Mapping graben-fissure systems in the Mead quadrangle, Venus

By

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in
partial fulfillment of the requirements for the degree of

Master of Science

in

Earth Sciences

Carleton University
Ottawa, Ontario

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Abstract

Graben–fissure systems can have radiating, linear or arcuate/circumferential geometry and are generally interpreted as the surface expressions of underlying dyke swarms on Venus. Coronae on Venus are large, circular surface features and form in response to magmatic loading of the crust over zones of partial melting at the tops of mantle plumes that impinge on the base of the thermal lithosphere. This project has mapped 32 different graben-fissure systems in the study area (10° - 20° N, 30° - 50° E) within the Mead Quadrangle: 24 of these systems are spatially associated with 4 different coronae (Didilia, Pavlova, Isong, and Ninmah), and in 8 cases are genetically linked. Eight remaining systems are not related to coronae. Five have foci associated with known magmatic centers (corona or volcano). Two others radiate from a cryptic magmatic center. Additional arcuate systems are interpreted to be circumferential about magmatic centers.

Acknowledgements

To start from the beginning, I would like to thank my co-supervisor Dr. Richard Ernst, for his support, wisdom, knowledge, patience and encouragement. He provided me the opportunity to pursue a Master's degree at Carleton University and for that I am truly grateful. I would like to also thank my co-supervisor Dr. Claire Samson for her patience, attention to detail and knowledge. Without their aid, knowledge and guidance, this project wouldn't have been completed; my very sincere gratitude goes to them!

I would also like to thank Jamie Graff for assistance in preparing Figure 3.3, Erin Bethell for help with preparing Figure 1.4, and Sarah Davey for assistance in preparing Figure 3.12. Lastly, I would like to thank my parents for their love, support and encouragement.

Thank you.

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Chapter 1: Introduction

1.1 The planet Venus

Venus is the second closest planet to the sun at a distance of about 108 million km (67 million miles) or 0.72 AU, and orbiting it every 224.7 Earth days. Venus has no natural satellite and no rings (Figure 1.1). The planet Venus is the third brightest celestial object in the sky preceded only by the Sun and Moon, and named after the Roman goddess of love and beauty. Venus' sidereal rotation period (length of one day) is approximately -243 Earth days; the negative value indicates its retrograde rotation ^[1], because Venus spins backwards when compared to the other planets ; it means the sun rises in the west and sets in the east on Venus.

Venus possesses intense heat and volcanic activity. Venus' thick and toxic atmosphere is comprised primarily of carbon dioxide, carbon monoxide, nitrogen, hydrochloric acid, hydrofluoric acid, and sulphuric acid (Mueller et al., 2008), which forms clouds that obscure any view of the surface from orbit and effectively trap heat, all of which has resulted in a surface with conditions hostile to life as it exists on Earth. Venus has an average surface temperature of 462 °C and atmospheric pressure of 9030 kPa. Water is only present in miniscule amounts of between 1 ppm (parts per million) to 100 ppm (Prinn and Fegley, 1987), so Venus lacks water both in its atmosphere and on the surface. In addition, Venus also lacks a significant magnetic field (Russell, 1980) due to its sufficiently high surface temperature that a remnant magnetic record can't be preserved within the surface rock (Head, 1999) and it spins slowly enough that no magnetic field is generated in the planet's core (e.g., Nimmo, 2002). However, the lack of a

^[1] <http://solarsystem.nasa.gov/planets/profile.cfm?Object=Venus&Display=Facts&System=Metric>

self-sustaining magnetic field indicates that the liquid iron core has limited and insignificant convection (Nimmo, 2002).

Venus is a rocky terrestrial planet and is considered as Earth's "sister planet" because of their similarity in size, mass, gravity, and bulk composition. In likeness to Earth, Venus has 81.5% the mass of Earth, 95.5% its density and 95% the mean radius (Janle and Meissner, 1986). The average crustal thickness is 30 km calculated from gravity and topography data collected by the Magellan Spacecraft (Nimmo and Mckenzie, 1998; James et al., 2010). Also, the composition of Venus' surface is largely basaltic (Surkov et al., 1986). Similar to Earth, Venus is predicted to have a liquid iron core with an average temperature of 1300 ° C (Konopliv and Yoder, 1996; Nimmo and McKenzie, 1998).

Besides these similarities to the Earth, Venus also possesses several characteristics that differ greatly from those of Earth. Venus's topography is unimodal, unlike Earth's which has a bimodal distribution of heights representing continents and ocean basins. More than 80 % of the surface of Venus lies within 1 km of the mean elevation. Venus does not exhibit Earth-like plate tectonics; separate plates, subduction zones and transform faults are not observed on Venus (Phillips and Hansen, 1994). Instead, Venus displays a unique array of topography and surficial features associated with magmatism, meteorite impacts and aborted rifting. In addition, the surface of Venus exhibits an approximately uniform intensity of impact cratering across all types of geological units which has been interpreted as evidence that Venus underwent a global magmatic resurfacing event. The duration of the resurfacing event could have ranged for 10s of Ma to a few hundred Ma, and occurred sometime between about 500 to 900 Ma ago (e.g., Mckinnon et al., 1997; Ernst and Desnoyers, 2004, and references therein).

There are three primary types of topographic morphologies present on Venus: planitia, highlands, and mesolands, as described by Phillips and Hansen (1994). Planitia are radar smooth lowlands with relatively little relief and interpreted as areas of extensive volcanic flooding typically found below the mean planetary radius. Highlands are rough, mountainous, and volcanic areas with topography exceeding 2 km above the mean planetary radius. The mesolands are rolling plains which the areas found between 0 and 2 km (between planitia and highlands) above the mean planetary radius. The mesolands host the majority of coronae and chasmata (Phillips and Hansen, 1994). Tesserae terrains include areas with more than one set of grooves and ridges, and are commonly hosted in mesolands regions.

Figure 1.1: The planet Venus (circled) in our solar system. Extracted and modified from <http://solarsystem.nasa.gov/planets/profile.cfm?Object=Venus>.

1.2 Magellan Missions to Venus

The data used in this project were provided by the U.S. National Aeronautics and Space Administration (NASA) and collected by the Magellan spacecraft. Magellan was launched on May 4th, 1989, arrived in the vicinity of Venus on August 10th, 1990; it started mapping the planet Venus on September 15th, 1990, and after one cycle (one Venus day or 243 Earth days) had mapped 84% of the planet's surface. Magellan spacecraft orbited the planet Venus for four (Venus) years, completed three 243 –day mapping cycles, providing radar maps of 98 % of the planet's surface, with a resolution of 75 m/pixel. Gravity data were obtained during cycles 4 and 5, obtained after the orbit was circularized. Finally the spacecraft was commanded to enter the planet's atmosphere and crash on its surface on October 11th, 1994.

The Magellan spacecraft (Figure 1.2) collected and returned an image data volume greater than all previous planetary missions combined. In addition, Magellan has provided a fundamental data set for global assessment of volcanism, tectonism, impact processes and surface processes. The Pioneer and Venera missions occurred before the Magellan mission. The Pioneer Venus Team (Masursky et al., 1980) and the scientists who analyzed the Venera 15 and 16 image data (Barsukov et al., 1986) compiled the basic framework for Venus geology; their assessment of the global importance of plains and highlands were basically correct. However, the Magellan radar instrument has mapped 98 % of Venus at 100 m resolution, providing an improved global topographic map, global images, reflectivity, and emissivity.

The Synthetic Aperture Radar (SAR) used on the Magellan spacecraft transmitted microwaves with a wavelength of 12.6 cm, which are unaffected by the thick atmosphere cloud cover, onto the planet's surface. It used the delay and strength of the echoes to create an image of the surface. The spacecraft and radar data transmitted to Earth were processed by the Magellan

flight team through a collection of computer systems and electronic networks collectively referred to as the Ground Data System. For SAR images, the resolution is determined by the aperture of the instrument acquiring the image, which is the size of the radar system's antenna. The antenna was in motion while receiving the radar echoes back from the surface. So the Magellan radar instrument received information that otherwise, would have had to be collected with a much larger receiver.

There were three antennas used in the Magellan spacecraft: high-(HGA), medium-(MGA), and low-gain (LGA) antennas, as well as an altimeter antenna (Figure 1.2). The radar mapping, communication with Earth and other primary function were completed by the HGA, and the other two antennas were largely used to support the HGA and relay signals when the HGA could not be pointed directly toward Earth. Lastly, the altimeter antenna is used to calibrate the SAR data, also to adjust the orientation of the HGA during the mapping.

