geoid level (grey scale with value increasing from dark to light). NASA Magellan topographic data downloaded from from USGS Astrogeology Science Center (https://astrogeology.usgs.gov/search?pmi-target=venus).

features), (b) lava flows locally emanate from the grabens, (c) pit craters are aligned along the grabens[48,51] and (d) chains of shield volcanoes are aligned along the grabens (see Methods for a more detailed discussion of the evidence for recognising grabens which are overlying dykes, and distinguishing them from purely tectonic extensional lineaments).

The mapping of Atla Regio graben systems (interpreted as dyke swarms) is shown in Fig. 2, with more than 40,000 lineaments traced to date. Generalised (and colour-coded) linework is shown in Fig. 3 and S7. These giant radiating (and circumferential) graben systems are linked to the four recognised montes of Atla Regio (Ongwuti, Ozza, Unnamed and Maat mons), two

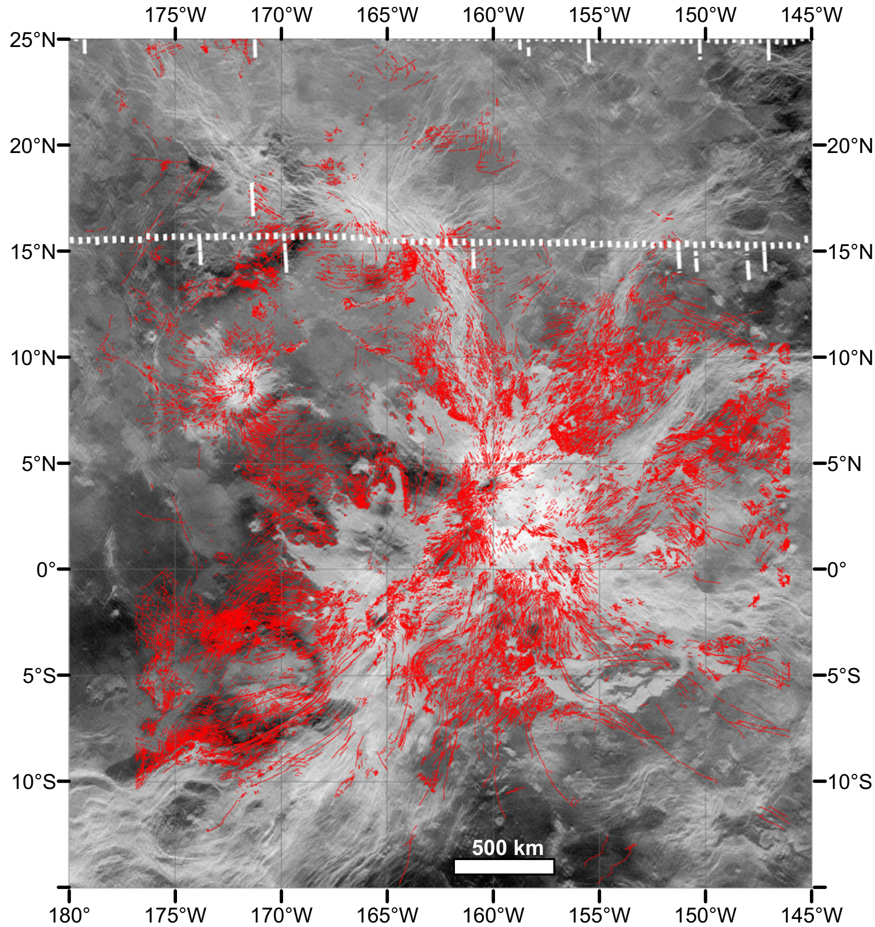

Fig. 2 More than 40,000 graben-fissure lineaments were mapped in this study and interpreted as underlain by mafic dykes. They are so densely mapped in some areas that they appear as continuous red colour. See the generalised distributions in Fig. 3, which show the geometric patterns with improved clarity. Background NASA Magellan SAR image in this figure and also in Figs. 2–5 and 6a are downloaded from the USGS Astrogeology Science Center (https://astrogeology.usgs.gov/search?pmi-target=venus).

additional named centres (Sapas Mons, and Zemina Corona), and multiple unnamed magmatic centres (Fig. 1). In this study, we focus our discussion on the four large volcanic centres of Atla Regio, Ongwuti, Ozza, Unnamed and Maat montes, whose graben systems extend radially for >1100, >2000, >1100 and >1500 km, respectively.

