AGU ADVANCING EARTH AND SPACE SCIENCES

JGR Planets

RESEARCH ARTICLE

10.1029/2024JE008815

Key Points:

- A new regional chronostratigraphic framework is proposed for the evolution of Atla Regio
- Volcanism began along Dali Chasma, then plume volcanism began at Ozza Mons and finally Maat Mons became the site of active volcanism
- The pattern of shield volcanoes with displaced centers at Atla Regio is indicative of crustal adjustment above a long-lived mantle plume

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Citation:

Mason, P. J., Klidaras, A., Cirium, D., Ghail, R. C., & Lea-Wurzbach, S. (2025). Evolution of plume volcanism at Atla Regio, Venus. *Journal of Geophysical Research: Planets*, *130*, e2024JE008815. https://doi.org/10.1029/2024JE008815

Received 4 NOV 2024
Accepted 3 FEB 2025

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Evolution of Plume Volcanism at Atla Regio, Venus

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Abstract Atla Regio is a large topographic rise, at the equator of Venus, considered to sit above a young mantle upwelling. Hosting several giant shield volcanoes, including Maat Mons, it is a strong candidate for recent eruptive activity. Through detailed analysis of material units and structures at Ozza, Maat and Sapas Mons, northern Dali Chasma and the surrounding plains, we have unraveled the tectono-magmatic evolution at Atla Regio. Lithostratigraphic analysis, of the volcanic styles, lava flow relationships, rift–associated shield clusters, graben-fissure systems and pit cratering, in relation to the regional plains and other older features, has enabled the establishment of a model of the evolution of volcanism. Structural analysis reveals that graben-fissure systems at Ozza Mons transition outward into three major rifts, and two new, unnamed volcanoes are identified. Our model is evidenced by analysis of lava flow stratigraphy and cross-cutting relationships with respect to the stratigraphic marker provided by the ejecta halo of the Uvaysi impact, and using sound stratigraphic principles. A relative chronostratigraphic framework for the area around Ozza and Maat Mons has thus been constructed, and our findings are in agreement with prior research. A new regional history is proposed here, where volcanism was initially concentrated along Dali Chasma, before plume volcanism took over at Ozza Mons and finally, Maat Mons became the most recent locus of volcanism. We propose that the pattern of large shield volcanoes with displaced centers here is indicative of minor crustal adjustments above a relatively long-lived mantle plume.

Plain Language Summary Atla Regio, near Venus's equator, lies above a rising section of the planet's mantle, which may be responsible for recent volcanic activity. This region is home to several large volcanoes, including Maat Mons, and shows signs of ongoing volcanic processes. By studying the volcanic features, lava flows, and geological structures around volcanoes like Ozza, Maat, and Sapas Mons, as well as the surrounding plains, a model to understand the evolution of volcanism in this area has been developed. This study examined how volcanic features, such as graben-fissure systems and pit craters, relate to older geological structures. The ejecta debris from the Uvaysi impact event has been used to date relatively in the region's volcanic history. The results show that volcanic activity in the area initially focused around Dali Chasma, then shifted to Ozza Mons, and later to Maat Mons, suggesting that a long-lived mantle plume may be driving the volcanic activity here. The spatial arrangement of these volcanoes, with their shifted positions, supports the idea of minor movements in the crust over time, allowing the mantle plume to influence volcanism in this region over a long period.

1. Introduction

1.1. Background

Despite being Earth's nearest neighbor, Venus may be the least well understood terrestrial planet in our solar system, but it is the one that potentially holds the most important clues about the evolution of such planets. With a hostile 720 K, 94 bar surface enshrouded by an optically impenetrable cloud deck, "Earth's twin" has eluded systematic scientific exploration that has been employed so successfully elsewhere; we have higher resolution imagery of the surface of Pluto than we do of Venus (77–80 m for Pluto from New Horizons and 120–300 m for Venus from Magellan). Hence, there are still many unanswered questions about Venusian geology. Almost everything we know comes from the near global imaging achieved by NASA's Magellan mission in 1990–1994, which revealed a complex landscape and abundant evidence for tectonic and volcanic activity. The origin and rates of these processes as well as their evolution through time are very poorly understood and fuel scientific investigation to this day.

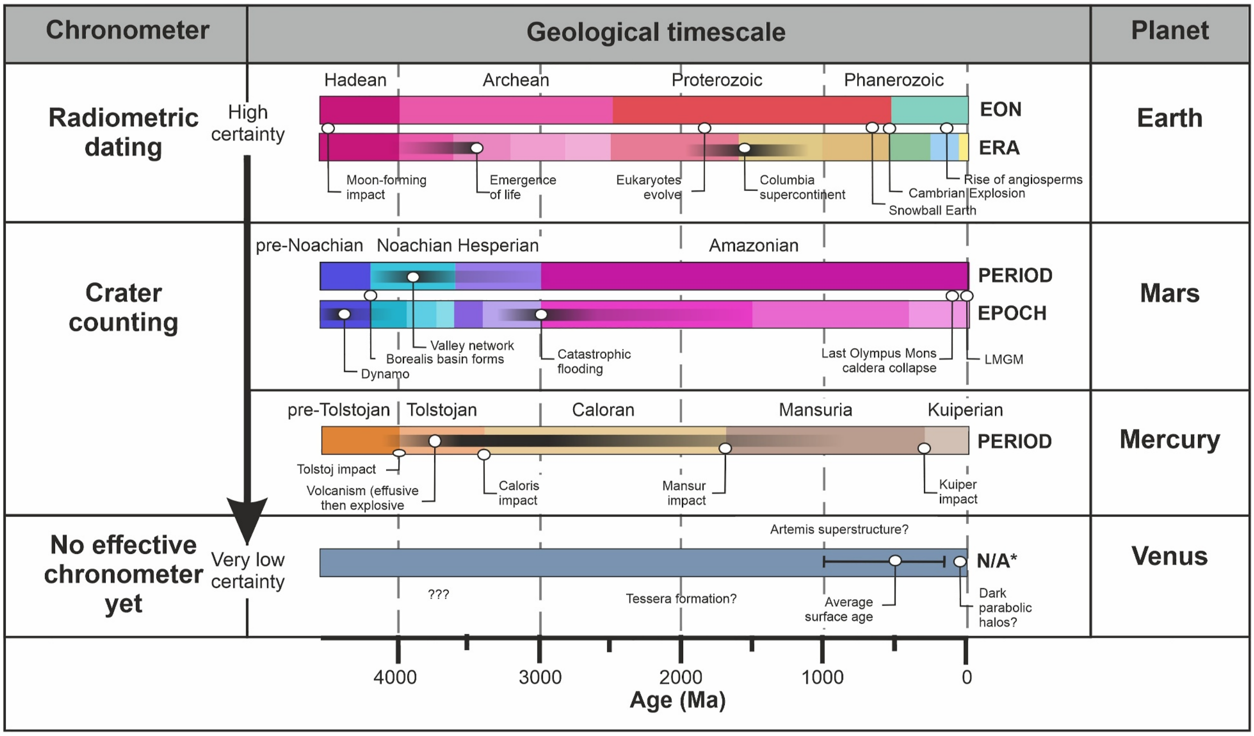


Figure 1. Approximate chronostratigraphic charts of the four terrestrial planets and key events. Earth time scale from International Chronostratigraphic Chart v2021/10. Mars time scale from Platz et al. (2013). Mercury time scale from Banks et al. (2017) and Thomas et al. (2014). * = A geological timescale for Venus was proposed by Ivanov and Head (2015) and was reviewed and updated by Head et al. (2023).

With low rates of crustal recycling, deposition and erosion, the Venusian surface preserves a rich record of volcanic and tectonic activity (Solomon et al., 1992). Inhibited by the planet's dry and viscous mantle (Nimmo & McKenzie, 1998), it is thought that terrestrial-style plate tectonics does not presently occur; strain is instead distributed across broad zones which are likely related to sites of mantle upwelling and downwelling (Solomon et al., 1991, 1992). Until recently, the Venusian lithosphere has been viewed as a relatively simple single plate, known as a “stagnant lid” (Solomatov & Moresi, 1996), though more complex models have been proposed in the last few years (Ghail, 2015; Tian et al., 2023). The planet's apparently random and uniform cratering distribution has been interpreted as evidence for a catastrophic global resurfacing event *ca* 500 Ma (Solomatov & Moresi, 1996; Strom et al., 1994; Turcotte et al., 1999), although the same cratering record is also consistent with steady-state equilibrium models of resurfacing (Bjonnes et al., 2012). The catastrophic resurfacing model predicts that Venus should be geologically quiescent today, with insignificant rates of resurfacing in the recent geological past. Recent research challenges this idea, and provides evidence for significant and geologically recent (potentially ongoing) resurfacing, concentrated at rift zones (Brossier et al., 2022; Byrne et al., 2021; Gülcher et al., 2020; Shalygin et al., 2015) and volcanic rises (Brossier et al., 2021; Senske & Head, 1992; Shalygin et al., 2012; Smrekar et al., 2010) in historic times (Esposito et al., 1988; D’Incecco et al., 2021; Herrick & Hensley, 2023), in stark contrast to Mars, Mercury and the Moon, where most geological processes have ceased (Figure 1). This evidence suggests that we should expect many changes to be detected by the forthcoming new missions, both over the 40 years period since Magellan but also during the EnVision and VERITAS missions; much work now focuses on predicting the changes we might expect, and how they should best be detected (Campbell & Hensley, 2024; Gallardo i Peres et al., 2024; Hahn & Byrne, 2023).

1.2. The Nature of Volcanism on Venus

Venusian volcanism differs substantially in style from that on Earth or Mars. The high atmospheric pressure and inferred low volatile content of magmas suppress vesiculation and favor effusion, although some candidate pyroclastic deposits have been identified (Ganesh et al., 2021, 2022; Ghail & Wilson, 2015). In comparison to Earth, Venusian shields tend to be larger, because of the slow or non-existent rapid plate motion, have lower slopes (<1–3°), and lack evidence for circumferential faults. Commonly, they consist of a broad, almost flat lava apron surrounding a steep central edifice, and have abundant extensional radial structures. Volcanic edifice growth seems to involve a combination of extrusive and intrusive activity. Models suggest they are basally welded and supported by thick elastic lithospheres and large shallow magma chambers, as suggested by the caldera complexes often found at their summits (McGovern & Solomon, 1998; McGovern et al., 2014; Mouginis-Mark, 2016; Stofan et al., 2001). As on Earth, fields of small volcanoes are also common on Venus. These consist predominantly of shields, though certain studies offer comparatively high counts of conical and domical volcanoes, sometimes associated with radar bright material which are inferred to be of pyroclastic origin (Guest et al., 1992; Kreslavsky & Head, 1999).