The radar images produced by the Magellan spacecraft were originally in the form of F-BIDRs (Full-resolution Basic Image Data Record), and then the data were processed and released in the forms of F-MIDRs (Full-resolution Mosaicked Image Data Record) and C-MIDRs (Compressed Mosaicked Image Data Record) for easier exchange and analysis. Then the F-MIDRs were converted to FMAPs (Full-resolution radar Maps) where each pixel represents a 75 meter by 75 meter square of Venus's surface (75m /pixel). For this research project, we are using images at full F-MIDR resolution of 75m /pixel.

Figure 1.2: The Magellan spacecraft in mapping configuration. After Saunders et al. (1990).

As part of an ongoing research on Venus, the Venus Express Spacecraft (European Space Agency) was launched November 9, 2005 from Baikonur, Kazakhstan on the Soyuz-Fregat rocket. The Venus Express spacecraft is equipped with seven instruments including a magnetometer, a planetary Fourier spectrometer, a Visual and Infrared Thermal Imaging Spectrometer (VIRTIS) and a wide-angle multi-channel monitoring camera. The Venus Express mission is currently in orbit, and is expected to run until December 31, 2014 to gain a better understanding of Venus' atmosphere and surface.

1.3 Geological Mapping

The Magellan Radar Mapping Mission to Venus has returned an unprecedented volume of digital data about the surface of our sister planet-Venus, and the data are publicly available on the United States Geological Survey (USGS) website ^[2].

The systematic geological mapping of Venus based on the Magellan data has been subdivided into 62 quadrangles where each quadrangle has, or will be, assigned to a scientist for mapping of surficial geological features such as volcanic plains units, volcanic edifices and corona, meteorite impacts, rift zones, tesserae (complexly deformed areas), wrinkle ridges (compressional features), giant dyke swarms (graben-fissure systems), and pit crater chains, etc. Currently, there are 27 quadrangles have been published, 8 are under review, 19 are in progress and 8 remain unassigned.

Campbell and Clark (2006) have produced a geological map of the Mead Quadrangle (V-21) of Venus (Figure 1.3) in which the study area of this thesis is located (see Chapter 2; and location on Figs. 1.3 and 1.4).

^[2] <http://astrogeology.usgs.gov/maps>

Figure 1.3: Location of the Mead quadrangle (V-21) on the globe of the planet Venus.

Study area is delineated by a red box. After Campbell and Clark (2006).

1.4 Venus Global Dyke Swarm Mapping Project

The Venus global dyke swarm mapping project (Figure 1.4) is aiming at producing the first global map of graben-fissure systems on Venus, assessing which of these systems are underlain by dyke swarms and contributing to the understanding of the tectonic and magmatic history of the planet, through an international effort with contributions from colleagues in the United States, Canada and Russia. Mapping is being done using Magellan synthetic aperture radar images at 75 m/pixel resolution, and is integrated with the global geological map produced by Ivanov and Head (2011) and quadrangle mapping to gain a better understand of the distribution of the intraplate magmatism.

The previous graben-fissure mapping studies which are part of the Venus global dyke swarm mapping project and have been completed over the past decade include Nepthys Mons Quadrangle (V-54) (Blair and Ernst, 2002), Guinevere Planitia and Beta Regio (Ernst et al., 2003; Ernst, 2014), Ulfrun Regio Quadrangle (V-27) (Studd et al., 2011) and (partially) Imdr Regio, Themis Regio, Ganiki Planitia and Ulfrun Regio (Davey et al., 2012).

Figure 1.4: Location of study area superimposed on: a) mapping of Global Dyke Swarm Mapping Project, and b) extensional lineaments extracted from published quadrangle maps. Maps are in a sinusoidal projection with central meridian at 300 degrees. Modified after E. Bethell (unpublished compilation).

1.5 Research objectives

In this project, systematic mapping of extensional lineaments (fractures, fissures, and graben) which are associated with the coronae in the Mead quadrangle area of Venus has been completed, using Synthetic Aperture Radar (SAR) data from Magellan mission. The emphasis is on identifying graben-fissure systems within and immediately adjacent to the coronae in the study area.

With the high density of graben-fissure systems that have been mapped in this study (Chapter 3), I then explore the approach of using cross-cutting relationship between individual graben-fissure systems and geological units to determine relative ages of different graben-fissure systems and by inference the relative ages of their associated volcanoes / coronae (Chapter 4). So, this mapping will provide a new context from which to examine the magmatic and tectonic evolution of the study area and better insight into the timing of the volcanic units mapped in Campbell and Clark (2006).

The objectives of this study are to: (1) contribute to the global map of graben-fissure systems on Venus, (2) unravel origin of structures related to coronae with a focus on their rims, and (3) propose a geological framework for the relationship between formation of corona and different generations of dyke swarms within and nearby a cluster of coronae in the Mead quadrangle. This study is part of the larger Venus Global Dyke Swarm Mapping project (Ernst et al., 2009).

Chapter 2 Background information

2.1 Study area

The study area for this project is within the Mead quadrangle (V-21) of Venus (bounded by latitudes 0° and 25° N, longitudes 30° and 60° E, see Fig. 2.1) and the study area is bounded by latitudes 10° and 20° N and longitudes 30° and 50° E. The Mead quadrangle (V-21) is one of 62 covering Venus at 1:5,000,000 scales and is named after the Mead crater, the largest crater on Venus. In addition, the Mead quadrangle is dominated by volcanism associated with five major coronae (Didilia, Pavlova, Calakomana, Isong, and Ninmah) in eastern Eistla Regio, Disani Corona and corona-like tectonic features (Campbell and Clark, 2006) (Fig. 2.1). Four of these major coronae (Didilia, Pavlova, Isong, and Ninmah) are located within the study area of this project. The general geology of the Mead quadrangle has been mapped by Campbell and Clark, (2006) and an extract from this map for the study area is presented in Figure 2.2. The annuli of coronae comprise densely lineated material, and occur as isolated outcrops embayed by regional plains (unit pr) and corona flow materials (unit fc). Flow materials of coronae embay the tectonically deformed annuli and the central regions of coronae, and superimpose regional plains materials (unit pr) (Figure 2.2). According to their map legend they identify two classes of extensional features: “graben” and “fractures”. However, in the portion of the map area shown in Figure 2.2, they only show “fractures”. The more detailed mapping in this thesis identifies many of these “fractures” to be a mixture of graben, fissures and fractures. Grabens are v-shaped troughs with a discernable floor, fissures are v-shaped troughs and fractures have unresolved topography but are typically along strike from grabens and fissures and are considered to be extensional features.

Figure 2.1: Radar map of the Mead quadrangle (V-21). Study area (2 million square km) is delineated by a red box. After Campbell and Clark (2006).

0 62.5 125 250 375 500 Kilometers

Legend

hb

Bright halo material—Localized deposits of very high radar return and high microwave emissivity have homogeneous appearance, with radar-dark streaks at margins and feathery edges. Superposes regional plains material (unit pr) and flow materials of coronae (unit fc); primarily occurs on exterior corona flank slopes, with at least one point of contact with densely lineated material (unit ld). *Interpretation:* Rough pyroclastic material erupted in most recent period of corona volcanism, likely by a ground-hugging surge mechanism rather than by airfall. Radar-dark streaks likely wind-deposited, fine material that blankets rough surface

fl

Localized flow material—Lobate deposits radiating from a central depression, low-relief dome, or chain of small domes in the plains. Typically less than 200 km in radial extent; variable radar brightness. Superposes regional plains material (unit pr). In northwestern portion of quadrangle, superposed by lobate materials of unit fc. *Interpretation:* Lava flows associated with small shield volcanoes and calderas in the plains

fc

Flow material of coronae—Low- to moderate-radar-return deposits radial to coronae and corona-like deformation patterns in eastern Eistla Regio. Morphology varies from sheetlike to narrow lobes. Embays tectonically deformed rim and central corona structures; superposes regional plains material (unit pr); topographically, is confined to south by deformation associated with Calakomana Corona. For Didilia and Pavlova Coronae, narrow, lobate, radar-bright deposits are stratigraphically lower; later materials form low-radar-return, sheetlike aprons that embay and flood earlier lobate terrain. *Interpretation:* Lava flows erupted in association with corona formation. Relative age of flows from individual coronae, in general, indeterminate. For Didilia and Pavlova Coronae, earlier eruptions appear to have higher volume or are more viscous, while later eruptions are characterized by lower eruption rate or lower viscosity

fK

Flow material of Kali Mons—Low- to moderate-radar-return, lobate deposits radial to Kali Mons. Superposes regional plains material (unit pr). To the northeast, characterized by moderate to low radar backscatter and enhanced emissivity. *Interpretation:* Lava flows from Kali Mons. Areas of enhanced emissivity may indicate a low-density, surface-mantling deposit or highly vesicular lava flow texture

fC

Flow material of Calakomana Corona—Low- to moderate-radar-return, lobate, and mottled deposits interior to Calakomana Corona, with low domical edifice in center of deposit; moderate-radar-return, lobate deposits east of Calakomana that superpose local structure and regional plains material (unit pr). *Interpretation:* Lava flows related to Calakomana Corona