The relative age of magmatism associated with the various montes of Atla Regio is determined based on cross-cutting relationships of lineaments, flows and craters, and is presented in Figs. S2–S6. These data indicate that the relative age order from oldest to youngest is Ongwuti, Ozza, Unnamed and finally Maat mons. However, the volcanism of Ozza Mons continued during the emplacement of the Maat Mons radiating graben set. Furthermore, the development of the major arms of triple-junction rifting (Fig. 1) are associated with the Ozza Mons stage. While Sapas Mons could also be related to the Atla Regio superplume given its proximity (Fig. 1), cross-cutting relationships (Figs. S2–S6) indicate that its magmatism preceded the magmatism of the four Atla Regio centres discussed above, and, hence, is likely not part of the Atla Regio superplume. Zemina Corona, which is further away (Fig. 1), is also thought to be older.

Atla Regio plume head stage. Giant mafic dyke swarms on Earth can be emplaced laterally for great distances beyond the edge of the underlying plume head because of a continued flux of magma being laterally injected from the plume centre region[40,43,52]. This mechanism solved an important problem related to the nature of graben systems on Venus and Mars[39,50]. On Venus, it explained how radiating graben-fissure systems could extend beyond the domal uplift[40]. On Mars, the problem was even more acute. It is impossible for the entire extent of the Tharsis region radiating graben systems (up to 4000 km in radius) to form only by domal uplift, since the small radius of curvature for Mars appeared to require two distinct modes for the formation of the radiating grabens: on the top of Tharsis (attributed to isostatic stresses) and on the flanks and distal portions of the rise (more consistent with flexure)[50].

The inferred dykes underlying large radiating graben systems on Venus are interpreted to be mainly mafic in composition (likely dolerites). This interpretation is based on: (a) the remarkable similarity in the distribution patterns of these graben systems with terrestrial giant mafic (dolerite) dyke swarms and (b) their spatial association and apparent plumbing system relationships with the widespread 80% of Venus that is inferred to be covered by basaltic volcanism.

The size of a plume head (as it spreads and flattens against the base of the lithosphere) can be estimated from the geometry of the associated giant radiating dyke swarm. This approach was developed for terrestrial LIPs, where the distance at which the dyke swarm transitions from a radiating pattern (due to the stress field associated with the underlying plume head) to a linear pattern (due to the dominance of the regional stress field) is a proxy for plume head size[5,43,52]. Similarly, Venusian swarms