The classification of volcanoes on Venus largely follows that of Head et al. (1992) and other authors herein referenced; volcanoes are commonly divided, by size and abundance, into "vents" or "fields" and then sub-classified by morphology. This division reflects differences in magmatic budget; higher flux tends to produce large isolated vents, while volcanic fields form under restricted flux insufficient to build a single large volcano (Crumpler & Aubele, 2015). Such large features include large shield volcanoes (>100 km diameter), intermediate volcanoes (20–100 km) sub-classified into anemones, ticks and steep-sided domes and pateras, which are nominally defined as isolated calderas (Head et al., 1992). Small volcanoes, on the other hand, are some of the most abundant features on Venus and display strong clustering behavior; as such they have previously been mapped into fields and not at the vent level, until the work of Hahn and Byrne (2023). Such fields and their constituents have been studied in some detail by Addington (2001), Guest et al. (1992), Aubele (1993), Kreslavsky and Head (1999) and Ivanov and Head (2004).

1.3. Plume-Driven Tectonic and Volcanic Processes at Atla Regio

Recent magmatic activity on Venus is concentrated around the Beta-Atla-Themis (BAT) province, a geologically young area comprising interconnected Rift-Dominated Rises (RDRs) and regionally abundant tectono-magmatic features, such as large volcanoes, coronoids, shield clusters and flow fields (Airey et al., 2016; Guseva, 2016; Hansen & Young, 2007; Shalygin et al., 2012, 2015). RDRs on Venus are broad domal features associated with extension and large-scale volcanism. They are widely interpreted to be the surface expressions of mantle plumes, as their positive gravity anomalies and associated large apparent depths of isostatic compensation (∼200 km) suggest active flexural support (Senske et al., 1992; Smrekar, 1994). The BAT province's RDRs are thought to represent multiple centers of triple-junction type rifting, with strong Earth analogs to plume-induced intraplate continental breakup (Ernst et al., 2007). Large triple junctions centered on Atla and Beta Regiones have been compared to the Afar system of East Africa (Figure 2) (Airey et al., 2016; Foster & Nimmo, 1996), and to other Large Igneous Provinces (Buchan & Ernst, 2021), while smaller incipient or failed triple junctions along Parga and Hecate Chasmata, located outside the radius of RDRs, have been compared to Atlantic rifting in the Mesozoic (Ernst & Desnoyers, 2004; Graff et al., 2018).

One such volcanic rise long thought to be a site of young volcanism and tectonism is Atla Regio (Basilevsky, 1993; Bilotti & Suppe, 1999; Brossier et al., 2021; Senske & Head, 1992; Shalygin et al., 2015), now confirmed by the recent discovery of visible surface changes to volcanic features at Maat Mons (Herrick & Hensley, 2023). Atla Regio has the highest swell height (∼2.5 km) of any RDR and features the greatest volume of erupted volcanic material (Stofan et al., 1995) since it hosts four giant shield volcanoes. Ozza Mons (OM) is the most voluminous of these and lies at the center of a gravity anomaly and at the tectonic junction of five rift zones (Senske et al., 1992), see (Figure 3). OM sits at the northern junction of Dali, Ganis, Parga and Hecate Chasmata. Maat Mons sits to the southwest of OM on the western flank of the Dali Chasma rift, and Sapas Mons lies some way off to the northwest of it. Ozza Mons also lies at the western end of what is now proposed as the Great Dyke of Atla Regio (GDAR), a 3,700 km long single mafic dyke underlying Parga Chasma (El Bilali & Ernst, 2024), the continuity of which is taken as evidence of a temporal and kinematic link between OM and Parga Chasmata (Figure 4). Maat Mons (MM) is less broad but twice the height, and is the tallest volcano on Venus, reaching +9.6 km elevation. The third giant shield volcano, Ongwuti Mons, is poorly studied but appears highly deformed and associated with an equally giant coronoid feature. A fourth large volcano, Sapas Mons (SM), lies some 1,000 km to the NW of the main Atla swell; this seems to represent an off-axis site of upwelling in its own right (Schinella et al., 2011) and its relationship to Atla is unclear. Atla Regio has been mapped at 1:10M as part of the Ivanov and Head (2015) global geological map, though detailed mapping by the USGS at 1:5M has not been conducted in quadrangles V-26 or V–38, which cover the Atla Regio area.

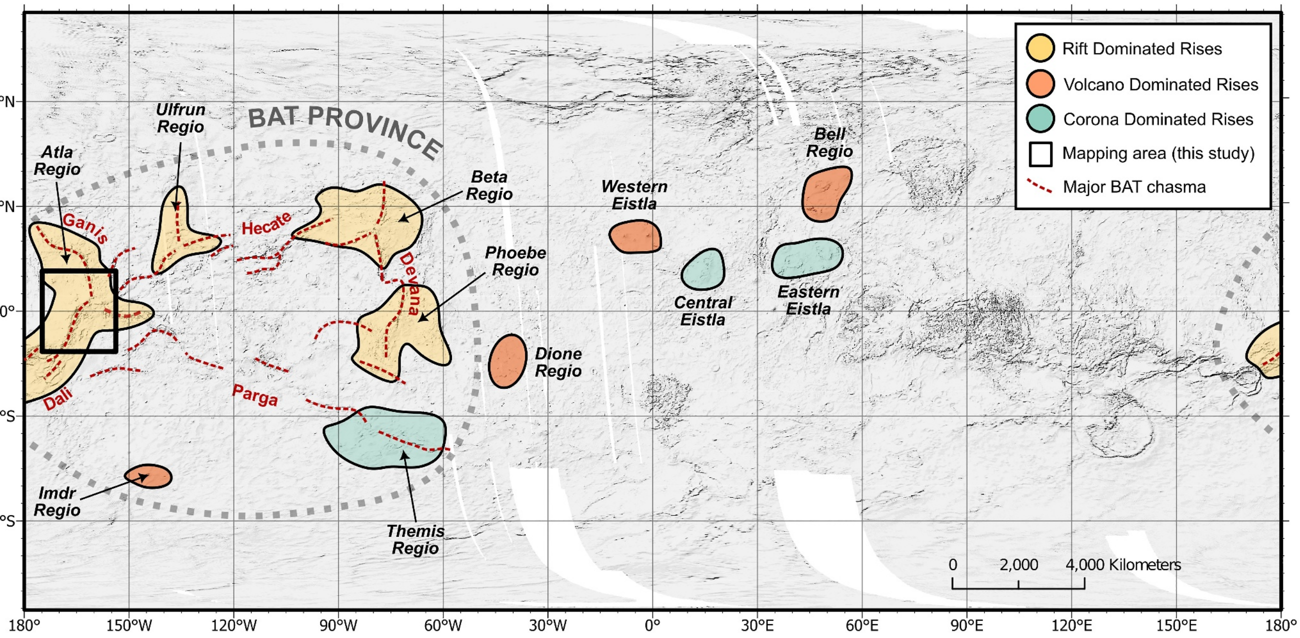


Figure 2. Venusian Highlands and the BAT Province, a broadly triangular region bound by the Parga, Devana and Hecate (and Ganis) Chasmata, where RDRs are concentrated and evidence of mature or incipient triple–junction rifting. Red dotted lines indicate the position of rifts in the BAT vicinity (simplified from Guseva (2016) and observations from Magellan altimetry). Regiones have been color–coded using the classification of Stofan et al. (1995), who suggest that RDRs and CDRs exist in a continuum.

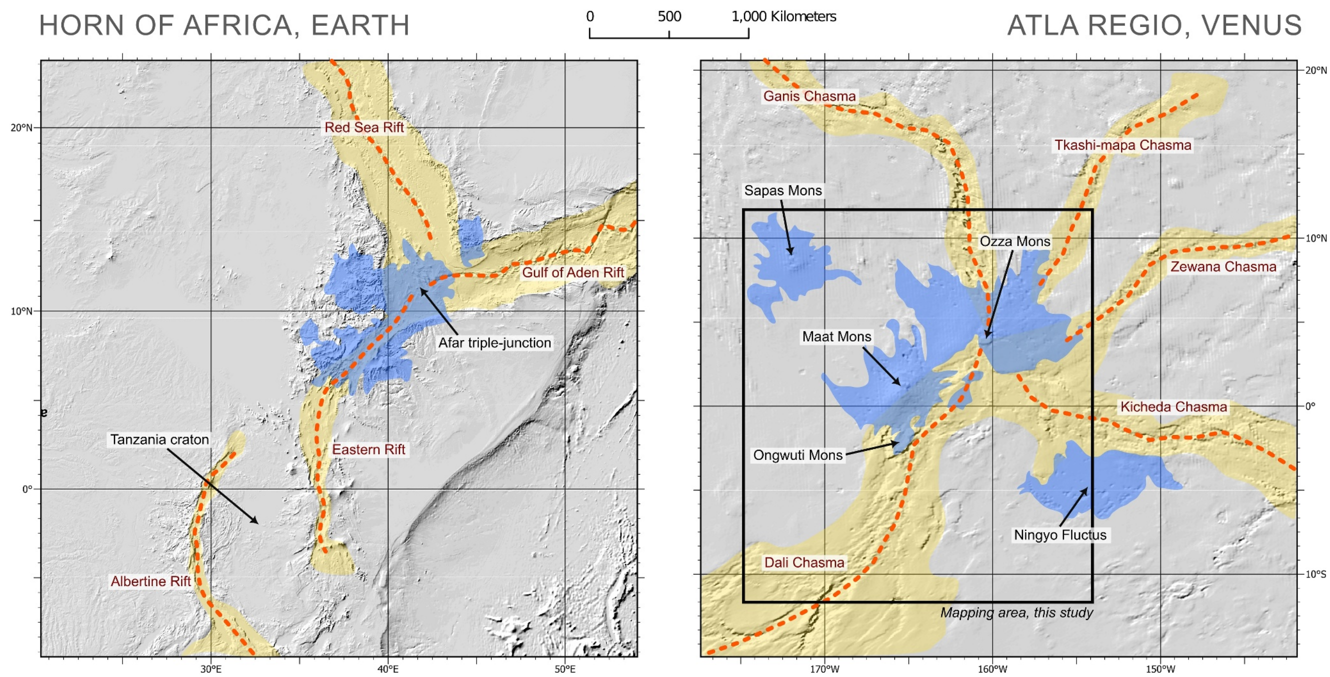


Figure 3. Triple Junction Rifting: Afar (Earth) compared with Atla Regio (Venus). Left: Afar rifting, with flood basalts in blue simplified from Ayalew et al. (2021) and rift zones in yellow with red dashed axial trace simplified from Macgregor (2015). Right: Atla Regio rifting, with significant lava flows in blue (simplified from this study) and rift zones in yellow with red dashed axial trace.

