Mapping radiating graben-fissure systems and pit crater chains on Venus

by

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Abstract

This study has mapped two types of extensional tectono-magmatic structures including radiating graben-fissure systems (RGFS) in the Idunn Mons and Mielikki Mons study areas, and pit crater chains in Idunn Mons, Themis Regio, Ulfrun Regio, and Ganiki Planitia on Venus. The areas selected to map RGFS host high emissivity anomalies focused on a single volcano and are proposed to reflect younger lava flows which might have occurred as recently as 250 ka. A relative chronology of RGFS is determined using cross-cutting relationships between interacting systems and surface geology. The Idunn Mons high emissivity anomaly is host to the youngest magmatic and volcanic activity, while the Mielikki Mons high emissivity anomaly is not the youngest. Hierarchical clusters of pit crater chains are predominantly focused on RGFS and coronae. It is hypothesized that hierarchical clustering is due to a lithology related variable as lithology may dictate how tensile stress is expressed.

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1 Chapter: Introduction

1.1 The planet Venus

Named after the Roman goddess of love and beauty, the planet Venus is the third brightest celestial object in the sky preceded only by the Sun and Moon (Figure 1.1). Depending on the season, it may be observed to the west during sunset and east during sunrise; for this reason, astronomers consider Venus both an evening and morning star, respectively. The sidereal orbital period of Venus is equivalent to 224 days on Earth¹. Venus' sidereal rotation period (length of one day) is approximately -243 Earth days; the negative value is due to its retrograde rotation¹. From orbit, a view of the surface is impossible because of Venus' thick atmosphere comprised primarily of carbon dioxide, carbon monoxide, nitrogen, hydrochloric acid, hydrofluoric acid, and sulphuric acid (Mueller et al. 2008). The high concentration of carbon dioxide in the atmosphere, in addition to the other contributing gasses, has resulted in an average surface temperature of 462°C and atmospheric pressure of 9030 kPa¹. One of the most notable differences between Earth and Venus is Venus' lack of water both in its atmosphere and on the surface.

In likeness to Earth, Venus is 81.5% its mass, 95.5% its density and 95% the mean radius (Janle and Meissner 1986). Calculated using gravity and topography data collected by the Magellan Spacecraft, the average crustal thickness is 30 km (Nimmo and Mckenzie 1998; James et al. 2010). The mean crustal density, calculated by Fegley (2004), is comparable to basalt measuring between 2.7 g/cm³ and 2.9 g/cm³; this result agrees with surficial studies made by Surkov et al. (1986) who used data acquired by

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

Russian Venera landers to conclude that the composition of Venus' surface is largely basaltic. Calculated by Aitta in 2012, the mantle convection strength (measured in terms of the Raleigh number) of Venus is 46% smaller than Earth. Like Earth, Venus is predicted to host a liquid iron core with an average temperature of 1300°C (Konopliv and Yoder 1996; Nimmo and McKenzie 1998). However, the lack of a self-sustaining magnetic field suggests that this liquid iron core does not convect significantly. Hypotheses explaining the limited convection suggest it may be hindered by the planet's slow sidereal rotation which would thwart a Coriolis effect, or the internal thermal gradient is minimal thereby limiting the potential for convection (Nimmo 2002; Stevenson 2003; Aitta 2012).

Venus' lack of dynamic, Earth-like, plate tectonics is but one of the many reasons scientists are compelled to study the second planet from the Sun. Upon the examination of Magellan satellite images in the early 1990's, characteristic features of plate tectonics, like separate plates, subduction zones or transform faults, were not observed (Phillips and Hansen 1994). While Venus does not exhibit Earth-like evidence of tectonism, it displays a unique array of topography and surficial features which, upon detailed study, have and will continue to provide an improved understanding of the planet's tectonic and magmatic evolution.

Planitia, mesolands and highlands, described by Phillips and Hansen (1994), are three primary classes of topographic morphologies present on Venus. Planitia are radar smooth lowlands interpreted as areas of extensive volcanic flooding found below the mean planetary radius. The mesolands are the areas found between 0 and 2 km above the mean planetary radius. At altitudes between planitia and highlands, the mesolands host

the majority of coronae and chasmata (Phillips and Hansen 1994). Highlands are areas with topography exceeding 2 km above the mean planetary radius. Tessera terrain includes areas with more than one set of grooves and ridges, and are commonly hosted in highland regions. Less commonly, tessera terrain are found as isolated sections in planitia and mesolands (Phillips and Hansen 1994).

With only approximately 1000 impact craters identified on Venus, most of which are morphologically pristine, the low crater density is interpreted as an indication that the surface of Venus is both relatively young and of uniform age (McKinnon et al. 1997, Basilevsky and Head 2002; Ernst and Desnoyers 2004). It is proposed that Venus underwent a dramatic global resurfacing event 750 Ma ago (McKinnon et al. 1997; Basilevsky and Head 2002; Ernst and Desnoyers 2004). McKinnon et al. (1997) suggest that the global resurfacing event lasted from 300 to 500 Ma, while Ernst and Desnoyers (2004) offered that the global resurfacing event could have spanned longer than 900 Ma. These age predictions are challenged by the poor statistical quality of the crater count sample set (Campbell 1999) and by the novel data acquired by the Venus Express satellite, proposing volcanism may be as young 10,000 to 100,000 years old (Smrekar et al. 2010).

