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ABSTRACT

We present a 1:2,500,000 geological map of the Alpha Regio (V-32) quadrangle, Venus. The V-32 quadrangle extends from 0° to 25° S, 0° to 30° E with an area of approximately 7,600,000 km². Geological mapping was conducted using full resolution (maximum 75 m/pixel) SAR, altimetry and stereo-derived topography data from NASA’s Magellan mission in ArcGIS 10.5. Nearly 40,000 lineaments were mapped. The oldest unit, tessera terrain, is present in two major regions: Alpha Regio and Minu-Anni Tessera. Two major fracture belts, both oriented approximately NNW-SSE, and four minor fracture belts have been identified and characterized. Two previously unrecognized wrinkle ridge trends of radiating and circumferential orientation have also been identified in the northeastern corner of the quadrangle. A total of 77 geological units were mapped. Plains material, previously mapped as global regional plains units, was divided into 27 units. Earlier estimates of the diameters of several coronae have been extended by hundreds of kilometres.

1. Introduction

1.1. Exploration of Venus

Venus is Earth’s closest neighbour, and shares similarities to Earth in size (85.7% of Earth volume), mass (81.5% of Earth mass), and composition (Colin, 1983). Venus and Earth, however, differ in many ways. Venus has a thick, dense atmosphere, with a composition of approximately 96.5% CO₂, 3.5% N₂, and ~20 ppm H₂O (Donahue & Russell, 1997; Von Zahn, Kumar, Niemann, & Prinn, 1983). The predominantly CO₂ composition of its atmosphere, and the planet’s proximity to the Sun, have created a ‘runaway greenhouse’ effect. The average surface temperature on Venus is 464°C (737 K), with a surface atmospheric pressure of approximately 95 bar (Donahue & Russell, 1997).

It has long been recognized that the surface of Venus is relatively geologically young, as evidenced by its few impact craters (about 940) and impact-related features, and is characterized by volcanism and tectonic deformation (Basilevsky & Head, 2003; McKinnon, Zahnle, Ivanov, & Melosh, 1997; Saunders & Pettengill, 1991). The low density of impact craters and impact-related features, as well as their apparently random spatial distribution, points toward extensive resurfacing. Various authors have used the cratering record to estimate the approximate mean age of the surface; these estimates range from about 0.2 to 1 Ga (e.g. Kreslavsky, Ivanov, & Head, 2015, and references therein). Most models proposed to explain Venus’ resurfacing fall between two broad endmember categories: (1) global resurfacing models, where resurfacing over a relatively short timescale has occurred globally at least once (e.g. Bullock, Grinspoon, & Head, 1993; Kreslavsky et al., 2015; Romeo & Turcotte, 2009; Turcotte, Morein, Roberts, & Malamud, 1999); and (2) equilibrium resurfacing models, where resurfacing occurs continuously, at similar rates to impact crater formation (e.g. Bjønnes, Hansen, James, & Swenson, 2012; Guest & Stofan, 1999; Phillips et al., 1992).

Surface features on Venus include expansive basaltic lava fields, shield volcanoes, large individual volcanoes, and tectono-magmatic structures such as coronae. Features on Venus are relatively well preserved, as the lack of water and low surface wind speed (0.3–1.0 m/s) produce little erosion (Phillips & Hansen, 1991). Tectonically deformed terrains such as fold belts, plains with wrinkle ridges, fracture belts, rift zones, and topographically elevated, deformed regions (known as tesserae) are present on Venus (Basilevsky & Head, 2000a; Basilevsky & Head, 2003; Ivanov & Head, 1996; Phillips & Hansen, 1991). Earth-like plate tectonics do not appear to have occurred throughout the observable portion of Venus’ geological history (e.g. Nimmo & McKenzie, 1998; Phillips & Hansen, 1994; Solomon et al., 1992).

Venus has a long history of exploration, from the early Mariner, Venera, VEGA, Pioneer Venus, and Magellan missions to the more recent Venus Express...
and Akatsuki (currently active) missions. The Magellan mission (National Aeronautics and Space Administration (NASA); 1989–1994) collected the most complete dataset (to date) of the surface of Venus, including the following products: synthetic aperture radar (SAR), altimetry, radiometry and gravity data (Phillips & Hansen, 1991).