fM

Flow material near Mead crater—Moderate- to low-radar-backscatter, low-rms-slope deposits that embay Mead crater ejecta (units cMu, cMt) along north, south, and east sides of crater. Image texture often featureless. Superposes regional plains material (unit pr), wrinkle ridges, pit craters, and other features in low terrain surrounding Mead crater. Contact with unit fc uncertain and likely controlled by topography. *Interpretation:* Lava flows generated by volcanic sources north and east of Mead crater

cMf

Mead crater floor material—Moderate-radar-return, patchy image texture; emissivity lower than planetary average in eastern portion of crater. Central region characterized by short, radar-bright lineaments; margins characterized by localized lobate or patchy variations in radar brightness. *Interpretation:* Impact melt sheet formed during impact event or post-excavation lava flows. Crater floor lineaments may reflect fracturing of deposit during cooling. Low emissivity suggests modest increase in bulk dielectric constant relative to planetary average

cMu

Mead crater distal ejecta material—Radar-bright hummocky or patchy terrain. Features typically radial to Mead crater. Superposes unit pr; embayed by units fc and fM. *Interpretation:* Rugged ejecta from Mead crater impact event, embayed by later flows from coronae to the west and other sources east and north of the crater

cMt

Mead crater terrace material—Moderate to low radar return; mottled image texture. Occurs on gently sloped terrain concentric to Mead crater floor. *Interpretation:* Topographic terrace formed as part of collapse of Mead crater cavity during impact event. Surface materials likely represent overturned target terrain, because low-emissivity signature associated with crater floor material (unit cMf) is not evident

ld

Densely lineated material—Bright radar return, with typically single principal lineament orientation. Forms parts of corona rim deposits. Occurs as isolated outcrops embayed by regional plains (unit pr) and corona flow materials (unit fc). *Interpretation:* Material of uncertain origin (though likely regional plains, unit pr) that has been pervasively deformed by compression

Figure 2.2: Geologic Map of study area (10°N-20°N, 30°E-50°E), Venus. Note extensional features labelled graben and fractures. After Campbell and Clark (2006).

2.2 Synthetic aperture radar (SAR)

SAR images are generated by the sensing of the emitted radar microwave energy that was reflected off the surface of Venus. Radar images are therefore a measure of the roughness of the scattering surface (Oliver and Quegan, 2004).

Aperture refers to the size of the antenna that sends and receives the wave energy (echoes) - the greater the aperture, the higher the resolution. The aperture is considered synthetic as it catches the delay of the returning signal (echo) from the ground surface while in motion resulting, in effect, in obtaining information that otherwise would have had to be collected with a much larger receiver (Figure 2.3).

Figure 2.3: Difference between radar (left) and Synthetic Aperture Radar (right) systems.

The intensity (radar bright or dark) of a pixel is a function of surface roughness and orientation with respect to the transmitter and is determined by the amount of reflectance from the scattering surface (Figure 2.4). Radar bright sections represents rough surfaces or areas pointing towards the receiver, whereas radar dark sections represents surface composed of smooth material or facing away from the receiver.

Figure 2.4: Surface controls on SAR response. Left looking illumination against a smooth (left) surface, and a rough (right) surface.

In addition, radar shadows (not illustrated in Figure 2.4) are areas of an image (black areas) from which no echo response was received by the instrument because they are located on the far side of steep topographical slopes.

The Magellan radar had an incidence angle which varied from 18° at the poles to 50° at the equator, with 70% of the surface mapped at above 30° to minimize the effects of foreshortening which is a geometric distortion that reduces the width of topographic slopes which face towards the instrument (Saunders et al., 1990).

2.3 Tectono-magmatic features

2.3.1 *Graben-fissure systems*

Graben–fissure systems (Figure 2.5) are most often surface expressions of underlying dyke swarms on Venus. There are sets of long extensional lineaments (predominantly grabens, fissures and related fractures) in a linear, radiating or circumferential pattern (Ernst et al. 2003; Ernst and Grosfils, 2014a, b; Grosfils et al., 2014). Terrestrial analogues are discussed in Ernst et al. (2001) and Ernst (2014). Graben and fissures can be superposed by pit chains, pit troughs, lava channels, rilles and small shield volcanoes. Those that radiate are ~50–~2800 km in radius with an average radius of ~325 km (Grosfils and Head, 1994; Ernst et al., 2003). Radiating systems tend to focus on a tectono-magmatic center, with graben, grading into fissures and then grading into fractures at increasing distance from the center (Grosfils and Head, 1994).

Figure 2.5: The relationship between graben-fissure systems and underlying laterally-propagating dykes: radiating systems with graben, grading into fissures and then grading into fractures at increasing distance from the center. After Grosfils and Head (1994).

2.3.2 Radiating graben-fissure systems

The origin of Venusian graben–fissure systems with radiating geometry (radiating graben-fissure systems) has been intensively studied and two end-member scenarios were considered (Grosfils and Head, 1994; Grosfils et al., 2014). The first is a purely tectonic origin related to domal uplift of the surface above an ascending diapir. In some cases, part of the corona-forming process on Venus creates radial extensional lineaments whose lateral extent is effectively limited to that of the dome topography, in which case the radiating pattern should not continue beyond the edge of the uplift.

In the second mode of origin, which accounts for the remaining (probably majority of) systems on Venus, the extensional lineaments are the surface expression of underlying laterally propagating dykes. The radiating pattern was derived from outward (lateral) injection of dykes fed by magma injected laterally from a centrally located source (McKenzie et al., 1992; Parfitt and Head, 1993). In this scenario, given sufficient magma supply in the center region, the dykes (and their overlying surface expression as graben and fissures) can laterally propagate beyond any central topographic uplift into a region influenced by the external regional stresses. The radiating patterns could be generated from stresses surrounding a central magma chamber in which case no central topographic uplift would be required (McKenzie et al., 1992; Wilson and Head, 2002). On the other hand, the association with an underlying mantle plume (Ernst et al., 1995) would typically require a central domal uplift (e.g., Campbell, 2001; Sengör, 2001). In any case, those systems that extend significantly beyond any possible topographic influence must be underlain by dyke swarms (Grosfils and Head, 1994).

One type of radiating graben-fissure system is termed a radially fractured center (RFC) (nova); these are radiating graben fissure systems in which the radiating pattern reaches to the focus. However, there are many radiating graben-fissure systems in which the converging grabens in the focal region are obscured by younger lava flooding (Studd et al. 2011). Radiating graben-fissure systems are known to occur on Earth, Venus and Mars (Ernst et al., 2001), plus at least one example from Mercury (Head et al., 2009).

2.3.3 *Coronae*

Coronae (Figure 2.6) on Venus are large, circular to ovoidal surface features which are dominated by concentric tectonic features and have a raised rim, a central region and, commonly, a peripheral depression or "moat" (Janes et al., 1993). Some coronae also show significant amounts of radial tectonic structures (mainly graben-fissure systems), and in most cases this predates the concentric features.

A model (Janes et al., 1993, see Figure 2.7) for the formation of coronae on Venus begins with an ascending mantle diapir. Buoyant vertical mantle flow forces the lithosphere above the diapir upward, producing a gentle dome with a radiating pattern of extensional fractures. As the diapir impinges on the base of the thermal lithosphere, it flattens, spreads, and transforms the uplift area to a flat-topped shape. The diapir can cool rapidly due to this flattened near-surface configuration. Then, the raised plateau relax to form a central sag, a raised rim, and a depressed moat because of the subsequent loss of buoyancy. All phases of the uplift are associated with moderate to large quantities of volcanism and it may diminish as the relaxation stage occurs (Janes et al., 1993).

a) Magellan SAR image of a corona

b) Synthesized perspective view

Figure 2.6: Magellan SAR image of Fatua corona and synthesized perspective view of it.

After Janes et al. (1992).

Figure 2.7: The major stages in a generalized conceptual model of formation of a Venusian corona. Stages: (1) Rising mantle diapir; (2) Spreading beneath the lithosphere; (3) Cooling and sagging. After Janes et al. (1992).

A more recent model for the formation of coronae on Venus has been developed by Dombard et al. (2007; see Figure 2.8). They considered corona formation due to a melt zone and not directly to an impinging upwelling. In their model, they proposed that magmatic loading of the crust over zones of partial melting at the tops of mantle plumes that impinge on the underside of the lithosphere causes the formation of a corona.

With respect to the corona literature, two types are typically recognized (e.g., Stofan et al., 2001; Stofan and Smrekar, 2005). Type 1 coronae are surrounded by more than 180° of a “fracture annulus”. Type 2 coronae are those in which the “fracture annulus” is less than 180°; some of these may represent features that have been partially flooded by younger lava flows. The “fracture annulus” of corona of both types includes graben, fissures and fractures as well as ridges, and the distribution of extensional vs compressional features is generally not separated. The presence of compressional features circumscribing coronae is still a poorly understood phenomenon.