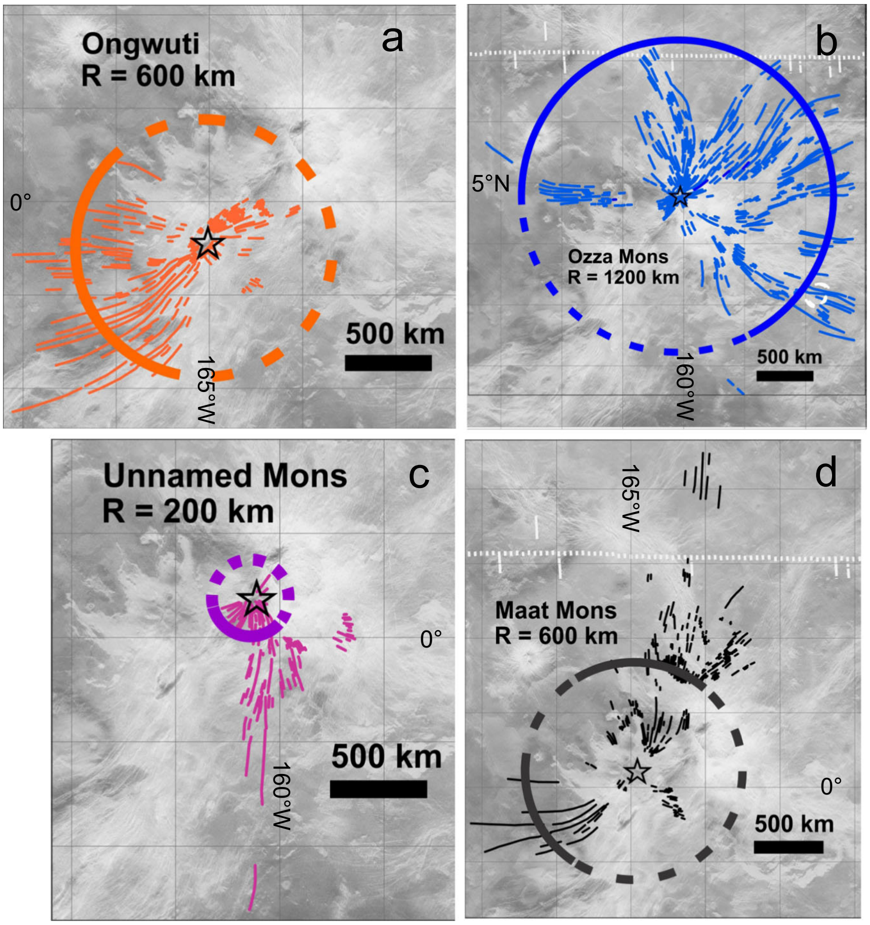

Fig. 3 Generalised graben-fissure systems (from Fig. 2) associated with the four main centres on the background of NASA Magellan SAR images. Circles indicate the inferred plume head size based on the radius (R) of transition in the dyke swarms, from radiating to linear; dashed where unconstrained (see text for discussion). Additional generalised lines are shown in Fig. S7. The maximum radius of each swarm is: **a** Ongwuti Mons = >1100 km, **b** Ozza Mons = >2000 km, **c** Unnamed Mons = >1100 km, **d** Maat Mons = >1500 km.

typically transition from a radiating to a linear geometry, with the latter reflecting a regional stress field[5,40,53]. We apply this criterion to the radiating swarms of Atla Regio in order to estimate the size of the underlying and evolving plume head that is responsible for the uplift and the transition in dyke trend.

The current topography of Atla Regio is the result of multiple magmatic centres and stages of uplift. Similar complications occur for some plume/LIP associations on Earth (ch. 12 in ref. [8]). Our dyke swarm approach circumvents these issues. On Earth, each dyke swarm (radiating or circumferential) represents a short-duration snapshot (confirmed by precise U-Pb dating) of the stress pattern associated with a specific magmatic centre. Therefore, multiple intermixed dyke swarms associated with a single magmatic event capture the stress history of the evolving plume head in a series of timestep snapshots. Implicit in this view is that dyke swarm trends accurately reflect the regional stress (at each timestep); this has been repeatedly shown to be true for terrestrial swarms, with only local influence of pre-existing fractures or zones of weakness[8].

Applying this dyke swarm method, we conclude that the largest plume head associated with Atla Regio is that of Ozza Mons, with an inferred radius of 1200 km (Fig. 3). The plume heads of the other three major magmatic centres (with radii of 600, 600 and 200 km) are all enclosed within the extent of the Ozza Mons plume head (Fig. 4).

On the basis of this scale comparison, we interpret all four Atla Regio magmatic centres (Ongwuti, Ozza, Unnamed and Maat montes) to be related to a single large plume (or superplume; variably defined[4,11,54], but here used to refer to a large plume derived from the deep mantle) centred on Ozza Mons. In the absence of radiometric dating (no rock samples are available from Venus), the spatial clustering of these major magmatic centres is strong circumstantial evidence in support of these four volcanic centres being approximately coeval and all belonging to a single plume/LIP event. The spatially associated negative Bouguer gravity anomaly (Fig. 1c, see also Fig. 1b in ref. [55]) is explained by the decreased density associated with an underlying plume head that is still hot.

Maximum mafic dyke swarm length and flow length are simple proxy parameters for identifying whether a volcanic centre is at the plume head or plume tail stage. On Earth, giant radiating dyke swarms are associated with plume head events. They extend at least several hundred km, and in some cases nearly 3000 km away from the plume centre[8], owing to the high flux of magma from shallow buffered magma reservoir sources (continuously resupplied from deeper reservoirs) that feed these long dyke swarms[56]. In contrast, plume tail volcanism consists of smaller volume flows (fed from essentially unbuffered magma reservoirs), and their dyke swarms have a maximum length of about 100 km (ref. [43] and references therein). Lava flow length can also be a discriminant, with plume head stage lava flows extending up to hundreds and even >1000 km[8], and plume tail lavas typically up to 10 s of km long extending in rare cases up to >100 km (e.g. refs. [57–59]).