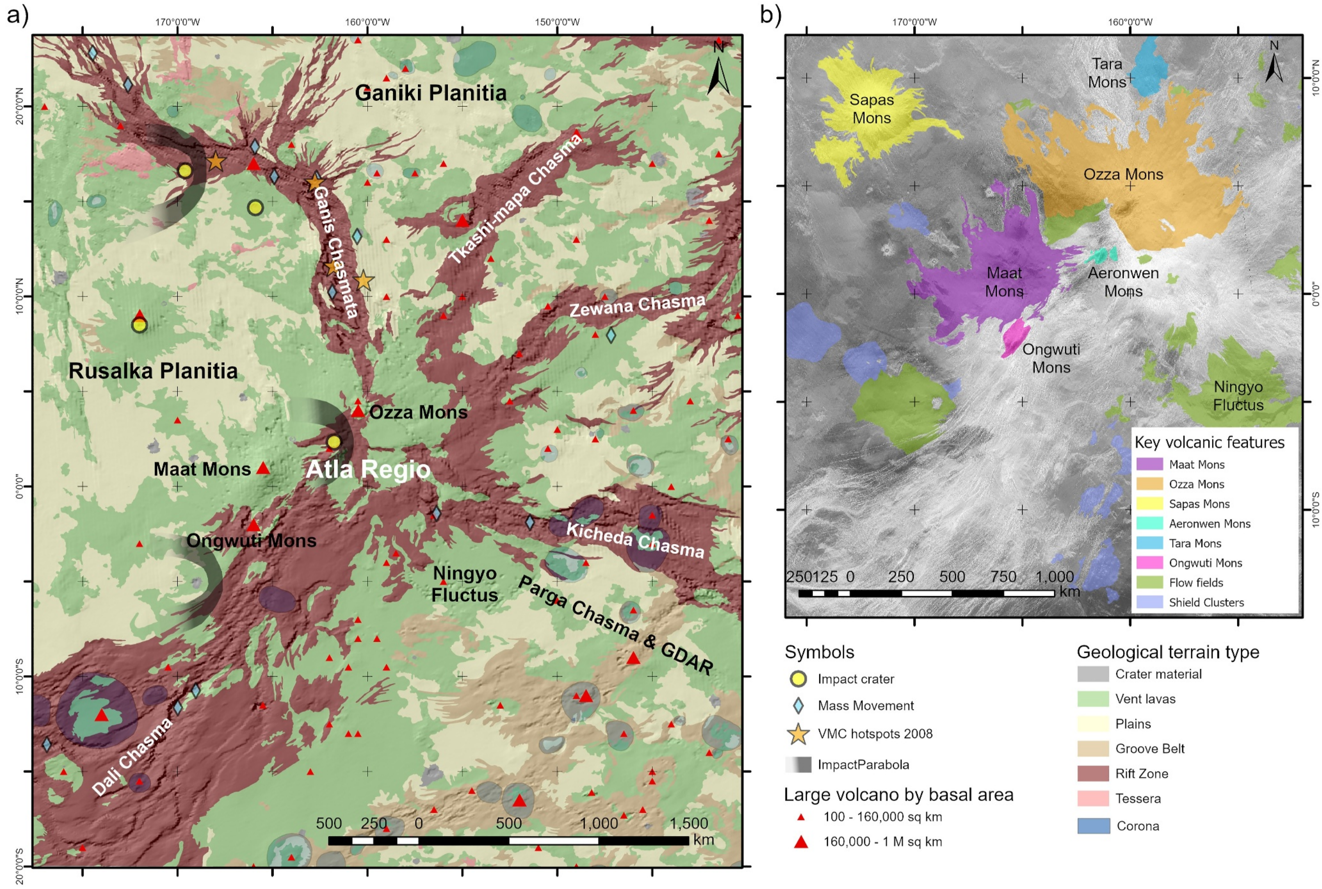


Figure 4. (a) Regional geological map of the area around Atla Regio, with units simplified from Ivanov and Head (2011), coronae, volcanoes and landing sites from Airey et al. (2016), VMC hotspots from Shalygin et al. (2015), Parabolic Radar-Dark Halo impact craters were extracted in this study; and (b) Left-Look SAR image close-up with summary map of the major volcanic centers and their lava aprons, with Tara and Aeronwen representing unnamed intermediate sized shield volcanoes, first described in Klidaras and Mason (2022).

The patterns of radial dyking and topographic swelling at the Atla Regio resemble terrestrial settings where a large plume leads to the formation of a Large Igneous Province-like system of magmatic centers and volcanic edifices. El Bilali et al. (2023) concluded that the largest plume head at Atla Regio is associated with OM, and that those of MM, Ongwuti Mons and the unnamed volcanoes all lie within the radius of OM's plume head. Their work suggests that all three are approximately coeval and that, in each case, the pattern of dyke swarms suggests that each is at the plume head stage of development (not plume tail). Their geological history inferred from graben-fissure system mapping suggests that the Atla Regio system is no older than ~50 Ma.

1.4. The Need for a Geological and Chronostratigraphic Framework for Atla Regio

Providing constraints on patterns, rates and chronology of volcanism and tectonism is an important task in understanding the evolution of Venus but also of all terrestrial planets (Ghail et al., 2024); the two processes are linked and it is impossible to consider one in the absence of the other. Our Atla Regio study area is the locus of several extensive rift zones of potentially different ages, several giant shield volcanoes (on and off-rift), vast flow fields, several shield clusters in association with extensional belts, complex multi-phase deformation, and a diversity of small-intermediate volcanoes, including the only subset of anemone volcanoes on Venus. It is now widely accepted that the most recent period of Venus history is referred to as the Atlian System (Head et al., 2023; Ivanov & Head, 2011), and in the light of recent discoveries (Brossier et al., 2022; Herrick & Hensley, 2023; Shalygin et al., 2015), Atla Regio thus represents a very compelling target in the drive to construct a relative chronostratigraphic framework of young volcanic and tectonic activity, but the task is not an easy one.

A major challenge to examining recent geological processes on Venus is the paucity of impact craters caused by the thick atmosphere, which means that "crater counting" is perhaps an unreliable dating technique for the planet's surface. Crater counting and the apparently random crater distribution are the means by which an approximate and relatively uniform age of approximately 0.5 Ga has been attributed to the Venus surface (Phillips et al., 1992; Strom et al., 1994). Beyond that broad value, Venus's geological time scale remains unknown (Figure 1), but it is hard to imagine how a highly deformed and geologically active planet can possibly have a surface of uniform and uniformly young age.

Prior mapping efforts focused on lava flows without considering the structures or on a subset of structures without considering the material units. Here, we present the first fully integrated structural and material geologic map of Atla Regio, which uses sound stratigraphic principles and considers the material units as well as the structures that deform them. This approach is badly needed for the whole of Venus, but it is extremely challenging to establish a meaningful global stratigraphic framework without further information (better topographic data, global imagery of higher spatial resolution and repeated imaging). It has been done successfully on a regional scale, and on a case-by-case basis, using very careful, detailed mapping and where suitable stratigraphic markers can be identified (D'Incecco et al., 2020). Above a Venusian 'snowline' of ca 2 and 3 km, the accumulation of an unknown weathering product greatly decreases the radar emissivity over time, and this may provide a crude, uncalibrated proxy for age (Brossier et al., 2021, 2022). Employing basic stratigraphic principles of cross-cutting relationships and superposition, especially when demonstrably young features such as craters with RDHs are seen to be overprinted, is another method by which relative ages can be established and geologically recent activity can be interpreted (Basilevsky, 1993; D'Incecco et al., 2020). The summit of Maat Mons was mapped in Mouginis-Mark (2016), and the lava aprons of Ozza, Maat and Sapas Montes were divided into lithostratigraphic units in Brossier et al. (2021) although neither study mapped the structures. In this study, an area of ca 4,200,000 sq km has been mapped in detail. This region includes Ongwuti, Ozza, Maat and Sapas Montes, the closest parts of Dali, Ganis, Devana, Hecate and Parga Chasmata, and the eastern part of Rusalka Planitia. A transient VIRTIS hotspot was identified in 2008 along Ganis Chasma during the VenusExpress mission, and has been correlated with emissivity patterns in Magellan data (Brossier et al., 2022; Shalygin et al., 2015). By careful examination of stratigraphic relationships, a relative stratigraphic framework has been created for this region, which enables insights into the region's evolution as well as the interpretation of several sites of potential current, ongoing activity.

2. Data and Mapping Strategy

2.1. Magellan Data

NASA's Magellan mission (1990–1994) collected a near global high-resolution SAR data set of the Venusian surface and simultaneously acquired medium-resolution altimetry and radiometry data. S-Band SAR (12.6 cm) was obtained over three cycles of variable coverage with left (83%), right (54%) and stereo-left (21%) -look geometries; 120 m resolution images were resampled to produce 75 m resolution FMAPs, mosaicked for geological mapping. Altimetry and radiometry data sets (4,641 m resolutions) were also processed to produce emissivity, reflectivity and permittivity maps available on the USGS Astrogeology server and Map–a–Planet. Detailed summaries on the aims and outcomes of the Magellan mission are provided by Ford and Plaut (1993).

Between 1990 and 1994, NASA's Magellan SAR instrument mapped 98% of the planet to a spatial resolution of 100–250 m/pixel. Variations in 'brightness' across a SAR image of Venus are predominantly a function of the surface's dielectric constant, surface roughness, and slope facing direction. At the equator, the left-look and right-look incidence angles were ~45 and ~25° respectively (Campbell, 2002). Magellan's altimetry data is of low spatial resolution (~10–30 km). Modern geological mapping of Venus places emphasis on the separation of primary materials relating to the original mode of emplacement (e.g., lava flows) from the secondary structures that deform them (e.g., lineaments). This allows for better discrimination of cross-cutting and stratigraphic relationships (Hansen & López, 2018; D'Incecco et al., 2020). In many areas, the density of secondary superimposed structures is high enough that the primary material characteristics are largely obliterated; these regions are considered "structural material units" such that the material should now be considered tectonic in nature. These are referred to as "lithodemic" units, and they bear no relation to lithostratigraphic units (e.g., "Devana formation" in Ivanov and Head (2011)) because the deformation visible now should be considered "time-transgressive" and thus they hold no specific temporal significance (Hansen & López, 2018).