Figure 2.8: Schematic cross section of a corona formation model. In this model, the mantle plume reaches the base of the lithosphere and partial melting occurs. Ascending magma pools at the base of the crust as an underplate. It also ascends, intrudes into the crust, and produces surface flows. Magmatic loading of the crust results in deformation and sagging. After Dombard et al. (2007).

2.3.4 Circumferential lineament systems

A circumferential lineament system is defined as a set of graben, fissures and related fractures with an arcuate to circular distribution and is associated with specific volcanic/tectonic features (e.g., coronae) that define an arcuate (circular to elliptical) pattern through more than about 90° (Ernst and Grosfils, 2014b). Most circumferential lineament systems often define part or all of a corona annulus, but also occur in association with calderas and at the margins of some unclassified down-sag features.

Circumferential lineament systems form due to radial extension during corona formation with or without injection of dyke magma. Concentric (circumferential) graben-fissure systems are mapped on Mars associated with volcanoes and interpreted to be caused by underlying dyke injection (Montési, 2001; Ernst et al., 2001). They can also be purely structural; they can form by purely tectonic processes as found in some calderas and related down-sag features (e.g., Ernst et al., 2003).

Chapter 3: Graben-fissure systems in the study area

3.1 Introduction

Within the study area ($\sim 2000000 \text{ km}^2$), 32 different graben-fissure systems have been identified, mapped and analyzed. Herein, detailed descriptions and analysis of these 32 different graben-systems are presented.

Twenty four of these graben-fissure systems are associated with four different coronae; either they are located within the coronae interior as a radiating magmatic center or are found on or near the corona annulus (rim). One of the graben-fissure systems is located within corona interior and also extends beyond the corona rim into the geological plains area outside the corona. In addition, there are eight remaining graben-fissure systems not directly related to the four coronae.

The following figures provide an overview: 1) the detailed mapping of all 32 different graben-fissure systems in the study area; 2) the detailed mapping of 32 different graben-fissure systems in the study area with superimposed graticule; 3) the corresponding schematic map (the legend indicates the relations between the graben-fissure systems and different coronae when applicable); and 4) the topographic map of the study area.

Detailed 32 graben-fissure systems in the study area

Legend

- ★ Magmatic center
- Lava flow
- Coranae
- System 1 (Pavlova Corona)
- System 2 (Pavlova Corona)
- System 3 (Pavlova Corona)
- System 4 (Pavlova Corona)
- System 5 (Pavlova Corona)
- System 6 (Pavlova Corona)
- System 7 (Pavlova Corona)
- System 8 (Pavlova Corona)
- System 9 (Pavlova Corona)
- System 10 (Pavlova Corona)
- System 11 (Pavlova Corona)
- System 12 (Pavlova Corona)
- System 13 (Pavlova Corona)
- System 1 (Didilia Corona)
- System 2 (Didilia Corona)
- System 3 (Didilia Corona)
- System 4 (Didilia Corona)
- System 5 (Didilia Corona)
- System 6 (Didilia Corona)
- System 1 (Ninmah Corona)
- System 2 (Ninmah Corona)
- System 3 (Ninmah Corona)
- System 4 (Ninmah Corona)
- System 1 (Isong Corona)
- System 1
- System 2
- System 3
- System 4
- System 5
- System 6
- System 7
- Miscellaneous System

Figure 3.1a): Detailed mapping of 32 different graben-fissure systems in the study area.

Detailed mapping of 32 different graben-fissure systems in the study area with graticule

Figure 3.1b): Detailed mapping of 32 different graben-fissure systems in the study area with superimposed graticule.

Schematic Map of the graben-fissure systems in the study area

Figure 3.2: Schematic map of 32 different graben-fissure systems in the study area.

Topographic map of the study area

Legend

Study area

Value

High : 14622 (m)

Low : 8242 (m)

Figure 3.3: Topographic map of the study area. Units correspond to surface elevation in meters above Mean Planetary Radius (MPR) of 6040 km (or 6040000m). Extracted and modified from <http://astrogeology.usgs.gov/tools/map>

There are four coronae in the study area: Pavlova corona, Didilia corona, Ninmah Corona and Isong Corona. The following content is a detailed description and analysis of the graben-fissure systems spatially associated with these four coronae.

3.2 Coronae and their associated systems

3.2.1 Pavlova Corona

Figure 3.4: Radar map of Pavlova Corona. For regional location see Figure 3.1b.

13 graben-fissure systems associated with Pavlova Corona

Legend

- ★ Magmatic center
- Lava flow
- Pavlova Corona
- System 1 (Pavlova Corona)
- System 2 (Pavlova Corona)
- System 3 (Pavlova Corona)
- System 4 (Pavlova Corona)
- System 5 (Pavlova Corona)
- System 6 (Pavlova Corona)
- System 7 (Pavlova Corona)
- System 8 (Pavlova Corona)
- System 9 (Pavlova Corona)
- System 10 (Pavlova Corona)
- System 11 (Pavlova Corona)
- System 12 (Pavlova Corona)
- System 13 (Pavlova Corona)

Figure 3.5: Graben-fissure systems related to Pavlova corona. Magmatic center (focal point; 39° E, 14.3° N) marks the convergence of radiating System 1. For location see Figure 3.1b.

Within the Pavlova corona area, there are three types of graben-fissure systems (Table 3.1):

1) A radiating system focused within the corona interior and which extends outside the corona rim: System P1;

2) Linear systems which are located on the corona annulus: Systems P4, P5, P6, P7, P8, P9, P10, P11, P12 and P13; and

3) Arcuate systems located within corona interior and which also extend beyond the corona annulus: Systems P2 and P3.

A prominent radiating system (System P1) is focused in the interior of Pavlova corona and likely continues outside the corona although in those areas it is covered, or partially covered, by younger lava flows. Two additional graben-fissure systems (Systems P2 and P3) converge to a similar central location, but each swings away from the center of Pavlova corona toward different directions: the NE-trending System P3 swings to the NW and the SE-trending System P2 swings to the SW. This geometry requires a superimposed regional stress along the extrapolated trend of each system that was not present during emplacement of System P1. This implies a time gap between the development of Systems P2 and P3, and System P1. Cross cutting relationships also indicate that System P1 is older than Systems P2 and P3 (see Chapter 4).

In the corona annulus, there are graben-fissure systems that belong to System P1 and an annulus-parallel segment (System P9) that could belong to a circumferential graben-fissure system possibly linked to the formation of the corona (Ernst and Grosfils, 2014b). However, there are additional graben-fissure sets with the corona annulus which have trends oblique to the corona annulus and which therefore cannot be linked to corona formation (Systems P4, P5, P6,

P7, P8, P10, P11, P12 and P13). We interpret that these are part of earlier regional graben-fissure systems preserved in the annulus by the uplift of the corona during its formation but obscured by younger lava flows both inside and outside the corona.

Table 3.1: Information of 13 graben-fissure systems associated with Pavlova corona.

system #	System Type	Associated magmatic edifice	Graben Type	Trend	Magmatic Center type	Approx. Center Location	Maximum Distance from Center(km)
P1	Graben	Pavlova Corona	Radiating	n/a	Visible	(39° E, 14.3° N)	930
P2	Graben	Pavlova Corona	Arcuate	SE-SW	Cryptic	n/a	n/a
P3	Graben	Pavlova Corona	Arcuate	NE-NW	Cryptic	n/a	n/a
P4	Graben	Pavlova Corona	Linear	NW-SE	Cryptic	n/a	n/a
P5	Graben	Pavlova Corona	Linear	N-S	Cryptic	n/a	n/a
P6	Graben	Pavlova Corona	Linear	NE-SW	Cryptic	n/a	n/a
P7	Graben	Pavlova Corona	Linear	NW-SE	Cryptic	n/a	n/a
P8	Graben	Pavlova Corona	Linear	NW-SE	Cryptic	n/a	n/a
P9	Graben	Pavlova Corona	Circumferential	n/a	Cryptic	n/a	n/a
P10	Graben	Pavlova Corona	Linear	NE-SW	Cryptic	n/a	n/a
P11	Graben	Pavlova Corona	Linear	N-S	Cryptic	n/a	n/a
P12	Graben	Pavlova Corona	Linear	NW-SE	Cryptic	n/a	n/a
P13	Graben	Pavlova Corona	Linear	NE-SW	Cryptic	n/a	n/a

3.2.2 *Didilia Corona*

Radar map of Didilia Corona

Figure 3.6: Radar map of Didilia Corona. For regional location see Figure 3.1b.