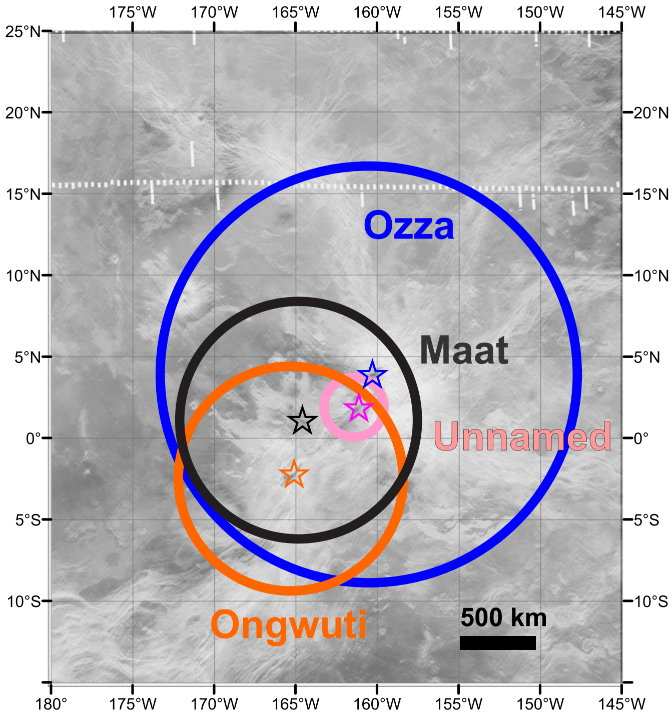

Fig. 4 Comparison of Atla Regio plume head locations and sizes. Plume head centres are marked by stars. Plume head sizes from Fig. 2 are based on the transition of dyke swarms from radiating to linear geometry. All plume heads can be encompassed within the radius of the Ozza Mons plume head. On a background of NASA Magellan SAR image.

We apply these terrestrial dyke swarm (and lava flow) observations to assess whether Atla Regio is at the plume head stage or has progressed to the plume tail stage. A potential caveat in applying these terrestrial relationships to Venus is considered. Unlike Earth, Venus does not have a low viscosity layer at the base of the lithosphere[6,60,61], which would lead to a wider plume tail reaching the base of the lithosphere on Venus compared to Earth (cf. ref. [62]. However, this will not result in longer plume tail dykes (nor greater lava flow length) on Venus, since the length of laterally emplaced dykes (and flows) is primarily controlled by available magma flux, which is much greater for buffered magma reservoirs[56] associated with the plume head stage and smaller for the unbuffered magma reservoirs at the plume tail stage.

Our approach is to examine the youngest magmatic centre at Atla Regio to see whether it represents an approximate equivalent to an Iceland plateau plume tail (small flux magmatism accumulated over many 10 s of million years). On Earth, plume tail magmatism is mainly expressed in the oceans (as hot spot trails) where crustal thickness is about 7 km and lithospheric thickness ranges from 50 to 140 km. Hotspots can be more rarely tracked into continents, but only where the lithosphere is thin (thinner than 110 km for hotspots of basaltic composition[63]). The Venusian crustal thickness at Atla Regio reaches about 40 km, but drops away to typical values for the plains of 20–25 km (Fig. 4c in ref. [55]; see also refs. [19,28]), and (elastic) lithospheric thickness is only about 20 km greater both beneath and away from Atla Regio (Fig. 6a in ref. [55]). With these values, plume tail magmatism should be able to traverse the Venusian lithosphere in the vicinity of Atla Regio and be observable.

The fact that giant radiating graben systems (giant dyke swarms, ranging in radius from 1100 to >2000 km) are associated with each of the four main volcanic centres on Atla Regio (Ongwuti, Ozza, Unnamed and Maat montes) indicates that each is at the plume head stage and not the plume tail stage. Of particular importance is the giant radiating graben system associated with the youngest volcanic centre of Maat Mons. Furthermore, there are no other major edifices recognised in Atla Regio that could represent an accumulation of plume tail magmatism above a stationary plate, or even any observed linear trend of volcanic edifices that could mark a hot spot track if there was some plate movement.

It should be noted that plume head graben systems and volcanics would likely be covered by any later plume tail magmatism (and their grabens). Therefore, the short plume tail grabens should be readily visible, and not simply intermixed with the older plume head grabens.