2.2. Mapping Strategies and Procedures

A suite of primary and secondary materials are observed over the surface of Venus and here they have been mapped into major groups of plains and tectonic units, and primary features and secondary structures, broadly following the approaches of Tanaka et al. (1994) and Ivanov and Head (2015), with considerations from Hansen et al. (2000), and in correlation with the stratigraphic framework developed by Head et al. (2023). Plains units are those emplaced coherently and often extensively, probably over discrete time intervals; they are distinguished by their primary features, geomorphology and radar characteristics. Here, they have been mapped as "pre–pwr," "pwr," and "post–pwr" (following the logic of Ivanov and Head (2015)), since the younger plains can usefully be divided by heterogeneities of relative radar brightness and by textural differences. The modification of older plains units is evidenced by the variable and increasing development of secondary structures as well as their embayed terminations, all of which need to be examined closely to distinguish their unit boundaries. Tectonic units are defined by secondary structures which have occurred after primary emplacement and in almost all cases, these obscure the underlying primary characteristics; they represent the shared history of units and events, and thus represent only the time interval during which secondary structures developed, not the unit genesis (Hansen et al., 2000; Ivanov & Head, 2011).

It is noticeable that there are almost no coronae present in the central Atla area, though many hundreds are present further afield, and in many cases in close association with the rift "arms"—Gali, Parga, Hecate, Devana, Dali Chasmata. This is interpreted as being caused by the intense eruptive volcanism and tectonism observed in the central Atla area that has buried or tectonically obliterated any surface expression of the coronae that might have been there. Alternatively, there may not be any smaller diapirs or sub-plumes in this region because it is dominated by the quite larger Atla plume.

2.3. Mapped Material and Structural Units

Primary features include volcanoes and lava flow fields, mapped separately and sub-categorized by their morphology (Table 1), and plains (smooth, mottled and undifferentiated). Secondary structures include fractures, lineaments, grabens, wrinkle ridges, pit crater chains, impact craters and other penetrative structural fabrics (Table 2). These individual structures represent discrete events related to a broader deformation period, and the structures are grouped by similar geometries, orientations and relative ages to reflect this. As summarized in Table 3. Lithodemic units include Densley lineated plains, rift terrain and deformed rift terrain, collapsed calderas, lineated volcanic edifices, and tessera "kipukas," and these are summarized in Table 4.

3. Volcanism and Geological Evolution at Atla Regio

3.1. Proposed Stratigraphic Framework

Through careful analysis of the regional stratigraphic relationships between structural units (cross-cutting relationships) and emplaced materials such as lava flows and impact ejecta (principle of superposition), we propose the following subdivision of Atla Regio's geologic history. We have grouped a series of early emplaced units and events into a "Pre-Atla era." The events and units associated with the arrival of the Atla mantle plume are mapped into the "Atla era," which continues to the present day. This has been further sub-divided into two stratigraphic sub-groups: a lower and upper phase, hereafter referred to as the lower Atla era and upper Atla era, each with a shield volcano as its focus, and each sub-group consists of a series of broadly sequential lava flow members. The lower Atla era encompasses the onset and early phase of tectonism and volcanism, and the upper Atla era, which is marked by the Uvaysi impact at its base, coincides with a shift in the style and location center of volcanism. Based on these findings, a conceptual diagram of Atla Regio evolution is shown in Figure 9.

3.2. Events Pre-Dating Plume Arrival (Pre-Atla Era)

The oldest materials in the study area are the tessera, fragments of which may underlie much of the region. At some later time, the plains units (Pwr) formed or were emplaced (referred to as psh, rp1 and rp2 by Head et al., 2023), and these are interpreted to have formed in an episodic rather than catastrophic manner, roughly at time T (1,000–150 Ma). The plain units have embayed TT, resulting in isolated tessera kipukas (Tk).

A prominent feature likely dating to the pre-Atla era is a previously unnamed intermediate-sized shield volcano, here named "Tara Mons" (TM) pending IAU approval. This shield is located in Ganiki Planitia at 159.2°W and

Table 1
Primary Volcanic Material Units and Features and Their Characteristics (See Figures 5 and 6)

Feature type and map code	Characteristics and interpretations (and related citations)
Volcanoes and lava flows	
Lava flows MM, OM, SM, TM, OgM	Lava flow units of the named volcanoes, numbered in sequence from oldest to youngest: Maat Mons (MM), Ozza Mons (OM), Sapas Mons (SM), Tara Mons (TM), Aeronwen Mons (AM), and Ongwuti Mons (OgM)
Shield cluster, SC	Flow unit located around the vents of a shield cluster. Lava field consisting of the composite but indistinct lava flows originating from several volcanoes in a shield cluster
Flow Fields, Ff	Discrete and coherent radar–bright lava flow units with cooling–limited margins, originating from point or fissured sources. May form as apron, fans, and may have sub–parallel or filamentary geometries (Lancaster et al., 1995; Mouginis-Mark, 2016)
Fan-shaped flow, Lf	Wide, fanning flow often having digitate margins and a clear vent. Low to moderate volume fissure or shield-fed flows on shallow slopes
Digitate flow, Ld	Finger-like flow, significantly longer than wide. Low to moderate volume fissure, shield or caldera-fed flows on steep slopes
Sheet flow, Ls	Extensive flow lacking internal textures, not radar-bright. May have Ld-like margins. High volume flood basalts with obscured vents (dykes?)
Ponded lava, Lp	Lava confined to a topographic depression. Often radar-dark. A lava-flooded depression with a smooth surface. Associated with calderas.
Indeterminate flow, Li	Features suggestive of lava flows but with unclear flow margins. Several causes—for example, kipukas, older homogenised flows above "snowline" with radar-bright indistinct textures
Plains units	
Smooth Plains *Pwr (dashed)*	Extensive, radar-dark flat, homogeneous, smooth terrain found at low elevations, overprinted by wrinkle ridges. Emplaced as sheet lava flows, which have homogenised over time and then underwent a period of contraction.
Mottled Plains *Pwr (dotted)*	Sheet-flow-like plains of intermediate, dark and bright backscatter, texturally heterogenous, often with characteristic speckled patter, or with irregular patches of differing brightness.
Undifferentiated Plains, P*wr*	Similar to *Pwr* but featureless, with no texturing. Radar dark to intermediate. Of indeterminate formation, could be sheet flows or secondary in origin.

Table 2
Secondary Structural Features (See Also Figures 5 and/or 6)

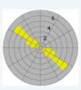
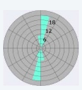
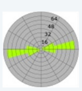
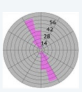
Feature type and code	Characteristics (and related citations)
Small shield volcanoes	Clustered volcanoes and their associated products, superimposed on older plains material. Spatially associated with distal graben belts and Rifted Terrain. Numerous types and styles, with inter- and intra-cluster age/style progressions. Characteristic of continuous or episodic volcanism with a restricted magma supply
Plains Fractures	Linear fracturing occurs in two dominant directions, Sometimes occurring as polygonal, cross-hatched morphology
Ring dykes	Circular to sub-circular radar bright structure, often occur in circumferentially in parallel sets around a volcanic edifice
Radial fractures	Radial lineation spatially associated with major volcanic center. Produced by radial dyke intrusion. Originates from magma chamber/supply of proximal volcano. Can occur as grabens due to associated extension (caused by swelling)
RIft Fractures	These include all graben fissure systems (tend to be fairly straight) and arcuate and cuspate normal faults and fractures, that are related to the major rifts that converge at Atla Regio
Lineaments (oriented NE-SW and NW-SE)	Generic term for unclassified linear feature (of an unclear genesis due to poor image resolution for small scale structures). Radar bright, linear to sub-linear structure. Without variations in surrounding lithologies, confident differentiation of linear structures is impossible. Broadly assigned as extensional if closely associated with graben structures
Graben (mainly N-S but also E-W oriented)	Linear depression formed by two parallel to sub-parallel, radar-bright lineations with a relatively flat floor. Representing paired normal faults (the individual segments may be more arcuate). Often flooded or spatially associated with major rifting or volcanism. Indicative of an overall extensional stress regime. Spatially associated with dyke swarms
Plains fractures	Radar-bright linear or polygonal-orthogonal fractures and fracture traces, sometimes with hackly inter-polygonal textures
Wrinkle RIdges	Non-linear (sinuous) ridges overprinting plains materials. Interpreted as compressional, surface expression of thrust faults and/or folding

Table 3
Deformed, Lithodemic and Secondary Material Units (See Also Figures 5 and/or 6)

Feature type and code	Characteristics and interpretation (and related citations)
Corona, Co	Quasi-circular volcano-tectonic structures with varied topographic shapes and diameters of 50–1000 km. Radial and/or concentric fractures and compressional tectonic structures in their annuli common. Often in association with groove belts and rift zones (Head et al., 1992; Solomon et al., 1992; Stofan et al., 2001)
Densley lineated plains, Pl	Flat, indeterminate radar-dark regions overprinted by radar-bright lineaments that generally occur in the same orientation and completely overprint and obscure the primary lithology. Often closely associated with RT
Rifted terrain, RT	Dense sets of radar-bright fractures and other lineaments with a dominant orientation, which are host to lava flows, pit crater chains and coronoids. Linear zones of thinned lithosphere that have undergone extension. Some deformed units with fractures at different orientations and a dense penetrative tectonic fabric
Flooded rifted terrain, FRT	Rift terrain onlapped partially or completely by younger ponded plains material. Flooded fracture belts with volcanism syn- or post- distal rift elements
Deformed Shield Clusters, DSC	Concentrations of volcanoes and their associated products. Strongly coupled to uplifted, fractured and flooded terrain. Dimpled topography. Often degraded by multiple stages of deformation (hackly fracture, polygonal fracture, wrinkle ridges) and recognizable by peaks amid quasi-circular radar-bright halos. Inter-shield material is often densely packed with central vents of older, amalgamated constructs; these are only partially discernible
Deformed Shield Plains, DSP	Radar intermediate to bright plains, deformed by a dense and faint network of hackly fractures and a sparse network of wrinkle ridges. Sparsely dispersed volcanoes, which are amalgamated, and often only the central vents are discernible. On a morphological continuum with deformed shield clusters. Embayed by younger plains with wrinkle ridges
Graben Belt, Gb	Rift-associated graben belts predating shield plains. Occur in sub-parallel limbs with varying degrees of deformation. Embayed by plains units
Tessera kipuka, Tk	Rugged, radar-bright terrain embayed by plains material and host to a tectonic fabric of multiple orientations. Fragment of high-standing tessera terrain fully encircled by lava flows
Impact craters, Cf	Circular depressions from hypervelocity impactors, bound by raised crater rims and radar–bright hummocky ejecta blankets. Radar–dark crater floors are primary flow units which post–date crater formation

10.0°N and has a relief of ∼1.5 km (Figure 4b). Its apron is circular and relatively undeformed, although its lava flows are indistinct and are overprinted by wrinkle ridges. The summit region has a high density of lineaments and a sheet flow (Ls) originates from TM before flowing northward beyond the mapped area. Distant from the Atla Regio swell and not clearly associated with any of its radial rifts, TM is interpreted as an extinct volcanic vent predating the Atla plume, and is proposed as a potential source vent or conduit(s) for late-stage plains emplacement. Following plains emplacement, a widespread phase of contraction followed, creating the wrinkle ridge (C1) suite ringing the Aphrodite Terra geoid.