6 graben-fissure systems associated with Didilia Corona

Figure 3.7: Graben-fissure systems associated with Didilia Corona. Magmatic center is at 37.5° E, 18.4°N. For regional location see Figure 3.1b.

Within the Didilia corona area, there are three types of graben-fissure systems (Table 3.2):

- 1) Radiating system which is focused within the coronae interior: System D1;
- 2) Linear systems which are located on the corona annulus: Systems D3 and D6;
- 3) Linear system which is located within corona interior and also extends beyond the corona annulus: System D5; and
- 4) Systems which are located adjacent to the corona annulus, but located outside the corona: Systems D2 (linear system), and D4 (arcuate system).

A prominent radiating system (System D1) is focused in the interior of Didilia corona and likely continues outside the corona although in those areas it is interrupted by younger lava flows. Systems D3 and D6, which are both trending N-S are located on different parts of the Didilia corona annulus. System D6 cuts across the annulus, while System D3 is parallel to the annulus and may mark part of a circumferential system. System D5 is located within corona interior and also extends beyond the corona annulus and into the geological plains area outside the corona. In addition, Systems D2 and D4 are located adjacent to, but outside the corona annulus. System D4 has an arcuate pattern.

Table 3.2: Information on graben-fissure systems associated with Didilia corona.

System #	System Type	Associated magmatic edifice	Graben Type	Trend	Magmatic Center type	Approx. Center Location	Maximum Distance from Center (km)
D1	Graben	Didilia Corona	Radiating	n/a	Visible	(37.5° E, 18.4°N)	210
D2	Graben	Didilia Corona	Linear	NE-SW	Cryptic	n/a	n/a
D3	Graben	Didilia Corona	Linear /circumferential?	N-S	Cryptic	n/a	n/a
D4	Graben	Didilia Corona	Arcuate	NW-SE	Cryptic	n/a	n/a
D5	Graben	Didilia Corona	Linear	NW-SE	Cryptic	n/a	n/a
D6	Graben	Didilia Corona	Linear	N-S	Cryptic	n/a	n/a

3.2.3 *Ninmah Corona*

Radar map of Ninmah Corona

Figure 3.8: Radar map of Ninmah corona. For regional location see Figure 3.1b.

4 graben fissure systems associated with Ninmah Corona

Legend

- ★ Magmatic center
- System 1 (Ninmah)
- System 2 (Ninmah)
- System 3 (Ninmah)
- System 4 (Ninmah)

Figure 3.9: Graben-fissure systems associated with Ninmah corona. Magmatic center is at 48.25° E, 17.18°N. For regional location see Figure 3.1b.

Within the Ninmah Corona area, there are two types of graben-fissure systems (Table 3.3):

- 1) A radiating system which is focused within the corona interior: System N1
- 2) Linear systems which are located adjacent to the corona: Systems N2, N3 and N4

Ninmah corona did not have a clear corona annulus such as those which are better displayed on the other above-mentioned coronae. It belongs to the subclass of irregular-shaped coronae (e.g., Squyres et al, 1991). A prominent radiating system (System N1) is focused in the interior of Ninmah corona and likely continues outside the corona although in those areas it is covered by younger lava flows. System N2 (in blue color) is located adjacent to the corona annulus, and oriented in a NE-SW direction. System N3 has a NW-SE orientation and is proximal to a meteorite impact, but not obviously related to this impact. System N4 has a linear NNE-SSW to NE-SW trend and is also located outside the Ninmah corona.

Table 3.3: Information on graben-fissure systems associated with Ninmah corona.

System #	System Type	Associated magmatic edifice	Graben Type	Trend	Magmatic Center type	Approx. Center Location	Maximum Distance from Center (km)
N1	Graben	Ninmah Corona	Radiating	n/a	Visible	(48.25° E, 17.18°N)	500
N2	Graben	Ninmah Corona	Linear	NE-SW	Cryptic	n/a	n/a
N3	Graben	Ninmah Corona	Linear	NW-SE	Cryptic	n/a	n/a
N4	Graben	Ninmah Corona	Linear	NNE-SSW to NE-SW	Cryptic	n/a	n/a

3.2.4 *Isong Corona*

radar map of isong corona

Figure 3.10: Radar map of Isong corona. For regional location see Figure 3.1b.

Graben fissure system associated with Isong corona

Legend

- ★ Magmatic center 1
- ★ Magmatic center 2
- Isong corona
- System 1 (Isong)

Figure 3.11: Graben-fissure system associated with Isong corona. Magmatic center 1 (~ 48.8 ° E, 12.4 ° N) and Magmatic center 2 (~ 49.25 ° E, 11.85 ° N). For regional location see Figure 3.1b.

One prominent radiating System I1 (Table 3.4) has been found in the vicinity of Isong corona; it is focused in the corona interior (48.86 ° E, 12.18° N) and continues outside the corona annulus (Figure 3.11). The orientation of the majority of the lineaments is consistent with a center indicated by a red star (Magmatic center 1). However, the lineaments on the east and south sides of the corona are better fit to a second center indicated by a yellow star (Magmatic center 2). A rose diagram (Figure 3.12) shows two preferred orientations of graben-fissure systems around Isong corona.

Table 3.4: Information on a radiating graben-fissure system associated with Isong corona.

System #	System Type	Associated magmatic edifice	Graben Type	Trend	Magmatic Center type	Approx. Center Location	Maximum Distance from Center (km)
I1	Graben	Isong Corona	Radiating	n/a	Visible	(48.8° E, 12.4 ° N) Red Star (49.25° E, 11.85 ° N) Yellow Star	180

Figure 3.12: A rose diagram shows the distribution of orientations of graben-fissure systems around Isong corona.

3.3 Additional major graben-fissure systems

There are 8 additional graben-fissure systems which are not spatially related to the above-mentioned four coronae. However, some of these additional systems are still significant because of their size. One of them is found to extend over the whole study area (System 7). Another two form a radiating pattern when considered together (combined Systems 1 and 2). In addition, some linear systems were located in the gap between two different coronae (Systems 5 and 6). Also, some systems are not as significant as those above one but still important because they also imply a potential local magmatic center (Systems 2 and 3). Lastly, there were also some other irregular fragments of graben-fissure systems which are named as a miscellaneous system.

3.3.1 Systems 1, 2, 3 & 4

Radar map of graben fissure systems 1,2,3 & 4

Figure 3.12: Radar image of Systems 1, 2, 3 & 4. For regional location see Figure 3.1b.

Graben-fissure system 1

Figure 3.13: Graben-fissure System 1. For regional location see Figure 3.1b.

Additional major System 1 was located west of the Didilia corona and extended to the SW of Pavlova corona and has an arcuate trend broadly in a NW-SE direction (Table 3.5). Also, the maximum potential length of System 1 is about 1100 km. System 1 has its highest emplacement density in the NW part of the Didilia corona. In contrast, System 1 is more difficult to recognize and has sparse distribution in the southeastern part of the map, presumably because of overprinting by other graben-fissure sets, and partial flooding by younger lavas.

Graben fissure system 2

Figure 3.14: Graben-fissure System 2. For regional location see Figure 3.1b.

An additional major graben-fissure System, 2 was also located west of the Didilia Corona and extends to the SW of Pavlova corona (Table 3.2.1). The maximum measured length of System 2 is about 1100 km. In addition, System 2 exhibits an overall radiating pattern ranging from E-W to ENE-WSW near Didilia corona (in the north), to NE-SW in the southern part of the map area. Systems 1 and 2 cross cut each other but the relative ages are not definitive (Chapter 4).

Graben fissure system 3

Figure 3.15: Graben-fissure System 3. For regional location see Figure 3.1b.

Additional major graben-fissure System 3 was located SW of Pavlova corona and has an overall radiating pattern with a dominance of NE-SW trending graben-fissure lineaments (Table 3.5). The maximum length of System 3 is about 450 km. Systems 1-3 cross cut, but relative age relationships were unclear (Chapter 4).

Graben fissure system 4

Figure 3.16: Graben-fissure System 4. For regional location see Figure 3.1b.

Additional graben-fissure System 4 was also located SW of Pavlova corona but adjacent to graben-fissure system 3 and trending in an N-S direction (Table 3.5). In addition, the maximum length of system 4 is about 160 km. Systems 3 and 4 did not have a cross cutting relationship (Chapter 4).

Graben fissure systems 1, 2, 3 & 4

Figure 3.17: Graben-fissure Systems 1, 2, 3 & 4. For regional location see Figure 3.1b.

Table 3.5: Information on graben-fissure Systems 1, 2, 3 and 4.