Young magmatism at Maat Mons is expressed as flows that postdate the major radiating dyke swarm. Some of these flows can reach hundreds of km long (e.g. Fig. 8 in ref. [26] and Fig. 1 in ref. [27]) in support of a plume head interpretation. However, the very youngest of these flows that are located at the summit of Maat Mons (Fig. 7[26]), have lengths of <100 km, and could possibly represent waning plume head activity or minor plume tail activity.

In conclusion, Atla Regio is interpreted to still be at the plume head stage, and potentially no older than about 50 Myr, by analogy with Earth (based on the maximum duration of plume-caused terrestrial LIPs[8]; see discussion above).

Geological history of Atla Regio. On the basis of our mapping, four stages are distinguished in the geological history of the Atla Regio (Fig. 5).

Stage 1. The initial stage of Atla Regio involves the Ongwuti centre. The elongation of this centre and its alignment with the younger Ozza and Unnamed centres suggest the presence of a proto-rift (parallel to the younger Dali-Diana Chasma). The radiating dyke swarm associated with Ongwuti is initially radial, but swings into a rift-parallel pattern (Fig. 3), further supporting the hypothesis of active extensional stresses associated with this proto-rift.

Stage 2. The next centre to be emplaced, Ozza Mons, is the largest, based on the inferred size of the plume head (>2000 km radius dyke swarm and inferred plume head radius of 1200 km). The four-armed 'triple-junction' rifting also occurred at this time. It has been previously suggested that "Hecate Chasma may be younger than Parga Chasma and could experience a secondary stage of corona formation in the future"[31]. From this perspective, the sequence of development of the rift arms is (from older to younger) Dali-Diana, Parga and then Hecate. The timing of the

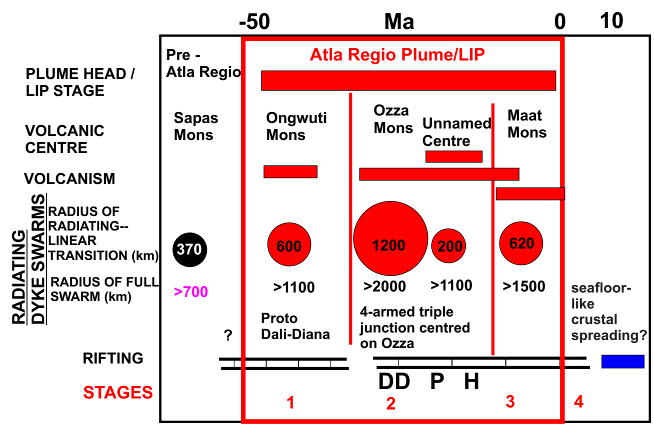

Fig. 5 Geological history inferred from graben-fissure mapping. DD Dali-Diana Chasma, P Parga Chasma, H Hecate Chasma, G Ganis Chasma.

fourth arm, Ganis, has not yet been assessed. It is notable that a detailed study of corona ages (from cross-cutting relationships of their graben-fissure systems) along Hecate Chasma[47] indicates a trend that is younger to the northeast along Hecate Chasma away from Ozza Mons, consistent with a zipper-style extension of Hecate trending away from Ozza Mons. It is also noted that the proto-rifting in Stage 1 is parallel to the development of the Dali-Diana rift zone in this stage. The unnamed centre is also part of this Stage 2 (Fig. 5).

Stage 3. The final centre, Maat Mons, has radiating dykes with trends that are not influenced by those of Ozza Mons. This suggests that the topographic uplift-related stress (which caused the radiating geometry of the Ozza Mons dyke swarm) had decreased before the formation of Maat Mons. Modelling indicates that topographic changes above plumes can occur within short periods of a few million years as the plume head spreads[7,9].

We interpret that Maat Mons was emplaced at this Stage 3, off the proto-rift zone along which the three earlier centres (Ongwuti, Ozza and Unnamed) were aligned. While Maat Mons lava flows are clearly younger than most flows from Ozza, Unnamed and Ongwuti, the NE sector of the Maat Mons radiating swarm is covered by an NW trending flow field from Ozza Mons. This indicates a pulse of Ozza Mons volcanism overlapping in time with, or post-dating the graben-fissure system of Maat Mons.