The following information about Magellan’s mapping cycles has been summarized from Ford et al. (1993) and Tanaka (1994). The sensor on the Magellan spacecraft was a single instrument which collected radar data in three modes (SAR imaging, radiometer, and altimeter modes) that operated in bursts. The spacecraft executed a total of six cycles around Venus, including three radar mapping cycles and a cycle dedicated to collecting gravity data (Cycle 4). The first mapping cycle had the radar antenna positioned in a left-looking sense and captured SAR images covering 83.7% of Venus’ surface. Cycle 2 was performed to fill in the gaps left from Cycle 1, as well as to conduct right-looking radar mapping, resulting in 54.5% surface coverage. The final radar mapping cycle, Cycle 3, was dedicated to left-looking radar mapping for the purpose of generating stereographic SAR images in combination with Cycle 1 data. Cycle 3 covered 22.8% of Venus’ surface. The three mapping cycles brought the total coverage of SAR images to 98.3% of Venus’ surface, at a maximum resolution of 75 m/pixel.

1.2. Mapping of Venus’ surface

Radar technology is required to image the surface of Venus as the thick and opaque Venusian atmosphere shrouds the surface from visible light. The SAR sensor generates its own illumination through bursts of microwaves and then measures the echoes reflected from the surface (Ford et al., 1993; Tanaka, 1994). The appearance of SAR images is dependent on the properties of the surface, as well as the incidence angle and look direction (i.e. left or right) of the radar sensor. The brightness (i.e. reflectivity) of SAR images is mostly a function of changes in slope and the roughness of the geological surface (Ford et al., 1993). Slopes which face toward the sensor will appear relatively bright and shortened, whereas slopes which face away from the sensor will appear relatively dark and elongated. Brightness can also be affected by intrinsic material properties, such as the permittivity of the material; materials with high dielectric constants will produce increased radar backscatter.

Many of the previous mapping efforts on Venus have been conducted at relatively large scales. The surface of Venus has been divided into 62 quadrangles. At present, regional-scale geological maps for 33 of these quadrangles have been published by the United States Geological Survey (USGS) in collaboration with NASA, most at a scale of 1:5,000,000 (USGS, n.d.; Figure 1). Other studies of Venus’ surface have conducted mapping at scales smaller than 1:5,000,000 (e.g. Copp, Guest, & Stofan, 1998; Graff, Ernst, & Samson, 2018; Grindrod & Guest, 2006; Hansen & Phillips, 1993; Studd, Ernst, & Samson, 2011). For example, detailed geological mapping of graben-fissure systems by Ernst, Desnoyers, Head, and Grosfils (2003) at a scale of 1:250,000 in the Beta Regio and Guinevere Planitia regions of Venus identified five times as many systems than were previously identified from mapping conducted at larger scales.

1.3. The Alpha Regio (V-32) quadrangle

The Alpha Regio (V-32) quadrangle extends from 0 to 25° S latitude and 0 to 30° E longitude and covers an area of approximately 7,600,000 km². This quadrangle hosts the presence of several coronae and numerous other tectono-magmatic features. There are five named coronae: Atargatis, Cybele, Fatua, Kuan-Yin, and Thouris, as well as an additional unnamed corona-like structure located approximately 60 km northwest from the annulus of Cybele Corona. There are also volcanic flows, and circumferential and radiating extensional lineaments that may be attributed to Heng-O (in the neighbouring Sif Mons (V-31) quadrangle, to the northwest) and Thermuthis Coronae (in the neighbouring Scarpellini (V-33) quadrangle, to the west). Other major geological features include the extensive Alpha Regio and the smaller Minu-Anni tessera terrains, Dewi-Ratih Chasma, Dudumitsa Dorsa, Brynhild Fossae, Graham Patera, and Banumbirr Vallis. Several impact craters are also present throughout the map area: Lara (not shown on the accompanying map, due to its limited extent of <5 km), Vanessa, Linda, Rebecca, Xantippe, Leslie, Frank, Karen, Carreno, Paige, Tiffany, Andami, and Adamson. The largest crater is Carreno, with a diameter of approximately 60 km.

The V-32 quadrangle is situated in the low-lying volcanic plains (Tinatin Planitia), evidenced by the altimetry and geoid data, with the exception of the Alpha Regio highland. A large proportion of the quadrangle is dominated by the coronae and their associated structures and volcanic units. Other notable tectonic domains include many densely spaced NW-SE trending extensional structures surrounding Dewi-Ratih Chasma along the western boundary of the quadrangle, and a regional system of ENE-WSW trending, relatively long (>100 km) and closely spaced wrinkle ridges that are prevalent in the northern half of the quadrangle.