Table 4
Tectonic Regimes

Orientation	Label	Characteristics	Interpretation
	E3	Entirely graben. Low density. Overprints E2. Overprinted by northern Maat Mons flows	NE-SW oriented extension. Distal from the rifts zones
	E2	Mainly graben. Coeval with western Ozza Mons flows. Overprinted by E3	E-W extension. Roughly circumferential to OM
	E1	Graben and other fractures. High density. Coeval with ZC and TC. Overprinted by C1 WR in some areas	Early N-S extension
	C1	Wrinkle Ridges, restricted to Pwr Plains. Overprinted by all other regimes	ENE-WSW oriented compression. Widespread

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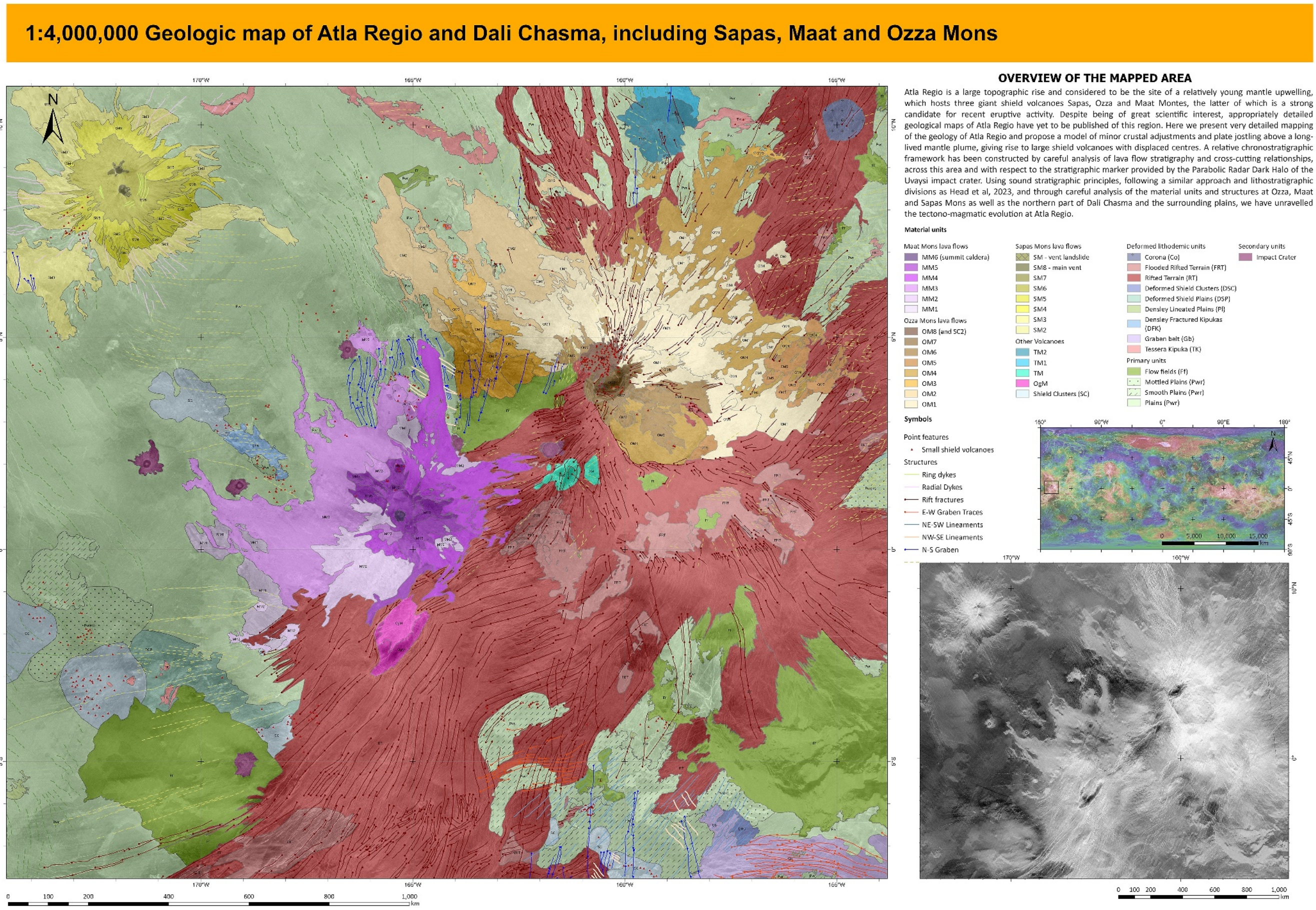

Figure 5. Detailed geological map of Atla Regio including Sapas Mons and extending along Dali Chasma down to Ongwuti Mons and Nyingo Fluctus.

3.3. Early Volcanism and Rift Development (Atla Era, Lower Phase)

The lower Atla era begins with the arrival of the Atla Regio mantle plume, triggering a major phase of volcanism and rifting that may continue to the present day. The associated decompression melting of upwelling material and thermal melting of the lower lithosphere would have generated vast volumes of melt, and the initial focus of volcanism appears to have been along Dali Chasma, where magma-assisted rifting may also have occurred. Three significant volcanic centers formed along this axis: Ongwuti Mons in the SW, Ozza Mons in the NE, and "Aeronwen Mons" roughly in-between them. Ongwuti Mons is heavily deformed by rifting , whereas at OM, overprinting by rifts appears just beginning, suggesting that Ongwuti is the oldest volcano of the three and OM the youngest. This pattern of an incipient volcanic chain which "youngs" toward the northeast could be explained by a relatively mobile lithosphere moving above a static hotspot, even though the conventional view of Venus's lithosphere is usually a static one; similar "chains" have not been observed elsewhere on the planet. These three may have formed simultaneously and their differing degrees of deformation may reflect spatial variation in the rate of tectonism and heterogeneity in the distribution of melt and upwelling. A noticeable feature of this early volcanism is the occurrence of large lava flow fields flanking the rifts. The most notable of which is the Ningyo Fluctus, a very extensive flow field, ca 1,200 km long, emanating from the SE flank of Atla Regio. It is thought to lie at the point marking the limit of the OM plume head radius, and may be structurally related to the GDAR and Parga Chasma.

3.3.1. Shield Clusters

Shield clusters (SC) represent low volume, episodic volcanism that is often distally spatially associated with major volcanic and tectonic events and with major and minor rift zones, as well as with the large shield volcanoes. They are thought to represent an important stage in the volcanic and structural evolution of this area. We see

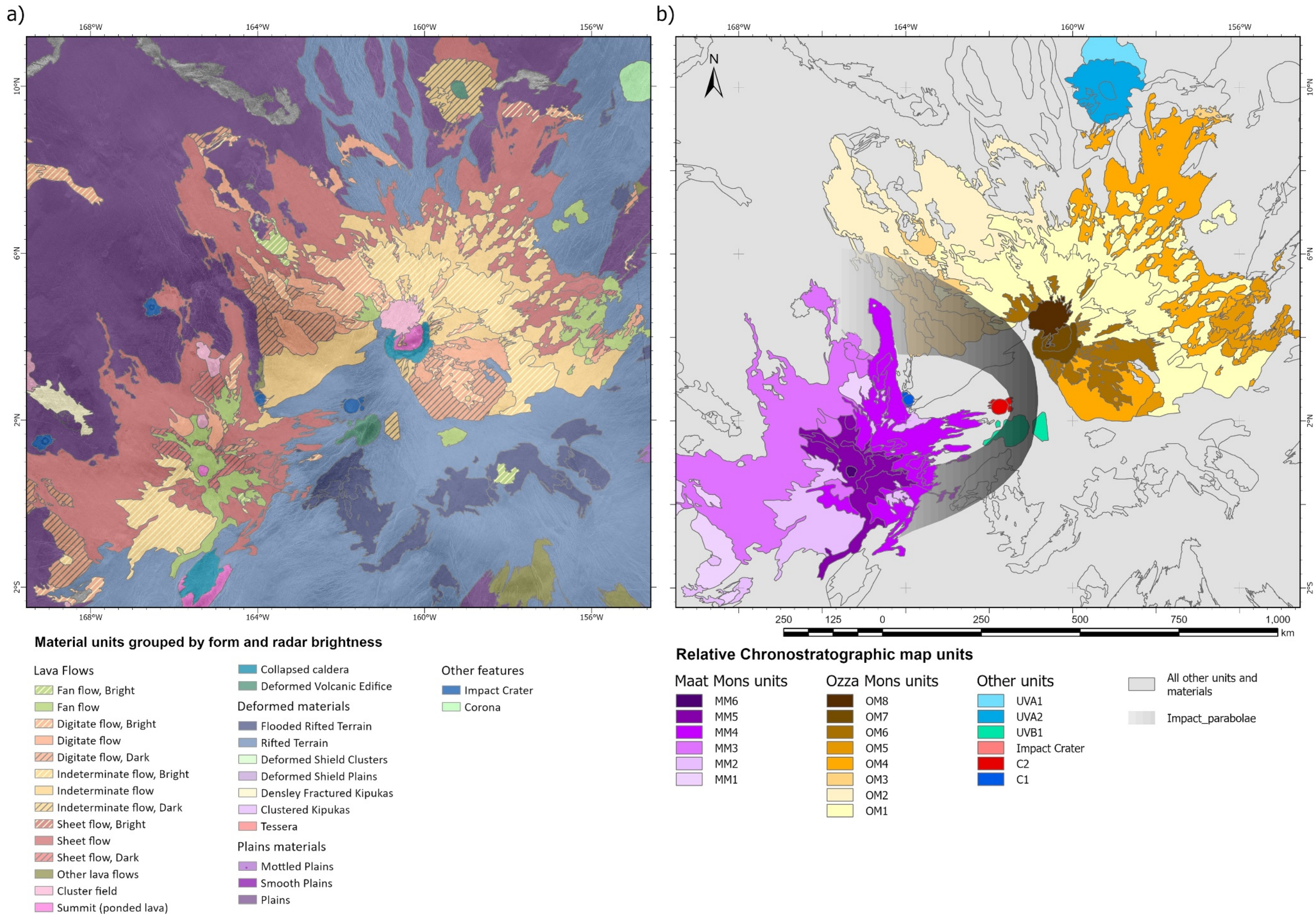

Figure 6. Detailed maps of (a) geology of Ozza Mons and Maat Mons and (b) units colored by relative age and showing the PRDH of the Uvaysi Crater. Gray "Other" units are lava flows, pains units, rifted terrain and other units interpreted to be relatively small, that were not assigned their own individual units to avoid chart clutter, or were of indeterminate source and age.