Stage 4. On Earth, when a plume is at the plume head stage and triple-junction rifting has occurred, the next step (often within 5–25 Myr) is attempted continental breakup. However, as discussed in the section on Triple-Junction Rifting below, triple-junction rifting associated with Atla Regio on Venus is not expected to lead to an actual breakup.

Geographic shifts between the four volcanic centres. Figure 6 shows the age progression between the four main centres. Having shown evidence that these centres are all at the plume head stage (and not the plume tail phase, except possibly at the very end of Maat Mons history) we consider several models to explain the minor geographic shifts between the centres (Figs. 3, 4, 6): (1) lateral movement of the lithosphere above a stationary plume (akin to plate movement on Earth, but presumably at a much slower rate for a single-plate planet) (Fig. 6b), (2) lateral movement of the plume itself (due to 'mantle wind' associated with mantle convection)[64,65] (Fig. 6c), (3) lithospheric controls (including development of incipient rift zones, or lithospheric thin-spots above a stationary plume head)[12] (Fig. 6d) and/or (4) a pause of the rising plume at a mid-mantle boundary, spread along this boundary and resumed ascent as multiple separated plumes/diapirs (e.g. ref. [11]) (Fig. 6e). With respect to model 1 (shifting lithosphere) or model 2 (plume shifting in the mantle wind), it has been proposed that mantle convection might lead to some horizontal motion and associated surface deformation (e.g. refs. [66–68]). On the basis of our data, we provisionally favour model 3 (development of incipient proto-rifting) to explain the alignment of Ongwuti, Ozza and Unnamed montes.

Triple-junction rifting—prelude to a phase of Earth seafloor-like crustal spreading? On Venus, there is currently no evidence of ongoing global plate tectonic activity[1], but plate tectonics could have existed prior to the postulated ca. 700 Ma Great Climate Transition on Venus[2] during which the atmosphere is suggested to have changed from more Earth-like conditions (temperate climate, water cycle and potential plate tectonics) to the present-day conditions (atmosphere with 450 °C, 96% CO_2, 9 MPa).