2. Methods

2.1. Datasets

The primary datasets used for this map were collected during NASA’s Magellan mission. A map package for the V-32 quadrangle consisting of Magellan datasets.
(stereo- and left-looking SAR FMAPs (mosaicked full resolution basic image data records (F-BIDRs)), C3-MIDRs (compressed mosaicked image data records), and the Global Topographic Data Record (GTDR)) and an ArcGIS database was provided by the USGS Astrogeology Science Center. Additionally, stereo-derived topography generated by Herrick, Stahlke, and Sharpton (2012) using Magellan left-looking and stereo left-looking data was used to inform geological mapping. The stereo-derived topography has increased the resolution of the Magellan topography dataset from an average original horizontal resolution of approximately 10–20 km, to a horizontal resolution of approximately 1–2 km and a vertical resolution of approximately 100 m (Ford & Pettengill, 1992; Herrick et al., 2012). This newly derived topography dataset covers approximately 20% of the surface of Venus, and 50% of the V-32 quadrangle. However, due to inconsistencies in the absolute elevation values along the boundaries of the F-BIDRs, the stereo-derived topography dataset was primarily used for analysis of relative elevation values and generalized morphologies of features. Other specific details about the Magellan mission and its various datasets can be found in Saunders et al. (1992), Ford et al. (1993) and Tanaka (1994).

2.2. Geological mapping procedures

2.2.1. Linear and point features

Linear features such as graben, fissures, fractures and wrinkle ridges appear as bright lines on grayscale SAR images (Figure 2). These bright lines represent reflections from the left or right wall of the feature, depending on the look direction of the SAR sensor. Linear features were mapped along the illuminated side; for the V-32 quadrangle, the left-looking SAR dataset was primarily used for mapping as there is no right-looking SAR dataset for this area. Interpretations were supplemented with stereo left-looking data where available. Linear features were described as small (<30 km long, a few km wide; typically localized) or large (>30 km long, a few to tens of km wide; typically of regional extent). Extensional structures, generally expressed as narrow troughs and scarps, were grouped into two categories based on their geometry: (1) graben, defined as having observable ‘floors’ bounded by inward angling scarps (Grosfils & Head, 1994b; Figure 3A-i) and (2) other extensional structures, including: fissures (defined as features that have a ‘V-shaped’ geometry (Grosfils & Head, 1994b; Figure 3A-ii)), fractures (defined as features limited to the near-surface (Grosfils & Head, 1994b; Figure 3A-iii)), and normal faults. Groups of extensional structures (comprising graben, fissures, and fractures) that share a common geometry (and often an inferred genetic relationship) have been referred to as ‘graben-fissure systems’ (e.g. Ernst et al., 2003; Grosfils & Head, 1994a, 1994b; Studd et al., 2011). Low-amplitude, sinuous ridges, known as wrinkle ridges, were also mapped (Figure 3B-i and -ii). Wrinkle ridges are widely interpreted to be contractional in origin (Bilotti & Suppe, 1999; McGill, 1993). Due to the nature of the illumination

Figure 1. Current geological mapping status of 1:5 million scale Venus quadrangles. Modified after schematic from the International Astronomical Union (IAU)/USGS/NASA.
of features in SAR images, extensional structures and wrinkle ridges can be differentiated by tonal contrast. Scarps associated with extensional structures display sharp tonal contrasts, whereas the tonal contrast associated with wrinkle ridges is more gradual (Suppe & Connors, 1992; Figure 2). The along-strike morphology of these features is also different; wrinkle ridges are typically more sinuous (McGill, 1993). Due to the complex structural fabric that is characteristic of tessera terrain, only representative structures were mapped within this unit; these structures were grouped broadly into ridges (e.g. fold crests), and troughs and fractures (e.g. graben, fissures, scarps). Canali and sinuous rilles, interpreted to represent channels formed by lava (Williams-Jones, Williams-Jones, & Stix, 1998), were also mapped as linear features.

**Figure 2.** Examples of the SAR properties (left) and superimposed mapping (right) of the two main types of linear features, extensional structures (A,B) and wrinkle ridges (C,D). A representative number of linear features, consistent with the map scale, were mapped.