shield cluster volcanism at several other locations along the rifts, generally along the flanks, and on the plains more distal to the rifts. One particularly large area of cluster volcanism lies on the SE flank of Dali Chasma, where a very distinctive region of anemone volcanoes can be observed (Cirium & Mason, 2021). These features vary hugely in form, shape and style, from simple cones to rather beautiful flower-like complex fans of fissure-erupted lavas; in general, they have erupted onto (deformed) plains materials. Very similar features can occasionally be found on the western flank of Dali, but they are much less common. Being indicative of low volumes of melt, these features may be characteristic of the early pre-plume phase, when volcanism was just initiating, thus producing small and complex eruptions on the plains and related to fissuring. Head et al. (2023) refer to this early Atla period as the Boala Group. In other settings, they may be relatively late features indicative of waning volcanism, such as at the summit of OM or at the distal parts of SM.

3.3.2. Ongwuti Mons

Ongwuti Mons is a heavily deformed, now elongated volcanic center with a radiating dyke swarm that may have been initially radial but is now deflected by the differential regional stress of rifting and extension, suggesting that Ongwuti may be the oldest volcano of the shields at Atla Regio. Deformed early rift terrain at this time is exclusively associated with Dali Chasma, distal to both Ozza and Maat Montes. A sharp boundary between deformed and undeformed rift terrain (RT) was observed in both LL and RL SAR images but is of uncertain origin; it is speculated to be a relict boundary between the highly deformed Ongwuti Mons apron and later Dali Chasma, which were resurfaced more recently and so are deformed to a lesser extent.

3.3.3. "Aeronwen Mons"

An additional unnamed intermediate-sized shield volcano with a relief of ∼2.75 km lies along Dali Chasma roughly midway between Ongwuti and Ozza Montes, located at 161.4°W 1.8°N (Figure 4). Here named "Aeronwen Mons" (AM), pending IAU approval, it is heavily deformed by DC structures to the point where its lava apron is no longer preserved or visible. El Bilali et al. (2023) found a radial lineament network interpreted as a radial dyke swarm associated with this feature, which is further evidence that this construct is volcanic in origin. On its western flank, a partially overprinted caldera structure is preserved, with a ∼20 km diameter elliptical depression post-dated by at least three subsequent smaller circular collapse structures. Since the Uvaysi impact crater is superimposed on top of the AM flank, volcanic activity was likely restricted to the lower Atla era.

3.3.4. Ozza Mons

OM is a broad, low volcano with a 1,000 × 800 km apron , but while the elevation of its summit reaches 7.5 km, the relief of the volcano is only ∼3.5 km, and its flanks are very gentle sloping. The upper slopes are dominated by a homogenous radar-bright (Li) unit, and the lower flanks by extensive radar-dark (Ls) flows which embay the (Li) unit, reaching ca 750 km from the summit. The flanks are heavily deformed by a radial graben-fissure system and by three incipient rifts. Many lava flows are seen to infill the graben and overprint rift structures, but the reverse is also common, suggesting that at OM rifting and volcanism were coeval.

The literature is divided on whether Ozza Mons hosts a "tectonized caldera" (Brossier et al., 2021) or a 1.5-km high radar-dark oval plateau (Senske & Head, 1992) at its summit and it is unlikely that both are true. The Magellan GDTR product shows a prominent elevated plateau, but the patterns of radar-brightness and -darkness in the SAR imagery support a caldera hypothesis. The extremely low radar return of the 80 km diameter oval-shaped region is expected from the smooth texture of ponded lava. Both the floor and rim of the caldera host small domes and pit craters, some of which are very large (<20 km in their longest axis). The margins host circumferential structures which may be normal faults. As the rim appears degraded and partially buried by a younger SC lava field, the larger structure is interpreted to be a relict caldera, perhaps deformed by down-sagging. If this interpretation is correct, then OM may host the largest shield volcano summit caldera on Venus yet identified. Such circumferential structures are also seen at Sif Mons (Stofan et al., 2001), Zeus patera on Olympus Mons (Mouginis-Mark, 2021), and Arsia Mons. The caldera hypothesis may be supported by the fact that this structure lies at the convergence point of a series of pit crater chains, which suggests the presence of a magma chamber.

The effects of weathering have rendered the earliest exposed lava flows of Ozza Mons (OM1) difficult to separate; they are so radar bright and featureless that the individual flows are indistinguishable. These were followed by more episodes of high volume, likely dyke-fed eruptions, further from the summit, forming the OM2 and OM4 sheet flows. These are extensive and may have significantly drained the magma chamber and triggered caldera collapse(s). Near-summit units such as OM6 and the uppermost OM3 flows may have originated either from caldera overflow events or from circumferential faults forming ring dykes. The OM7 unit is interpreted to represent a lava lake that formed and ponded during the last large caldera collapse event at OM.

Following this, the most recent phase of volcanic activity formed the cluster of shields (OM8), which partially filled the relict caldera and incipient Ganis Chasma graben. The summit caldera is no longer quasi circular but is significantly deformed and now elongated in form; it may be relatively old in comparison to the morphologically fresh summit caldera at Maat Mons. This suggests that the magma chamber either remains partially molten but has not been replenished recently or it has cooled and crystallized. In sharp contrast to MM, OM's flank lavas show low spatial variability of emissivity, and rifting has propagated far up toward the summit. These features hint that Ozza Mons is older, and thus a cooled and inactive magma chamber may be favored. Stratigraphic analysis shows that the bulk of the volcanic construct pre-dates the Uvaysi impact PRDH and formed during the lower Atla era; however, since the PRDH does not extend to the summit region, it cannot be ruled out that the youngest units OM7-8 were emplaced in the Atla era's upper phase, contemporaneously with MM. The nature of the youngest volcanic deposit, the small OM8 summit shield cluster, indicates that overall volcanism at Ozza Mons has waned over time. However, sporadic low volume eruptions in this shield cluster could conceivably continue to the present day. On longer timescales, the magma chamber could 1 day be replenished and the volcano could re-enter a more energetic phase.

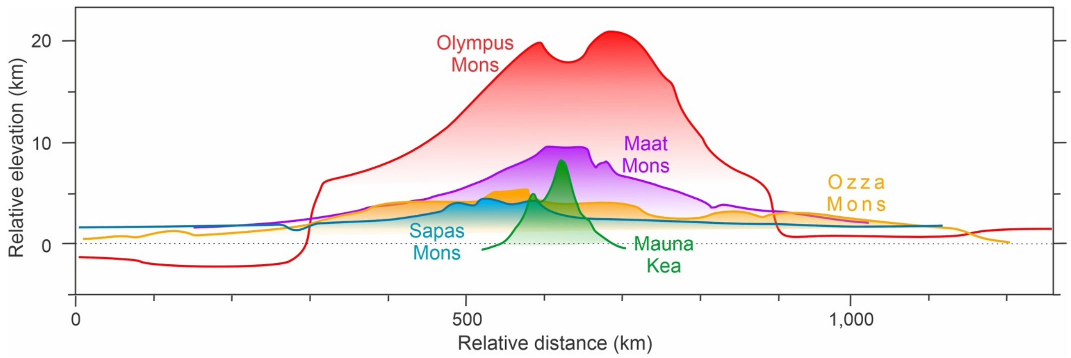

Figure 7. Relative topographic profiles across Maat, Ozza and Sapas Montes, in comparison to those of Olympus Mons, Mars and Hawaii, Earth, contrasting the size and extent of these volcanoes. Elevation sources: Global Topographic Data Record (GTDR-SINUS.3;2), Venus, Mars Orbital Laser Altimeter (MOLA) and Earth Shuttle Radar Topography Mission (SRTM V3, 1 arc-second).

3.4. Later Volcanic Activity (Atla Era, Upper Phase)

The upper Atla era begins at the time of the Uvaysi crater (UC) impact and the deposition of its Parabolic Radar Dark Halo (PRDH) apron, which forms a widespread stratigraphic marker readily distinguishable in radar imagery that has been tentatively dated at less than 60–9 Ma (Brossier et al., 2021). The Uvaysi event coincides with a significant shift in the center of active volcanism at the Atla Regio. At this juncture, volcanism along Dali Chasma seems to have ceased, although tectonism clearly continued, since there are fractures which cross-cut the Uvaysi crater rim and ejecta. At this point, Ozza Mons may be in decline or dormant while Maat Mons becomes the main site of active volcanism. UC lies in Dali Chasma on the northern flank of Aeronwen Mons and has a ~35 km diameter and a radar-bright floor. The UC airfall ejecta PRDH blankets all the older OM units but is post-dated by MM lava flows (Figures 6 and 9).

It seems clear that volcanic activity at Ongwuti, Aeronwen, and Ozza Montes has declined or terminated at this time, and the same may be true for tectonism at Dali Chasma (as no DC structures overprint the MM3 flows that have flooded it), though the reason for the decline is unclear. Perhaps successive eruptions at the three older volcanoes built the lithosphere up to a point where magma ascent is more difficult, and so the replenishment of magma chambers eventually declined or ceased. This would cause migration of melt to a new site with thinner lithosphere, where MM is located now, but the fact that MM is twice the height of OM challenges that idea.

The unusual profile of Maat Mons is another mystery, being much steeper than Ozza or Sapas Montes (Figure 7); could this be a result of differing lava composition? Perhaps the lavas of the lower Atla era represent early higher temperature, low-viscosity "plume-head" melts, whereas the upper Atla era MM lavas were sourced from lower temperature melts that were more viscous, flowed less far, accumulated faster and constructed a steeper edifice. Either Maat formed recently in the Upper Atla Era or it was present in the lower Atla era but resurfaced its flanks later in the Upper Atla Era. The lower diameter and structural complexity of Maat's summit caldera and the high frequency of radar bright flows, as compared to Ozza's, suggest that it is significantly less mature.