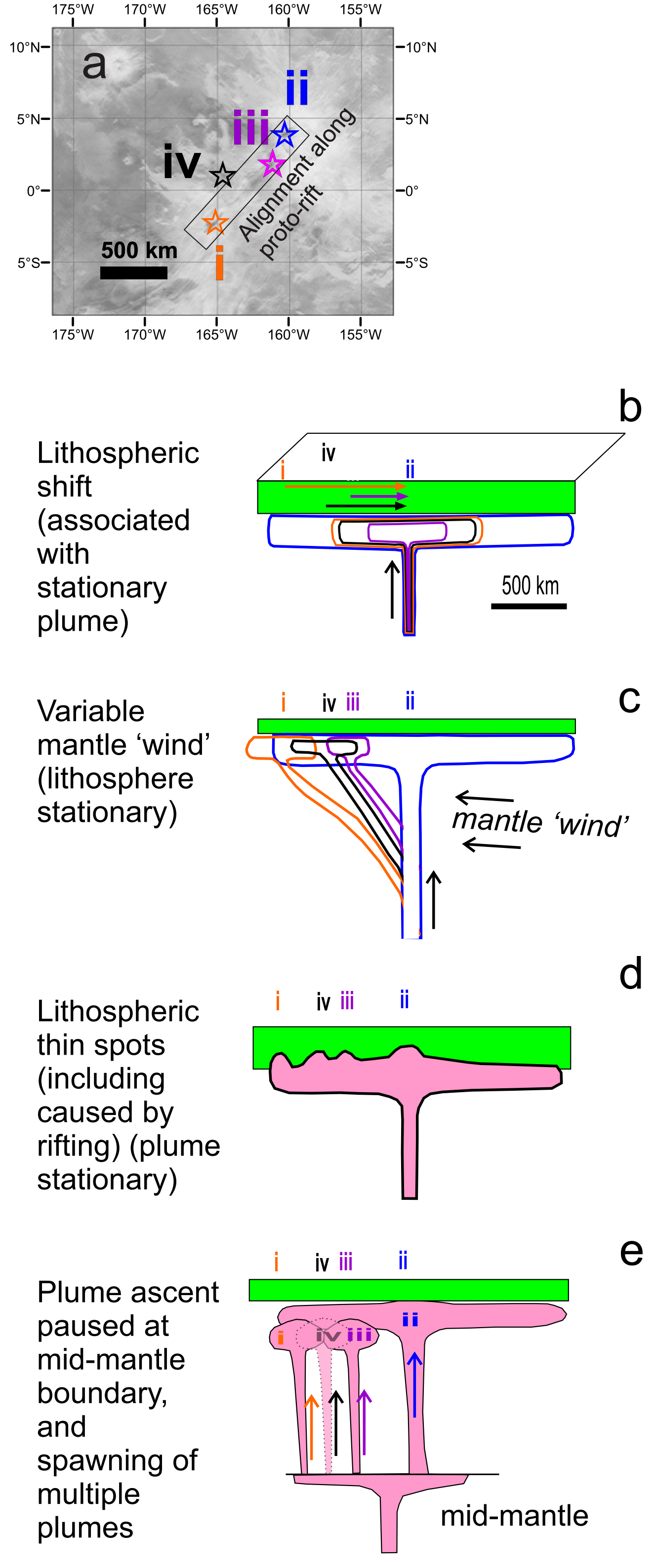

Fig. 6 Models for shifting of magmatic centres. a Location map and relative age of the four volcanic centres on the background of the NASA Magellan SAR image. The centres are numbered from i (oldest) to iv (youngest). **b**–**e** Possible explanations for the geographic shifts between the four volcanic centres.

Could the young age of Atla Regio (being at the plume head stage with incipient pronounced four-armed 'triple-junction' rifting) indicate that seafloor-like crustal spreading might be re-initiated within a few million years?

A terrestrial example of a plume/LIP at the incipient ocean-opening phase is the Afro-Arabian LIP[69]. This LIP is associated with plume-related magmatism in both NE Africa and the adjacent Arabian Peninsula, initial opening of the Red Sea and Gulf of Yemen and incipient opening along the East African Rift System. On Earth, the time gap between the initial rifting and ocean-opening (if it actually occurs) is typically 5–25 Myr[8,70]. There are also numerous other examples in the terrestrial record of LIP events being linked to continental breakup. Examples include the 201 Ma Central Atlantic LIP, 134 Ma Parana-Etendeka LIP and 52–55 Ma North Atlantic LIP (pulse 2) associated with the central, southern and northern portions of the Atlantic Ocean, respectively[29]. More generally, major ocean-opening events typically are associated with major LIP[8].

Given this terrestrial perspective, we can consider the potential for application to Venus. In the case of Atla Regio, the most likely rift arm to develop into active rifting within the next few Myr is Hecate Chasma, because it is arguably younger than Parga[31]. However, sustained spreading and development of oceanic-like crust would require complementary subduction elsewhere on Venus. Several studies have discussed potential subduction initiation by mantle plumes on Venus[71]. But such incipient subduction is unlikely to lead to seafloor spreading and ongoing plate tectonics. In their classic paper, Campbell and Taylor[72] suggested that water is essential for the formation of granites via subduction and essential for the formation of continents. This is also emphasised in subsequent papers (e.g. ref. [73]), and it is observed that a considerable volume of water is subducted and hydrates the mantle during subduction[74]. Therefore, although the Atla Regio rift arms (particularly Hecate or Parga) are inferred to be at the plume stage and ready to progress to full breakup and initiation of an oceanic spreading ridge, this is unlikely to occur given a dry Venus mantle. We are currently assessing the amount of extension involved and how this deformation is accommodated laterally in the absence of subduction and crustal spreading.

Lessons for mapping dyke swarms of other major mantle plume centres on Venus. Other Venusian regios, including Beta, Bell, Phoebe and Eistla, are also inferred to be linked to major mantle plumes[4,20,21]. Following the approach employed in the present study of Atla Regio, all these regions can be assessed to (1) determine the full scale of radiating dyke swarms in order to establish which magmatic centres are at the plume head vs plume tail stage, (2) determine the plume head sizes from the transition distance at which the radiating patterns swings into alignment with regional stresses, (3) identify additional cryptic magmatic centres from their radiating and circumferential dyke swarms, (4) establish the relative ages of the magmatic centres from cross-cutting relationships of dyke swarms and volcanic flows and (5) reconstruct the tectonic and geological history. Such studies will be valuable for contributing to target selection by the fleet of new missions to Venus planned over the next decade (VERITAS, DAVINCI, EnVision, Venera-D, Shukrayaan-1, VOICE).