**Figure 3.** Schematic cross-sections of the interpreted geometries of structures mapped in this study. A) Geometries of extensional structures, modified after Grosfils and Head (1994b): i) graben, ii) fissure, and iii) fracture. B) Hypothetical geometries of wrinkle ridges interpreted to represent anticlines and thrust faults, modified after Okubo and Schultz (2004): i) primary thrust, and ii) secondary forethrusts and backthrusts.
Other features, such as small volcanic edifices, colles (small hills or knobs), and pit craters, were mapped as point features. Small volcanic edifices may include shields, domes, and cones, as defined in Guest et al. (1992); the outlines of associated summit craters with diameters larger than approximately 2 km were mapped. Pit craters, defined as quasi-circular, shallow, and steep depressions (Bleamaster & Hansen, 2001; Wyrick, Ferrill, Morris, Colton, & Sims, 2004) were mapped individually, though they often occur in chains. The outer rims of impact craters were also mapped.

2.2.2. Geological units

Geological units were defined on the basis of their brightness, as well as their relationship with other units and structures. Geological units fall within two main categories: material and lithodemic (Hansen & López, 2018; Figure 4). In some cases, units could be defined solely based on their distinct SAR and textural properties; these represent material units (e.g. relatively young, undeformed lava flows; Figure 4C,D). In other cases, post-emplacement features and structures were pervasive enough that material units could not be defined. Within these areas, post-emplacement features and structures were also used to define units and these represent lithodemic units (e.g. fracture belts; Figure 4A,B). Units are referred to as ‘intensely deformed’ where there is a high density of secondary structures. Units with mostly similar characteristics were grouped together as sub-units of a major unit in the following scenarios: (1) where there were only minor differences in characteristics (such as radar brightness), (2) where units were separated by large distances and could not be confidently correlated with each other, or (3) where units were interpreted to have similar modes of origin (e.g. distinct volcanic flows associated with a single corona or plains material with abundant wrinkle ridges). Contacts between adjacent geological units were grouped into two categories: (1) certain, where clear boundaries between units could be discerned, and (2) uncertain, where clear boundaries between units could not be discerned. Flow outlines are superimposed on map units where boundaries of individual volcanic flows were observable on SAR images but could only be partially traced. Detailed information on the procedures used for geological mapping on Venus can be found in Tanaka (1994) and Ford et al. (1993).

3. Overview of the main geological features

3.1. Tessera terrain

Tessera terrain is characterized by its high radar brightness, relatively high relief in comparison with its surroundings, and intense deformation patterns consisting of intersecting networks of ridges, scarps, troughs, and other lineaments (Gilmore & Head, 2000; Hansen & Willis, 1996, 1998). It is considered the oldest stratigraphic unit on Venus and comprises approximately 8% of the surface (Basilevsky & Head, 2000b; Ivanov & Head, 1996). There are two major tessera regions in the quadrangle: Alpha Regio (1300 by 1500 km; Bindschadler, DeCharon, Beratan, Smrekar, & Head, 1992; Bender, Senske, & Greeley, 2000; Gilmore & Head, 2000) and Minu-Anni Tessera (composed of multiple blocks, the largest being 220 by 500 km), along with numerous smaller tessera inliers. Tessera terrain in the quadrangle is almost always contained within areas of regionally or locally elevated topography, typically a few hundred metres to several kilometres above the surrounding areas.

3.2. Chasmata and fracture belts

Rift zones and fracture belts, frequently interpreted to represent zones of extension, are characterized by numerous closely spaced extensional lineaments (e.g. graben, half-graben/normal faults, fractures) of similar orientation (Hansen, Willis, & Banerdt, 1997; Tanaka, Senske, Price, & Kirk, 1997). The main distinction between these two features is based on their topographic expression: rifts and their associated chasmata (steep, elongated valleys) are mainly topographic troughs, whereas fracture belts are mainly topographic highs (hundreds of metres to >1 km above the surrounding areas) (Basilevsky & Head, 2000b; Hansen et al., 1997; Tanaka et al., 1997). Previous workers have interpreted age differences between these features: rifts, chasmata and their associated structures are suggested to be younger than the regional plains, and fracture belts are suggested to be older than the regional plains (Basilevsky & Head, 2000a, 2000b; Head & Basilevsky, 1998).