System #	System Type	Associated magmatic edifice	Graben Type	Trend	Magmatic Center type	Approx. Center Location	Maximum Distance from Center (km)
1	Graben	Outside coronae field	Arcuate	NW-SE	Cryptic	n/a	1100
2	Graben	Outside coronae field	Radiating	E-W to ENE-WSW near Didilia corona , NE-SW in the southern	Cryptic	n/a	1100
3	Graben	Outside coronae field	Radiating	NE-SW	Visible	(37. 13° E, 11.7°N)	450
4	Graben	Outside coronae field	Linear	N-S	Cryptic	n/a	160

3.3.2 Systems 5 and 6

Radar map of systems 5 & 6

Figure 3. 18: Radar map of Systems 5 and 6. For regional location see Figure 3.1b.

Additional major graben-fissure Systems 5 and 6 were located in the gap between two different coronae (Ninmah corona and Pavlova corona).

Graben fissure systems 5

Figure 3. 19: Graben-fissure System 5. For regional location see Figure 3.1b.

Additional major System 5 is located west of the Pavlova corona and east of Ninmah corona, and trends in NE-SW direction (Table 3.6). The maximum observed length of System 5 is about 360 km. Systems 5 and 6 cross cut each other, but their relative ages were ambiguous (Chapter 4).

Graben fissure systems 6

Figure 3.20: Graben- fissure System 6. For location in study area see Figure 3.1b.

Major NE-trending System 6 is also located west of the Pavlova corona and east of Ninmah corona (Table 3.6). The maximum observed length of System 6 is about 600 km.

Graben fissure systems 5 & 6

Figure 3.21: Graben-fissure Systems 5 and 6. For regional location see Figure 3.1b.

Table 3.6: Information on graben-fissure Systems 5 and 6.

System #	System Type	Associated magmatic edifice	Graben Type	Trend	Magmatic Center type	Approx. Center Location	Maximum Distance from Center (km)
5	Graben	Outside coronae field	Linear	NE-SW	Cryptic	n/a	360
6	Graben	Outside coronae field	Linear	NW-SE	Cryptic	n/a	600

3.3.3 System 7

Radar map of system 7

Figure 3.22: Radar map of System 7. For location see Figure 3.1b.

Graben fissure system 7

Figure 3. 23: Graben-fissure System 7. For location see Figure 3.1b.

Additional major graben-fissure System 7 was found distributed across the entire study area, and trending in an overall E-W direction. The maximum observed length of System 7 is about 1800 km. System 7 is particularly well preserved in the eastern part of the map. In other areas it is obscured by local flooding by lava flows. However, the consistency of trend of the several fragments of this graben-fissure system suggests that it might be present over the entire study area. Because it is so 'fragmented' by younger flooding it might be one of the oldest graben-fissure systems among the 32 mapped graben-fissure systems within the study area.

3.3.4 Miscellaneous System

Miscellaneous graben fissure system

Figure 3. 24: Miscellaneous System. For regional location see Figure 3.1b.

3.4 Summary

Within this study area, there are 32 different graben-fissure systems that have been mapped. 13 of these systems are associated with the Pavlova corona, six graben-fissure systems are associated with the Didilia corona, and four graben-fissure systems are associated with the Ninmah corona and one radiating graben-fissure system which is associated with the Isong corona. Besides these, there are seven additional major graben fissure systems which are not directed found associated with these coroneae, but which are significant for understanding local Venusian geology, magmatism and the history of graben-fissure system development. In Chapter 4, detailed cross cutting relationship between different graben-fissure systems will be presented in order to assess their relative ages.

Chapter 4 Cross-cutting relationships

4.1 Introduction

The cross-cutting relationships between different graben-fissure systems and their host geology can give us insight into the relative ages of those systems. The methodology used to unravel the relative ages of cross-cutting graben-fissure systems is presented below.

4.2 Methodology

Four different styles of cross-cutting relationships between graben-fissure systems have been observed.

4.2.1 Type 1

Figure 4.1: Type 1 style of cross-cutting relationships between graben-fissure systems.

a) Radar image

0 5 10 20 30 40 Kilometers

b) Mapped radar image

Figure 4.2: Example of Type 1 style of cross-cutting relationship between graben-fissure Systems 1 (blue) and 2 (yellow). For location within study area see Figure 3.1b.

Graben-fissure System 1, which is mapped in blue, is more continuous than graben-fissure System 2, mapped in yellow. In addition, the system, which is mapped in yellow, looks like it has been disturbed, has lost trending continuity, and is cross cut by the graben-fissure system in blue. So, from observation of the mapped radar image, it can be inferred that the more continuous graben-fissure system in blue is younger, that the system in yellow is older, and that partial flooding occurred between the times of development of these two graben-fissure systems.

4.2.2 Type 2

Figure 4.3: Type 2 style of cross-cutting relationship between graben-fissure systems.

a) Radar image

b) Mapped radar image

Figure 4.4: Example of Type 2 style of cross-cutting relationship between graben-fissure Systems 1 (yellow) and 2 (red). For location within study area see Fig. 3.1b.

System 1, mapped in yellow, has wider grabens / fissures. As a result, even though graben-fissure System 2, mapped in dark red, is continuous through graben-fissure System 1, it is ambiguous to determine which system is younger than the other.

4.2.3 Type 3

Figure 4.5: Type 3 style of cross-cutting relationship between graben-fissure systems.

a) Radar image

b) Mapped radar image

Figure 4.6: Example of Type 3 style of cross-cutting relationship between graben-fissure Systems 1 (green) and 2 (yellow). For location within study area see Fig. 3.1b.

Individual grabens within System 1 (mapped in green) have survived partial flooding and are very well preserved on the radar image. In contrast, graben-fissure System 2 (mapped in yellow), is partially covered by the flooding. So, it can be inferred that the development of graben-fissure System 2 predated the flooding, and that graben-fissure System 1 occurred after the flooding. It is concluded that graben-fissure System 1 is younger than graben-fissure System 2.

4.2.4 Type 4

Figure 4.7: Type 4 style of cross-cutting relationship between graben-fissure systems.

a) Radar image

b) Mapped radar image

Figure 4.8: Example of Type 4 style of cross-cutting relationships between graben-fissure Systems 1 (pink) and 2 (green). For location within study area see Figure 3.1b.

This pattern (Figure 4.8) can be interpreted in two different ways. Graben-fissure System 1, mapped in pink, can be interpreted to be younger than graben-fissure System 2, mapped in green, on the basis that the discontinuities observed along System 2 are fault offsets with right lateral displacement. So, it can be inferred that graben-fissure System 2 has been emplaced first. The fault offset and displacement later affected it. Finally, graben-fissure System 1 was emplaced. In this scenario it can be argued that System 1 is younger than System 2. Alternatively, if the apparent fault offsets are actually primary en echelon offsets, then no age relationship can be determined.

4.3 Examples of cross-cutting relationships between graben-fissure systems

System P2 (Pavlova Corona) is younger than System P1 (Pavlova Corona), and the cross-cutting relationship is interpreted as Type 3.

a) Radar images of Systems P1 and P2 cross-cutting each other.

b) Mapped radar image of System P1 and System P2 cross-cutting each other

Figure 4.9: Radar image of System P1 (older) and System P2 (younger) associated with Pavlova corona cross-cutting each other. Points indicate locations where detailed observations of cross-cutting relationships were made. For location within study area see Figure 3.1b.

System P3 (Pavlova Corona) is younger than System P1 (Pavlova Corona), and the cross-cutting relationship is interpreted as Type 1.

a) Radar image of Systems P1 and P3 cross-cutting each other.

b) Mapped images of Systems P1 and P3 cross-cutting each other.

Figure 4.10: Radar image of Systems P1 (older) and P3 (younger) associated with Pavlova corona cross-cutting each other. Points indicate locations where detailed observations of cross-cutting relationships were made. For location within study area see Figure 3.1b.

It is ambiguous to determine the relative age relationship between Systems 5 and 6 and the cross-cutting relationship is interpreted as Type 2.

a) Radar image of Systems 5 and 6 cross-cutting each other.

b) Mapped images of Systems 5 and 6 cross-cutting each other

Figure 4.11: Radar images of Systems 5 and 6 cross-cutting each other. For location within study area see Figure 3.1 b.

4.4 Overview of cross-cutting relationships between different graben-fissure systems

The cross-cutting relationships between the 32 different graben-fissure systems mapped in the study area are presented in Table 4.1. These have been determined by using the methodology which is described in the previous section. In total, 37 intersections have been observed but only 5 cross-cutting relationships were unambiguous. The difficulty of finding robust cross-cutting relationships was discussed in Ernst et al. (2003) and Studd et al. (2011). This is often due to the small scale of some features in comparison to the resolution of the SAR images (75m/pixel) and to an unfavorable orientation of features with respect to the radar-looking direction.

Figure 4.12 shows in color only the graben-fissure systems for which there are conclusive cross-cutting relationships. Their spatial distribution is too sparse to allow the reconstruction of a relative geological history for the study area as a whole.