3.4.1. Maat Mons

Maat Mons is the tallest volcano on Venus, and its summit is twice as high as that of OM despite having a less broad apron [Figure 8]. As at OM, the flanks at low elevation are dominated by extensive Ls flows which flood local topography, but at high elevations there is no equivalent to the radar-bright homogenous (Li) unit. Instead, discrete (Lf and Ld) flows are present, varying in radar brightness and either emanating from the summit caldera region or from lower flank vents. Maat Mons' high radar-emissivity summit is anomalous compared to other high elevation regions on Venus, such as Ozza, Sapas, and Maxwell Montes, which have a very low radar-emissivity. This has been interpreted to indicate a relatively young age of emplacement (Brossier et al., 2021; Klose et al., 1992), although a low radar-emissivity (Li) region on the SW flank may be older. It is noteworthy that no lineaments or structures are found to overprint MM's lava flows, despite the fact that distal (Ls) flows flood large areas of Dali Chasma's rift (Figure 5). This is in strong contrast to OM, which has been partially overprinted by rift

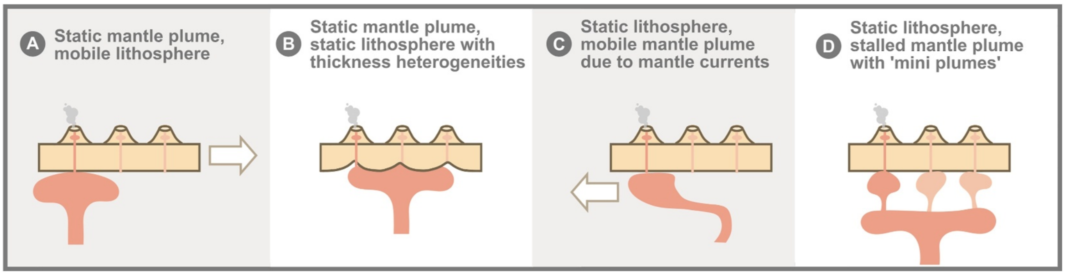

Figure 8. Diagram depicting plausible mechanisms to explain Atla Regio's displaced volcanic centers and time-varying activity, simplified from El Bilali et al. (2023).

structures, Aeronwen and Ongwuti Mons which have been completely overprinted by structures, and even other volcanoes that are proposed to be presently active such as Idunn Mons (D'Incecco et al., 2017, 2021). Hence, it appears that these flows at Maat Mons are very young indeed or that the recent rate of tectonic deformation in Dali Chasma is low or zero or both. The absence of summit-radial lineaments and the paucity of pit craters suggest that the MM radial graben-fissure system is much less well developed than at OM.

At the northern edge of Maat Mons' lava apron, prominent elongate (Ls) lava flow propagates across the UC PRDH, infilling a topographic low. Basilevsky (1993) noticed that this lava flow remains radar-bright and shows no evidence of mantling by PRDH material, clearly indicating that the flow is younger than the PDRH and impact. This observation places a key stratigraphic constraint on the relative ages of Ozza and Maat Montes. Despite being proximal to Dali Chasma, the surface flows of MM remain completely undeformed. Indeed, in some places Maat Mons lava flows infill Dali Chasma but are themselves undeformed, clearly implying that MM is the younger. This makes it unlikely that MM formed from rift-associated volcanism, as without active rifting, the geotherm would equilibrate and magma supply would cease. Additionally, MM lava flows overprint all surrounding impact craters, another indication of their youth.

There are several large shield clusters in the plains between Maat and Sapas Montes. One of these shield clusters is visible through, within, or on top of the MM1 (earliest) lava flows and it is not clear if MM lavas flow around them or if they remained active after the flows were emplaced. The MM1 lavas lack clear flow structures and so it seems more likely that the clusters post-date the earliest Maat flows.

3.4.2. Sapas Mons

Sapas Mons has an estimated volume of 3.1 × 104 km^3, similar to the total volume of an Earth-analogue shield volcano, such as Mauna Loa, with a volume of 4.25 × 104 km^3 and it is thought that a large magma chamber exists underneath (Keddie & Head, 1994). Circumferential fractures outline an area 75–125 km in diameter around the peak of the volcano. These may represent sag structures associated with the emptying and subsequent collapse of the magma chamber, extensional features associated with the filling and swelling of the magma chamber, or the surface expression of a suite of circumferential dykes, similar to ring dykes seen on Earth.

Sapas Mons also has a suite of radial grabens associated with it. These features present themselves as a collection of grabens and lineations interpreted as associated with dyke emplacement. This association is common; graben production is conducive to dyke intrusion, and vice versa. The radial pattern of the graben and dyke sets suggests that they formed from extensional forces (from local swelling and uplift), as commonly observed on Earth. These fracture patterns indicate a competent upper crust and they offer a potential insight into differences between Sapas and Maat Montes, as these features are not observed at Maat.

Sapas Mons displays an upward-younging sequence of lavas, and an apparent upward increase in viscosity, as evidenced by the lower (older) flow units having notable lower angle and far greater lateral extent than the upper, steeper slopes and less extensive flows (Figure 5). This pattern implies that an evolution and maturation of the magma supply occurred in time. This may have occurred within the magma chamber, following a similar process of magma differentiation as seen on Earth but, given the high volume of magma and extended period over which it may have extruded (Figure 5), as suggested by Keddie and Head (1994), this seems an unlikely interpretation; their study suggests reducing effusion rate and increasing viscosity from units 1 to 6 (from base to top) and they

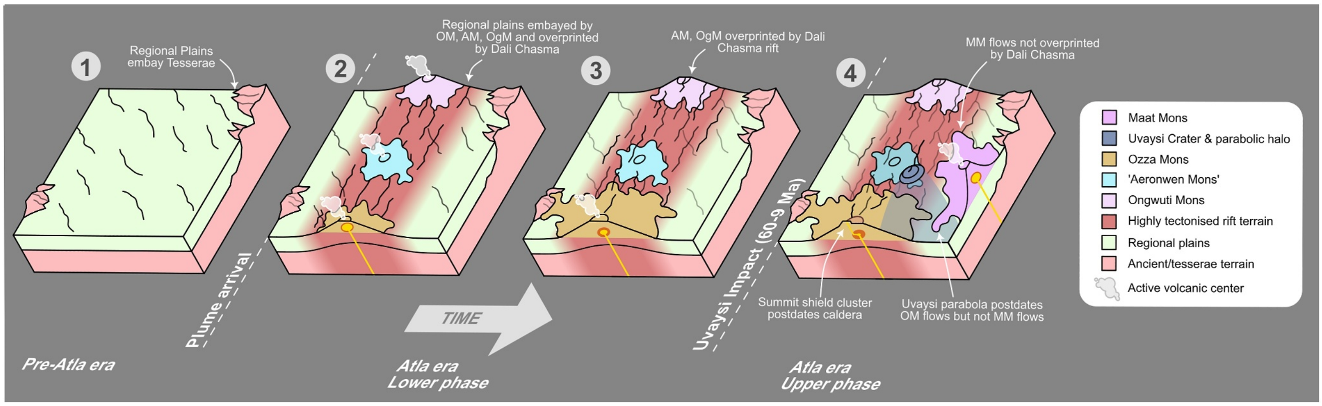

Figure 9. Simplified block diagram depicting the evolution of central Atla Regio through time, as evidenced by stratigraphic relationships between different units and structures. Key stratigraphic relationships are labeled with arrows. Colors are the same as the geologic map (Figure 6b). (1) Emplacement of regional plains at time T, (2) Plume volcanism begins, initially centered along Dali Chasma rift, (3) Ozza Mons activity continues whilst other volcanic centers wane and become overprinted by rift (4) Ozza Mons activity wanes and Maat Mons becomes the center of activity.

also estimated similar volumes and eruption durations. It seems more plausible that this evolution is a representation of the maturation of the mantle plume providing the magma. The early stage extruded melt may be less viscous, potentially more basaltic, and the late stage melt from the plume is more viscous, potentially more silicic.

The isolation of Sapas Mons' mappable features from the rest of the Atla Regio's mappable volcanic and tectonic features (Sapas Mons lies *ca* 800 km to the northwest of MM) makes it challenging to place them into our stratigraphic framework for Atla Regio. Its relative age, and its relationship (if any) with the other Atla volcanic centers, is therefore enigmatic.

3.5. Spatio-Temporal Shifts in Activity

A graphical depiction of a potential evolutionary pathway for Atla's young shield volcanoes is depicted in Figure 9. The fact that Maat Mons lies slightly off the center of the main topographic rise is intriguing but may be indicative of Maat's very young age (thought to be no more than 50 Ma, El Bilali et al. (2023)) and may represent a very recent shift in activity. Here we propose the evolution of Atla Regio as a shifting locus of volcanism over time, caused by minor crustal adjustments and shifts above a relatively static and long-lived mantle plume. This pattern of development is evidenced by the presence of several shield volcanoes clustered that are displaced around the triple-junction of Atla Regio; these are active at overlapping time-frames but with activity shifting in time from Dali Chasma (Ongwuti Mons and Aeronwen Mons) northwards to Ozza Mons and then south to Maat Mons. The spatiotemporal relationship between Sapas Mons and the other more central volcanoes is unclear. On a global scale, they appear closely associated (the nearest seemingly unrelated large volcanoes are more than 1,500 km from Sapas Mons), and this suggests that Sapas Mons is related to the Atla Regio plume in some way. Lava flows and activity at Maat Mons are dominantly younger than at Ozza Mons, which is demonstrated through meticulous analysis of Magellan data and highly detailed geological mapping across this region, using sound principles of stratigraphy and superposition, to develop both thematic mapping data sets, a relative chronostratigraphic framework (see Figure 10) and an interpreted evolutionary sequence of events for Atla Regio.