At least two distinct and prominent zones of closely spaced extensional structures are present in the V-32 quadrangle. Dewi-Ratih Chasma trends NNW-SSE and is located along the western edge of the quadrangle, where it extends into the neighbouring Carson (V-43) quadrangle to the west (Figure 5). The chasma itself is approximately 30 km wide, 450 km long, and has an elevation of approximately 200 m below the surrounding areas. The chasma is flanked by regions of extensional structures that are elevated a few hundred metres above the surrounding plains. The entire Dewi-Ratih system, including its extension into neighbouring quadrangles, has maximum dimensions of approximately 450 km wide and 1150 km long. We have classified this lithodemic unit as the Dewi-Ratih fracture belt (Fracture Belt Unit 1 (bf1)). A second, unnamed, fracture belt (Fracture Belt Unit 3 (bf3); centred at 9.7° S, 15.0° E) is present in the central
region of the V-32 quadrangle (Figure 6). It is approximately 350 km wide and 430 km long, with the long axis and extensional structures oriented NNW-SSE. This fracture belt stands a maximum of approximately 775 m above the surrounding plains. Several other minor fracture belts have also been mapped (Fracture Belt Units 2, 4–6, 5, 6).

3.3. Volcanic plains

Volcanic plains are the most widespread plains on Venus and cover approximately 80% of its surface (Basilevsky & Head, 2000a; Basilevsky & Head, 2003). In their global geological map of Venus, Ivanov and Head (2011) subdivide these volcanic plains into the following units: densely lineated plains, ridged plains, shield plains, regional plains (further subdivided into a lower unit and an upper unit), smooth plains and lobate plains. In the V-32 quadrangle, Ivanov and Head (2011) mapped the majority of the volcanic plains as shield plains, and lower and upper regional plains.

While the boundaries of our geological units are generally consistent with the global mapping of Ivanov and Head (2011), our mapping revealed several localized material and lithodemic units that were previously grouped as part of the global regional plains units (Figure 7). We also linked many volcanic units (e.g. the shield plains and lobate plains of Ivanov and Head (2011)) to their sources, such as individual coronae (e.g. Fatua Corona Flow Material (cmF)) or volcanic edifices (e.g. Dzalarhons Mons Flow Material (fDM)). Volcanic units Digitate Flow Material Units 1–4 (fd1–4) overlie adjacent extensional structures and wrinkle ridges and are particularly recent and undeformed by secondary processes. Some channel-like features are present within these relatively young volcanic flows.

Figure 4. Examples of the types of geological units: lithodemic (A,B) and material (C,D). A) SAR image (centred at 10.2° S, 1.2° E) of Fracture Belt Unit 1 (bf1), a lithodemic unit; B) geological map corresponding to A; C) SAR image (centred at 21.6° S, 13.6° E) of Unsourced Flow Material Unit 2 (fu2), a material unit; and D) geological map corresponding to C.
3.4. Coronae

Coronae are quasi-circular tectono-magmatic features that are typically hundreds of kilometres in diameter but may extend up to over 1000 km in diameter (e.g. Heng-O Corona) (Stofan et al., 1992). They are associated with a topographic expression (the most common profile, representing approximately 25% of the corona population, is an uplifted rim surrounding an interior depression), volcanic features, as well as tectonic structures, including radiating and circumferential graben-fissure systems, and wrinkle ridges (Smrekar & Stofan, 1997; Stofan et al., 1992). Coronae are a predominant feature in the V-32 quadrangle, with their radiating and circumferential graben-fissure systems comprising major structural features and their associated volcanic flow material covering a significant portion of the surface.

A ring of structures, referred to as the annulus, commonly encircles the centres of coronae and is often spatially associated with the topographic rim, when present (Squyres et al., 1992; Stofan et al., 1992). All the coronae are associated with a circumferential graben-fissure system contained within the annulus. We have chosen to define the maximum size of coronae using the maximum diameter of the associated circumferential graben-fissure system. Our detailed structural mapping has significantly increased the observed diameters of coronae from initial estimates within the global corona catalogue by Stofan et al. (1992). For instance, Fatua Corona is described by Stofan et al. (1992) as morphological type ‘concentric double-ring’ and volcanic category 2 (moderate volcanic activity), with a maximum diameter of 310 km and a maximum annulus width of 85 km. The maximum diameter of all circumferential graben-fissures within the annulus is, however, approximately 870 km.