Conclusions

Atla Regio is a major mantle plume centre in the BAT (Beta-Atla-Themis) Region, which is the locus of voluminous young volcanism on Venus. Our goal was to determine the relative timing of the main magmatic centres and to assess whether Atla Regio is still at the plume head (LIP stage) or has reached the plume tail (hot spot) stage. On Venus, owing to the absence of significant plate movement, plume tail magmatism (spanning 10 s to 100 s of Myr) could accumulate in a single location, producing a magmatic centre of LIP size. Therefore, on the basis of magma volume, it is difficult to distinguish plume head from stationary plume tail magmatism.

We note that the length of mafic dyke swarms is an excellent proxy for distinguishing plume head (swarm lengths 100 s up to 3000 km in length due to high flux) from plume tail volcanism (swarms <100 km in length due to low flux). Through the mapping of more than 40,000 graben-fissure lineaments, interpreted to overlie dykes, we show that all the major magmatic centres of Atla Regio (Ongwuti, Ozza, Maat and Unnamed mons) have large radiating dyke swarms (>1000 km radii) and, therefore, each represents a plume head event. Furthermore, the size of the flattened plume head can be determined for each of the four centres from the radius at which a radiating swarm transitions to a linear swarm. All four plume heads fit within the interpreted flattened plume head size of Ozza Mons (1200 km radius), consistent with all four belonging to a single plume event.

Cross-cutting relationships indicate the emplacement of the volcanic centres in the order of Ongwuti, Ozza, Unnamed and finally Maat. A final stage of magmatism is marked by late flows of Ozza Mons covering portions of the graben-fissure system (dyke swarm) of Maat Mons.

Based on dyke swarm and lava flow length criteria, our key conclusion is that Atla Regio is currently at the plume head stage (with an inferred maximum age of 50 Myr in analogy with Earth), and, therefore, should today be very active both magmatically and tectonically.

Methods

Data and mapping tools. For our geological mapping study of the Atla Regio region, we used full-resolution (75 m/pixel) Magellan Synthetic Aperture Radar (SAR) images and its altimetry data. SAR images are greyscale images where pixel brightness indicates the intensity of radar signal return, due to either surface roughness or the orientation of a structure relative to the incident radar. Mapping was done using ArcGIS v.10.6. JMARS (Java Mission-planning and Analysis for Remote Sensing) was used for regional reconnaissance and to generate topographic profiles from the Magellan topographic data.

Interpretation of graben-fissure systems as overlying dyke swarms. A key focus of our approach is the interpretation of regional graben-fissure sets (radiating, circumferential and linear geometry) as overlying dykes. There was an important debate in the 1990s, as the Magellan SAR images were initially being interpreted, regarding whether the widespread extensional lineaments were of purely structure origin[75] or could be formed by underlying dykes (e.g. ref. [40]). A key criterion noted by Grosfils and Head[40] was that radiating extensional systems (graben-fissure-fractures) which extend beyond any central domal uplift must be underlain by dykes. Where mapped in detail many radiating sets clearly meet this criterion and can be inferred to be underlain by dykes[5,40,43,48]. More generally, the scale and patterns of radiating graben-fissure systems on Venus is remarkably similar to that of giant radiating dolerite dyke swarms on Earth[41,43], again strengthening the interpretation of graben-fissure systems on Venus as analogues of terrestrial dyke swarms. More recently Buchan and Ernst[5] have recognised a class of giant circumferential dyke swarms on Earth and have proposed that the circumferential grabens associated with coronae on Venus may also in many cases be underlain by dykes. It is always valuable to employ supporting observations, such as lava flows emerging from such grabens [e.g. refs. [19,46]], aligned shield volcanoes[27,43] and pit chains[48], and in the present study, we made such observations.

Data availability

Source Magellan SAR images and topographic data are available from the USGS. (https://astrocloud.wr.usgs.gov).

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Author contributions
H.E.B.: conceived the project, mapped the grabens (dykes) and generalised them, wrote the initial manuscript, revised and finalised the manuscript with the co-authors. R.E.E.: Co-wrote the initial manuscript and assisted with revisions. K.L.B.: provided input into the initial manuscript and assisted with revisions. J.W.H.: provided input into the initial manuscript and assisted with revisions.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Richard E. Ernst.

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