Table 4.1: Cross-cutting relationships between 32 different graben-fissure systems.

32 Different Graben-fissure Systems In Total	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	D1	D2	D3	D4	D5	D6	N1	N2	N3	N4	I1	1	2	3	4	5	6	7	M
System 1 (Pavlova Corona)																																
System 2 (Pavlova Corona)	<																															
System 3 (Pavlova Corona)	<																															
System 4 (Pavlova Corona)	?		?																													
System 5 (Pavlova Corona)																																
System 6 (Pavlova Corona)						>																										
System 7 (Pavlova Corona)	?	?				>	?																									
System 8 (Pavlova Corona)	?																															
System 9 (Pavlova Corona)			?																													
System 10 (Pavlova Corona)							?																									
System 11 (Pavlova Corona)	?																															
System 12 (Pavlova Corona)	?																															
System 13 (Pavlova Corona)																																
System 1 (Didilia)			?																													
System 2 (Didilia)			?											?																		
System 3 (Didilia)														?																		
System 4 (Didilia)																																
System 5 (Didilia)																																
System 6 (Didilia)			?																													
System 1 (Ninmah)	?																															
System 2 (Ninmah)																																
System 3 (Ninmah)																																
System 4 (Ninmah)																																
System 1 (Isong)																																
System 1																		?	?													
System 2																																
System 3																																
System 4																																
System 5																																
System 6																																
System 7	?					?	?				?							?								?	?	?		?	<	
Miscellaneous System																																?

P1— P13 = System 1 (Pavlova Corona) — System 13 (Pavlova Corona)

D1—D6 = System 1 (Didilia Corona) — System 6 (Didilia Corona)

N1—N4 = System 1 (Ninmah Corona) — System 4 (Ninmah Corona)

I1 = System 1 (Isong Corona)

Systems 1, 2, 3, 4, 5, 6 and 7 = System 1— System 7 and

M = miscellaneous system

The symbol “<” indicates that the System on the horizontal line of the table is younger than the System label above

The symbol “>” indicates that the System on the horizontal line of the table is older than the System label above

The symbol “?” means the age relationship is inconclusive

Legend

- ★ Magmatic center
- Coronae
- System 1(Pavlova Corona)
- System 2(Pavlova Corona)
- System 3(Pavlova Corona)
- System 5(Pavlova Corona)
- System 6(Pavlova Corona)
- System 7(Pavlova Corona)

Figure 4.12: The graben-fissure systems (shows in color) for which there are conclusive cross-cutting relationships.

Chapter 5 Discussion

5.1 Introduction

The mapping results in Chapter 3 and the crosscutting relationships in Chapter 4 are integrated in the present chapter to provide new insights into the magmatic history of the study area in Mead quadrangle. There are 16 systems per million km² (= 32 systems/ 2,000,000 km²) for this study area. This is broadly comparable with two other areas where detailed mapping was done, ~8 systems per million km² (= 66 systems/ 8,000,000 km²) for the Ulfrun Regio area (Studd et al., 2010) and ~6 systems per million km² (= 79 systems/ 14,000,000 km²) for the Guinevere Planitia and Beta Regio (Ernst et al., 2003). Note that the statistics for Ulfrun Regio (Studd et al., 2010) only include radiating systems and are a minimum estimate.

5.2 Radiating dyke swarms

5.2.1 Radiating and arcuate systems associated with Pavlova corona

As shown by the detailed mapping (Figure 5.1), there is a radiating graben-fissure system, System P1, whose focus (latitude 39° E and longitude 14.3° N) is located within the interior of Pavlova corona, although offset from its center. In addition, two arcuate graben-fissure systems, Systems P2 and P3, which are associated with System P1, curve into two different directions as they propagate away from the radiating center instead of following the same radial trend as system P1. Therefore, there was a time gap between the formation of system P1 and the two curved systems P2 and P3 during which the stress regime changed. During the time of System P1

there was no regional differential stress. However, at the time of Systems P2 and P3, their trends are influenced by a NW- and NE-trending sigma-1, respectively. At the distal end of each there is a tectono-magmatic edifice that may have caused the changed stress regime (due to associated topographic uplift). A radiating system (System 3, see Figure 5.5) is located at the end of System P2 and Didilia corona is at the end of System P3. The cross-cutting relationships between System P1 and Systems P2 and P3 suggest the two systems are younger than System P1 (Chapter 4).

Moreover, the fact that the focus of System P1 is not located exactly at the center of Pavlova corona (offset ~ 90 km to the west) indicates that this system does not belong to the same stage of Pavlova development during which the corona annulus was formed. Similarly, the arcuate trends of Systems P2 and P3, argue that these systems also do not belong to the corona annulus stage of formation of Pavlova corona. Furthermore, these three systems predate the emplacement of the lava flows in the corona interior.

In addition to Systems P1, P2 and P3, there are several different generations of graben-fissure systems preserved on the corona annulus. They are inferred to be remnants of older systems predating the formation of the corona, which have been partially preserved on the corona rim due to high topography of the annulus, and therefore survived subsequent lava flooding (see Section 5.3).

Figure 5.1: Radiating and two other systems which swing into NW and SW trends at associated with Pavlova Corona. For location in study area see Figure 3.1b.

5.2.2 Four other radiating graben-fissure systems within the study area

Other than the radiating graben-fissure system which is associated with the Pavlova corona, there are four additional radiating systems which have been discovered and mapped out in the study area. Three are associated with corona: 1) Isong corona (Figure 3.10 in chapter 3; centered at $\sim 48.86^{\circ}$ E, 12.18° N), 2) Didilia corona (Figure 5.2; centered at $\sim 37.5^{\circ}$ E, 18.4° N), and 3) Ninmah corona (Figure 5.3; centered at $\sim 48.25^{\circ}$ E, 17.18° N). A fourth radiating system (Figure 5.4; centered at $\sim 37.13^{\circ}$ E, 11.7° N) is not associated with any corona.

So, there are a total of five major radiating graben-fissure systems in the study area (Figure 5.5). For each of these a shallow magma reservoir is interpreted to be present at the focus of the radiating system, from which magma is emplaced radially as dykes which underlie the graben-fissures (Ernst et al., 2001).

Radiating system associated with Didilia Corona

Legend

- ★ Magmatic center
- Didilia corona
- System 1 (Didilia Corona)

Figure 5.2: Radiating graben-fissure system with approximate center location (37.5° E, 18.4°N) which is associated with Didilia corona. For location within study area see Figure 3.1b.

Radiating system associated with Ninmah corona

Legend

★ Magmatic center — System 1 (Ninmah Corona)

Figure 5.3: Radiating graben-fissure system with approximate center location (48.25° E, 17.18°N) which is associated with Ninmah corona. For location within study area see Figure 3.1b.

Radiating system which is located outside corona annulus

Figure 5.4: Radiating graben-fissure system with approximate center location (37.13° E, 11.7°N) which is located outside the corona annulus. For location within study area see Figure 3.1b.

Five Radiating Systems

0 125 250 500 750 1,000 Kilometers

Legend

- ★ Magmatic center
- Corona rim
- System 1 (Pavlova Corona)
- System 1 (Ninmah Corona)
- System 3
- System 1 (Didilia Corona)
- System 1 (Isong Corona)

Figure 5.5: The five radiating graben-fissure systems in the study area. For location within study area see Figure 3.1b.

5.3 Graben-fissure systems preserved on the annulus of corona

There are some graben-fissure systems on or near the corona annulus which have trends oblique to that of the corona annulus. Examples are the linear graben-fissure systems associated with Pavlova corona (Systems P4, P5, P6, P7, P8, P10, P11, P12 and P13; see Figure 5.6). In addition, some other minor graben-fissure systems display circumferential patterns, such as System P9 associated with Pavlova corona (Figure 5.6) and system D3 located on Didilia corona, both associated with the corona rim (Figure 5.7).

Graben-fissure systems trending oblique to the corona annulus are inferred to be remnants of older pre-corona graben-fissure systems that have survived subsequent lava flow flooding. These graben-fissure systems are preserved on the corona annulus because of the elevated topography that marks the annulus. It is presumed that these systems have much wider extent, which is now largely buried beneath the adjacent flooded areas.

An annulus-parallel segment (System P9) that belongs to a circumferential graben-fissure system likely linked to the formation of the corona. Such circumferential patterns of graben-fissure systems are associated with many corona annuli (Ernst and Grosfils. 2014b).

Graben-fissure systems which are preserved on the Pavlova corona annulus

Legend

★ Magmatic center	System 8 (Pavlova Corona)
— Pavlova corona	System 9 (Pavlova Corona)
System 4 (Pavlova Corona)	System 10 (Pavlova Corona)
System 5 (Pavlova Corona)	System 11 (Pavlova Corona)
System 6 (Pavlova Corona)	System 12 (Pavlova Corona)
System 7 (Pavlova Corona)	System 13 (Pavlova Corona)

Figure 5.6: Graben-fissure systems which are preserved on the Pavlova corona annulus.