Radiating graben-fissure systems have also been identified; at least four coronae, including Kuan-Yin, Atargatis, Cybele, and Fatua, are associated with at least one radiating system. The radiating systems associated with Kuan-Yin, Atargatis, and Cybele are concentrated within the central regions of the coronae. The largest radiating system in the quadrangle is associated with Fatua Corona and extends for a maximum distance of approximately 1700 km from the centre; this system includes the Brynhild Fossae of the neighbouring V-44 (Kaiwan Fluctus) quadrangle, to the south (Bethell, Ernst, Samson, & Buchan, 2017). Many radiating graben-fissure systems, especially those that extend significantly beyond the

Figure 5. Fracture Belt Unit 1 (bf1), associated with Dewi-Ratih Chasma (0°-20° S, 0°-9° E). A) SAR basemap and B) extent of the mapped bf1 unit and associated structures. See accompanying geological map for other mapped units and structures.
central region of coronae, are likely underlain by dyke swarms (Grosfils & Head, 1994a, 1994b).

### 3.5. Wrinkle ridges

Wrinkle ridges are prevalent throughout the V-32 quadrangle and are mostly concentrated in the volcanic plains units. A few discrete trends are observed. A regional system of relatively long (>100 km), closely spaced ENE-WSW trending wrinkle ridges is prevalent throughout the northern half of the quadrangle. The density and spacing of these wrinkle ridges increase and decrease toward the north, respectively. Regionally ENE-WSW trending wrinkle ridges diverge around regions of high topography (e.g. the outer rim of Kuan-Yin Corona) and converge into regions of low topography (e.g. the interior of Thouris corona) (McGill, 1993). A system of circumferential wrinkle ridges is present in the northeastern corner of the quadrangle, intersecting with a third system of approximately perpendicular wrinkle ridges that possess a radial geometry (Figure 8).

Wrinkle ridges are widely interpreted to be contractual structures, representing anticlines and associated thrust faults (e.g. Bilotti & Suppe, 1999; Golombek, Plescia, & Franklin, 1991; McGill, 1993, 2004; Okubo & Schultz, 2004; Schultz, 2000). Bilotti and Suppe (1999) identified the ENE-WSW-trending wrinkle ridges as belonging to a system circumscribing Eistla Regio in their global mapping of wrinkle ridges. Specifically, this trend appears to be centred on the geoid high of Sappho Patera (the circum-Sappho Patera trend, with the focus located in the neighbouring Sappho Patera (V-20) quadrangle, to the north).

### 4. Summary of the geological history

Tessera materials (including Tessera Terrain (tt) and Tessera Margin Material (tm)) are the oldest units in the V-32 quadrangle. The precursor terrain for tessera materials is unknown; it has been deformed by multiple tectonic events. The margins of tessera terrain are always embayed by younger volcanic units and are frequently cross-cut by younger structures (Figure 9A). The presence of numerous small tessera inliers throughout the quadrangle may indicate that the tessera terrain is akin to a regional ‘basement’ terrain. Tessera margin material is interpreted to represent tessera terrain that has been flooded by younger volcanic units.

Although fracture belts (bf1–6), as lithodemic units, do not conform to conventional laws of stratigraphy (Hansen & López, 2018; North American Commission on Stratigraphic Nomenclature, 2005), the material comprising these units must also be relatively old. This is evidenced by the cross-cutting relationships of their defining extensional structures, which are consistently embayed by surrounding units and cross-cut by younger structures (Figure 9B). Fracture belt units are also generally preserved in regions of elevated topography. Extensional structures in fracture belts also cross-cut tessera materials, suggesting that at least the deformation characterizing these units is younger than tessera materials. The extensive nature of the Dewi-Ratih system (bf1), along with its association with a central chasma and more than 8000 mapped extensional structures, suggests the system formed under regional extension. Many aspects of its morphology resemble extensional zones found elsewhere on Venus (e.g. rift zones in the Beta-Atla-Themis region or the Alpha-Lada and Derceto-Quetzalpetlatl.
extensional belts). We have classified the Dewi-Ratih system as a fracture belt due to its overall elevated topography, which is not typical of rift zones.