The displaced centers of these giant volcanoes may have several explanations: a stationary plume with shifting lithosphere in response to large-scale activity elsewhere; a stationary plume with static lithosphere but with thickness heterogeneities; "currents" in the mantle and a static lithosphere; or the existence of multiple mini-plumes arising from a super plume (Figure 8). While these different hypotheses are impossible to test with the available data, here we favor the first since it is the simplest explanation and since a completely static lithosphere is incompatible with the abundant evidence of activity and deformation in this area. Comparison of hypsometric curves across rift systems on Venus and Earth, viewed in relation to the volcanic styles and scales observed, indicates that for the slow moving (jostling) plate motion style at Venus, the giant shield type volcanoes of Ozza and Maat are exactly what should be expected (Byrne et al., 2021; Ghail, 2015). Like volcanic hotspots on Earth, some of these topographic rises host very large shield volcanoes, such as at Atla Regio (Senske & Head, 1992;

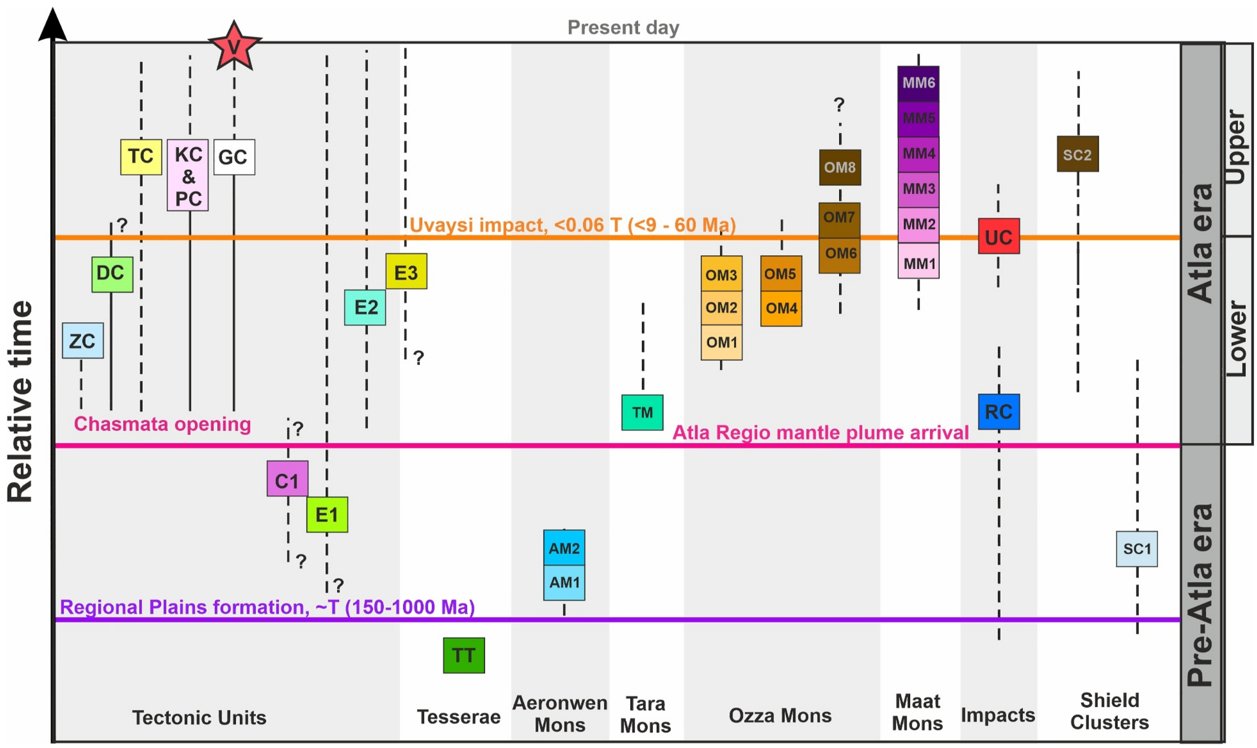

Figure 10. Summary regional relative chronostratigraphic chart. Red star "V" is a 2008 VIRTIS hotspot. TC = Tkashi-Mapa Chasma; ZC = Zewana Chasma; KC = Kicheda Chasma; PC = Parga Chasma; DC = Dali Chasma; GC = Ganis Chasma; C1 = first compressional event; E1 = first extensional event; E2 = second extensional event; E3 = third extensional event; SC = Shield Cluster; UC = Uvaysi crater; RC = Richards Crater; TT = tessera "basement."

Stofan et al., 1995). The most recent evidence for modern day activity comes from the discovery of a crater/caldera on the NW flank of Maat Mons, which can be seen to have collapsed and enlarged between cycles 1 and 2 of Magellan SAR data collection (Herrick & Hensley, 2023).

Comparing large shield volcanoes driven by mantle plume dynamics on Mars and Earth with those at Atla Regio, there is a clear inverse correlation between the size, style and scale of volcanism and the relative plate motion/stability (Figure 7). Two useful endmember examples to illustrate this idea are Olympus Mons (22 km high with 700 km diameter) on Mars and the Hawaiian volcanic chain (Mauna Kea is 4.2 km high with 200 km basal extent) on Earth. One represents a situation of lithospheric stasis above a super plume for billions of years, and thus becomes very large indeed (and it may still be active). The other represents continual plate motion (in more or less the same direction) above a static plume, producing a >6,000 km chain of small volcanoes over 60–85 Ma (Kilauea the youngest at 300 Ka, and Kure Atoll the oldest at ~28 Ma). Somewhere in between those extremes is Atla Regio, which hosts several sizable shield volcanoes (basal diameters between 400 and 600 km), is currently active and likely represents a situation of periodic minor lithospheric adjustments above a mantle plume, causing the focus of active volcanism to shift periodically, with Maat Mons appearing as the site of the most recent (current) activity. Some of these variations may be attributed to differences in gravity and atmospheric pressure between Mars, and Earth and Venus. Nevertheless, the patterns of radial dyking and topographic swelling at Atla Regio resemble terrestrial examples where a large plume leads to the formation of a Large Igneous Province-like system of magmatic centers and volcanic edifices (El Bilali et al., 2023). Atla Regio, at the center of a five-armed branching rift system, represents the site of the most voluminous outpourings of lava on Venus, perhaps over the longest period of time and with relative lithospheric stasis.

4. Summary

Through detailed geological mapping of the volcanoes of Atla Regio and its surrounding regions, a complex history of coeval rifting and volcanism driven by the Atla plume has been constructed. Analysis of Magellan SAR imagery reveals a relative chronology of lava flows emanating from the eruptive centers of Ozza, Maat and Sapas

Mons. Two newly described intermediate-sized shield volcanoes have also been identified (here called Tara and Aeronwen Montes), which shed light on the region prior to and just after plume arrival. Stratigraphic analysis of Ozza Mons reveals eruptions shifting from the western to eastern flanks and becoming increasingly restricted to the summit region through time. Its flanks are also deformed by radial graben-fissures and three rift systems approach the summit region. The radar-dark region at Ozza Mons' summit represents a deformed, relict caldera, potentially the largest summit caldera yet identified on Venus. Increasingly centralized eruptions of reducing extent at Ozza Mons suggest that volcanism along this axis is waning, although there is currently insufficient evidence to determine if the volcano is extinct or simply in a phase of inactivity.

The Uvaysi impact and its parabola of ejecta material form a very useful stratigraphic marker, being clearly distinguishable as post-dating lava flows on the SW flank of OM and pre-dating flows on the NW flank of MM. Having been tentatively dated between 9 and 60 Ma, this impact marks an important boundary between Lower and Upper Atla Era development. Using this local marker, in addition to the global marker of regional plains (corresponding to time T), and sound principles of superposition in mapping, a chronostratigraphic framework for Atla Regio is proposed here. This framework consists of several key elements: 1. "Pre-Atla era" consisting of tessera, plains emplacement, early shield volcanism and the newly described early "Tara Mons"; 2. "Lower Atla era," where early plume-induced magma-assisted rifting at Dali Chasma produces three large shield volcanoes: Ongwuti Mons, Ozza Mons, and the newly described "Aeronwen Mons." Evidence suggests that volcanism at OM is declining before the Uvaysi impact event; and 2. "Upper Atla era," where MM becomes the locus of active volcanism in Atla Regio, and which lasts until the present day; as supported by the recently discovered expansion of a caldera on the northern flank of Maat Mons (Herrick & Hensley, 2023) and in agreement with El Bilali et al. (2023) and El Bilali and Ernst (2024). This framework is in good correlation with the revised global framework proposed by Head et al. (2023). The younger Maat Mons flows, postdate the Uvaysi impact event and flood areas of Dali Chasma rift zone and yet are notably undeformed. Maat Mons also possesses a smaller and structurally simpler summit caldera and lacks a radial graben-fissure system. All these features suggest that Maat Mons is less mature than Ozza Mons and that it is active today.

5. Conclusions

We propose here a picture of active but shifting volcanism, caused by minor crustal shifts and adjustments, above a long-lived and static mantle plume system, likely driven by active rifting processes to the east, across the BAT province. With a second plume likely located beneath Themis Regio, which may be more or less active than the Atla plume at any one time, differential plume activity and accompanying volcanism may drive further crustal jostling behavior here. Our detailed mapping demonstrates that volcanism at Atla developed at several different centers over time. The identification of the Uvaysi impact PRDH as post-dating lavas at Ozza Mons but predating lavas at Maat Mons has provided a vital stratigraphic marker and has enabled the construction of a relative stratigraphic framework for this region. In time, if Maat remains the center of active volcanism for a considerable period of time, a new triple-junction style rift system may develop here, and some of the existing "arms" of the rift may decay and revert to what are classified elsewhere as "groove belts"; only time will tell. Nevertheless, the BAT region is clearly a site where significant change and evidence of young active volcanism should be expected in the data collected by the next surface imaging missions to Venus, EnVision and VERITAS.

Data Availability Statement

The primary data used was acquired by the Magellan mission. These data included 75 m Synthetic Aperture Radar (SAR) imagery (https://astrogeology.usgs.gov/search/map/Venus/Magellan/Venus_Magellan_LeftLook_mosaic_global_75m.xml) and the GTDR global topographic data product, GTDR-SINUS.3;2 (Ford, 1992a, 1992b; Morgan, 1994, https://astrogeology.usgs.gov/search/map/Venus/Magellan/RadarProperties/Venus_Magellan_Topography_Global_4641m_v02). Other elevation data sources include the Mars Orbital Laser Altimeter (MOLA, https://astrogeology.usgs.gov/search/map/mars_mgs_mola_dem_463m) and Earth Shuttle Radar Topography Mission (SRTM V3, 1 arc-second, https://www.earthdata.nasa.gov/data/instruments/srtm). The global geological terrain units, as published by Ivanov and Head (2011), were used and simplified to create the regional geological map shown here.

Acknowledgments

Funding from the Science & Technology Facilities Council is gratefully acknowledged (Grants ST/Z000513/1, ST/Y002911/1, ST/X002446/1, ST/W005298/1).

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