For location within study area see Figure 3.1b.

Graben-fissure systems which are preserved on the Didilia corona annulus

Figure 5.7: Graben-fissure systems which are preserved on the Didilia corona annulus. For location within study area see Figure 3.1b.

5.4 Combining graben-fissure systems to identify cryptic magmatic centers

5.4.1 Graben-fissure systems 2 and 6 and their possible cryptic magmatic center

Combining the trends of spatially separate graben-fissure Systems 2 and 6, neither of which are associated with coronae, a potential cryptic magmatic center can be identified centered at $\sim 39.5^\circ \text{ E}$, 19.88° N and referred to as a Cryptic Magmatic Center 2 (Figures 5.8 and 5.9). This center is interpreted to locate the magma source for the emplacement of the dyke swarms interpreted to underlie Systems 2 and 6. The maximum length of System 2 is about 1200 km and it displays a radiating pattern. According to Ernst et al. (2003), radiating graben-fissure systems can extend up to 2000 km (or perhaps even up to 6000 km; see Hansen and Olive, 2010) away from volcanoes or coronae at their foci.

Moreover, from the detailed mapping (Figures 5.8 and 5.12) and the schematic map (Figures 5.9 and 5.13), the major NW-SE trending linear graben-fissure System 6 located west of the Pavlova corona could be related to the same magmatic event which caused the development of System 2. The maximum observed length of System 6 is about 600 km.

Systems 2 and 6 and their possible cryptic magmatic center

Figure 5.8: Graben-fissure systems (Systems 2 and 6) and their possible cryptic magmatic center. For location within study area see Figure 3.1b.

Schematic map of graben-fissure systems and their interpreted cryptic magmatic center

Legend

- ★ Cryptic Magmatic Center 2
- System 2 — System 6

Figure 5.9: Schematic map of overall radiating graben-fissure system (combining Systems 2 and 6) and their interpreted cryptic magmatic center.

5.4.2 Graben-fissure systems 1 and D4 (associated with Didilia corona) and their possible cryptic magmatic center

Based on the orientation and morphology of graben-fissure Systems 1 and D4 (the latter which is associated with the Didilia corone), there is a potential cryptic magmatic center which is approximately centered at 39.5 ° E, 19.88°N and referred to as Cryptic Magmatic Center 1 (Figures 5.10 and 5.11). This center is initially defined on the basis of System D4 which is located on the NW corona rim of Didilia corona (Figs. 5.10-5.13). System D4 is about 120 km long and shows an arcuate pattern that covers ~90 degrees of arc. The trend of System 1 can also be linked; the observed maximum length of System 1 is about 1200 km and it displays weakly arcuate pattern that partially circumscribes Cryptic Magmatic Center 1 (perhaps covers ~20 degrees of arc). Provisionally, it is suggested that Systems 1 and D4 together define part of a circumferential pattern. However, an alternate interpretation is that System 1 is a linear system. This could be tested by extending the detailed mapping outside the study area to the north and west.

Furthermore, as shown in Figures 5.12 and 5.13, the magmatic center derived from combining Systems 2 and 6 (Cryptic Magmatic Center 2) and that from the circumscribing Systems 1 and D4 (Cryptic Magmatic Center 1) are relatively close to each other, given the scale of the systems (<200 km apart), suggesting that both the radiating and circumferential sets and their inferred magmatic centers could belong to a single magmatic event that was not previously recognized.

Systems 1 & D4 (Didilia Corona) and their possible cryptic magmatic center

Legend

- ★ Cryptic Magmatic Center 1
- System 1 — System 4 (Didilia Corona)

Figure 5.10: Graben-fissure systems Systems 1 & D4 (Didilia Corona), and their possible cryptic magmatic center. For location within study area see Figure 3.1b.

Schematic map of graben-fissure systems and their interpreted cryptic magmatic center

Legend

- ★ Cryptic Magmatic Center 1
- System 1 — System 4 (Didilia Corona)

Figure 5.11: Schematic map of graben-fissure systems, Systems 1 & D4 (Didilia Corona), and their interpreted cryptic magmatic center.

Major graben-fissure systems and their possible cryptic magmatic centers

Legend

★ Cryptic Magmatic Center 1	— System 1	— System 4 (Didilia Corona)
★ Cryptic Magmatic Center 2	— System 2	— System 6

Figure 5.12: Major graben-fissure systems and their possible cryptic magmatic centers. For location within study area see Figure 3.1b.

Schematic map of graben-fissure systems and their possible cryptic magmatic centers

Legend

- ★ Cryptic Magmatic Center 1 (CMC1)
- ★ Cryptic Magmatic Center 2 (CMC2)
- Systems associated with CMC 1 (System 1 & System 4- Didilia)
- Systems associated with CMC 2 (System 2 & System 6)

Figure 5.13: Schematic map of graben-fissure systems and their possible cryptic magmatic centers.

5.5 Extensive linear System 7 mapped over the entire study area

Graben fissure system 7

Figure 5.14: Linear graben-fissure System 7 which is mapped cross over the entire study area. For location within study area see Figure 3.1b.

Major graben-fissure System 7 was mapped over the entire study area with a consistent E-W trend. The maximum observed length of System 7 is about 1800 km and the width is about 900 km. System 7 is very well preserved in the eastern part of the map. In other areas, it is obscured by local flooding of lava flows. However, the consistency of trend of the several fragments of this graben-fissure system suggests that it might be present over the entire study area. System 7 is older than the formation of the coronae, which disrupt System 7, and also older than the lava flow flooding, which fragment the overall continuity of System 7, and it might be one of the oldest systems among these 32 mapped systems within the study area.

Linear lineament systems (Ernst and Grosfils, 2014a) may be linked with rift zones (e.g., Krassilnikov and Head, 2003), formed by extension of a thin brittle layer (Banerdt and Sammis, 1992), and/or be underlain by dykes (Ernst et al., 2003). Further mapping in adjacent areas is required to determine the full extent of System 7 in order to constrain models for their origin.

5.6 Linear graben-fissure System 5 of unknown setting

Graben fissure systems 5

Figure 5.15: Linear graben-fissure system System 5. For location within study area see Figure 3.1b.

Graben-fissure System 5 is located west of the Pavlova corona and east of Ninmah corona, trends in NE-SW direction. The maximum observed length of system 5 is about 360 km and width is about 300 km. System 5 is related neither with Pavlova corona nor with Ninmah corona. It displays a linear pattern, and it is not currently possible to assign it to any magmatic center or to link it with any observed rift zone.

Chapter 6: Conclusions

In this thesis the radar images from the Magellan mission were used for detailed mapping of graben-fissure systems. The study area for this project is within the Mead quadrangle (V-21) of Venus, bounded by latitudes 10° and 20° N., longitudes 30° and 50° E and is selected as part of Global Dyke Swarm Mapping project. Previous regional geological mapping of Mead quadrangle was done by Campbell and Clark (2006) and included some mapping of graben-fissure systems in the study area. However, only the most significant lineaments were mapped and their detailed assessment in terms of radiating, linear and circumferential systems (Ernst et al., 2003) was not done. The more focused and detailed mapping for this thesis is therefore an advance over the previous mapping work.

This thesis research identifies 32 different graben-fissure systems within the study area: 24 of these graben-fissure systems are associated with four different coronae (Didilia, Pavlova, Isong, and Ninmah), and eight remaining graben-fissure systems are not directly related to these four coronae. Five of these are radiating systems, four of which are associated with (and focus in the interior of) coronae and the 5th focuses on $\sim 37.13^{\circ}$ E, 11.7° N. An additional radiating center is based on converging trends from two widely separated systems (Systems 2 and 6): this center is not associated with any central volcanic/tectonic edifice and so represents a cryptic magmatic center identified newly herein. Several Systems (Systems P9 associated with Pavlova corona and D3 associated with Didilia corona) are associated with corona annuli and are interpreted as partial circumferential systems. Additional systems (Systems 1 and D4) are speculatively arcuate about a cryptic magmatic center, near to that cryptic center based on systems 2 and 6 (as mentioned above).

Additional systems are located on the corona annuli but these have trends that are oblique to the local trend of the annuli (neither normal nor parallel to it) and are therefore not part of radiating or circumferential systems genetically related to the corona. Instead they are interpreted as part of older regional graben-fissure systems that are preserved in the uplift corona annuli, but are otherwise covered by regional lava flooding.

For future work, areas adjacent to that of this study needs also be mapped in detail for graben-fissure systems, to gain more regional context for these 32 mapped graben-fissure systems and their relationship with regional Venus magmatism and tectonics, and also to advance the Global Dyke Swarm Mapping project.

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