Units classified as plains material display a range in relative ages, although the majority these (including the most areally extensive units, Smooth Plains Unit 1 (ps1) and Intermediate Plains Unit 1 (pi1)) are both mostly younger than tessera terrain and the extensional structures defining fracture belts, and relatively older than many localized volcanic units. Some plains units

Figure 7. Examples of some major plains material units. A) SAR image (centred at 5.5° S, 17.4° E) of Smooth Plains Material Unit 1 (ps1); B) geological map corresponding to A; C) SAR image (centred at 22.2° S, 15.7° E) of Intermediate Plains Material Unit 1 (pi1); D) geological map corresponding to C; E) SAR image of Mottled Plains Material Unit 1 (pm1) (centred at 23.2° S, 18.3° E); F) geological map corresponding to E.
(including Smooth Plains Units 4–5 (ps4–5) and Intermediate Plains Units 2–3 (pi2–3)) are interpreted to have formed relatively late (Figure 9E).

Corona materials also display a range in relative ages. For instance, Thouris Corona Fractured Material (cfT) is cross-cut by the extensional structures characterizing Fracture Belt Unit 3 (bf3) and is therefore relatively older (Figure 9C). A few coronae (Atargatis, Kuan-Yin, and Thouris) also display evidence for embayment by plains material. However, other coronae, such as Fatua, have interiors that are not embayed by plains material, and are associated with structures that cross-cut plains material (Figure 9D). Cross-cutting relationships demonstrate that volcanic units and structures associated with coronae mostly predate the formation of wrinkle ridges.

Many of the units classified as volcanic edifice and flow material are younger than the majority of the plains material units, and most of which have been

Figure 8. Map of the two previously unrecognized wrinkle ridge trends mapped in this study.

Figure 9. SAR images displaying examples of the major cross-cutting relationships in the V-32 quadrangle. A) Embayment of tessera terrain (tt; below, radar-bright) by plains material (pi1; above, radar-dark); B) embayment of NNW-SSE trending extensional structures within a fracture belt (bf1) by plains material (ps1); C) NNW-SSE trending extensional structures within a fracture belt (bf3) cross-cutting circumferential extensional structures associated with Thorius Corona; D) radiating extensional structures associated with Fatua Corona cross-cutting plains material (pi1); E) Smooth Plains Unit 4 (ps4; above, relatively radar-dark) truncating NNW-SSE trending extensional structures in the adjacent relatively Ridged Plains Unit 3 (pr3; below, relatively radar-bright), indicating different relative ages for plains material; and F) relatively recent volcanic flow material (fd4) overlying NE-SW trending regional wrinkle ridges.
subsequently deformed by wrinkle ridges. A few of these units, particularly Digitate Flow Material Units 1 and 3 (fd1,3) overlie all nearby units and cross-cut all observed structures (including wrinkle ridges; Figure 9F).

While wrinkle ridges are concentrated in volcanic plains material, they cross-cut most units and structures, suggesting their formation is one of the most recent events to occur in the quadrangle. Based on cross-cutting relationships between the different wrinkle ridge trends, the regional ENE-WSW trending wrinkle ridges appear to be younger than both the circumferential and radial wrinkle ridges in the northeastern corner of the V-32 quadrangle. Based on the varying ages and geometries of these wrinkle ridge systems, each is interpreted to represent an episode of contractional deformation related to different orientations of the maximum compressional stress. The V-32 quadrangle therefore records a history of polyphase contractional deformation, with at least three separate generations.

5. Conclusions
This mapping study represents the first detailed geological map produced for the Alpha Regio (V-32) quadrangle, and one of few maps of areas on Venus to be produced at a scale of 1:2,500,000. Detailed mapping of the V-32 quadrangle has revealed a complex tectono-magmatic history. In total, 39,523 lineaments were mapped, including 29,837 extensional structures and 8266 wrinkle ridges. Among the mapped extensional structures, 6 radiating and 8 circumferential graben-fissure systems were identified. At least two distinct extensional zones are present, which are defined as fracture belts that represent relatively old lithodemic units. A total of 77 units (including sub-units) were mapped. Twenty-seven of these units have been classified as plains material. Our mapping of volcanic units and structures (including radiating and circumferential graben material. Our mapping of volcanic units and structures, 6 radiating and 8 circumferential graben-fissure systems that represent relatively old lithodemic units.

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Software
Mapping was conducted using ArcMap 10.5.1 (of the ArcGIS 10.5.1 suite), using georeferenced, mosaicked raster images from the various Magellan mission datasets. Separate shapefiles were created for each type of geological feature and additional information (such as size, descriptions) were stored in attribute tables. Subsequent editing and manipulation of the map was carried out in CorelDraw X6.
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