1.2 Previous work

1.2.1 Missions to Venus

The early 1960's marked a pivotal era in the history of space exploration and the onset of vehicles sent to study Earth's sister planet, Venus. Four failed missions to Venus, three launched by the Soviet Union and one by the United States of America took place before the first successful mission, Mariner 2. Launched on August 27 1962,

Figure 1.1 A short time lapse of Venus as it transits the Sun on June 5, 2012 from approximately 6:00 – 6:20 pm. The photos were captured by a digital single-lens reflex camera attached to a Schmidt Cassegrain telescope at the Kessler Observatory, located on the roof of Carleton University's Herzberg building. Photo credit: E. Rollin and R. Killick.

Mariner 2 was not only the first satellite to successfully complete its mission to Venus but also the first successful mission to another planet². Since the success of Mariner 2, which collected information about surface temperature, sidereal rotation, atmosphere and magnetic field, 33 additional missions have followed. Those of recent significant scientific impact include the Magellan Mission led by NASA and the Venus Express Mission directed by the European Space Agency (ESA).

The Magellan Satellite was launched May 4 1989 onboard the space shuttle Atlantis from the Kennedy Space Centre in Florida. The scientific objectives of the Magellan mission improve understanding of landforms and tectonic features, impact processes, erosion, deposition and chemical processes, as well as to develop a model of the internal density distribution (Saunders et al. 1992). By the end of the mission, 98% of the planet's surface had been successfully imaged with a resolution of 75 m/pixel. Magellan was the first satellite to be launched from a space shuttle, the first to employ aerobraking, a method of piloting a satellite using a planet's atmosphere, and also the first to be purposefully crashed as a means of collecting information about the atmosphere². Arriving at Venus 15 months after its departure (August 10 1990), the Magellan Satellite completed three mapping cycles, two of which were left-looking, lasting until September 15 1992³. The remainder of the mission was focused on obtaining gravity data and testing the aerobraking method until contact was lost on October 13 1994, following an intentional crash to the surface².

The Venus Express Spacecraft was launched November 9 2005 from Baikonur, Kazakhstan on the Soyuz-Fregat rocket. Like many other Venus bound satellites before

² <http://www2.jpl.nasa.gov/magellan/>

³ <http://nssdc.gsfc.nasa.gov/planetary/magellan.html>

Venus Express, it is a technological pioneer. Currently in orbit, the objectives of the Venus Express mission are to gain a better understanding of Venus' atmosphere and surface. It 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 camera⁴. The Venus Express mission is expected to run until December 31 2014⁴.

1.2.2 Geological Mapping

Since the publication of the high resolution Magellan synthetic aperture radar (SAR) data, made publicly available on the United States Geological Survey (USGS) website, mapping of surficial features has been an ongoing process⁵. Managed by the USGS, geological mapping of Venus is subdivided into 62 quadrangles where each quadrangle has or will be assigned to a scientist for mapping⁶. Currently, 27 quadrangles have been published, 8 are under review, 19 are in progress, and 8 remain unassigned. Additionally, Ivanov and Head (2011) have produced a global geological map of Venus as described in detail in chapter 2.5. At this time, the Idunn Mons area, located in Imdr Regio, and Ulfrun Regio have yet to be assigned for mapping. A geologic map of Ganiki Planitia was recently published by Grosfils et al. (2011) and a map of the Themis Regio area, with lead author Ellen Stofan, is in review⁶.

In addition to the mapping projects mentioned above, further studies have been completed in the four study areas presented in this thesis: Idunn Mons, Themis Regio, Ganiki Planitia and Ulfrun Regio. The Idunn Mons area was examined as a volcano

⁴ <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47115>

⁵ <http://www.mapaplanet.org/>

⁶ http://astrogeology.usgs.gov/PlanetaryMapping/MapStatus/VenusStatus/Venus_Status.html

dominated rise in Stofan (1995) and later in Smrekar et al. (2010). Themis Regio has been of great interest because of its role in the Beta-Atla-Themis region, which has been identified as a volcanically young area dominated by mantle upwelling, generating extensive rifts involving both intrusive and extrusive igneous activity (Senske et al. 1991; Squyers et al. 1992). The majority of work completed in Ganiki Planitia is fairly recent including the publication of a geological map by Grosfils et al. (2011). Older material, notably Raitala and Kauhanen (1991), examined the tectonics of the ridge belts located in Ganiki Planitia. Finally, the radiating graben-fissure systems in Ulfrun Regio were thoroughly studied by Studd et al. (2011).

1.2.3 Venus Global Dyke Swarm Map Project

The Venus global dyke swarm map project is an international effort with contributions from the United States, Russia and Canada aimed at producing the first global map of graben-fissure systems on Venus. Using Magellan synthetic aperture radar data (75 m/pixel resolution), mapping is being combined with the global map produced by Ivanov and Head (2011) to contribute to a better understanding of the distribution of intraplate magmatism in time and space as well as Venus' planetary evolution.

Previous mapping initiatives which are part of the global Dyke Swarm Map Project have been completed over the past decade some of which include Nepthys Mons Quadrangle (V-54) (Blair and Ernst, 2002), Guinevere Planitia and Beta Regio (Ernst et al. 2003), and Ulfrun Regio Quadrangle (V-27) (Studd et al. 2011).

1.3 Research objectives

The objectives of this research project involve the investigation of two classes of tectono-magmatic features on Venus. The first objective aims at better understanding

radiating graben-fissure systems and the second is to better understand pit crater chains. As part of the Global Dyke Swarm Map Project, the former includes systematic mapping of extensional lineaments (grabens, fractures and fissures) in the areas surrounding Idunn Mons, located in the Imdr Regio quadrangle, and Mielikki Mons, located in the Themis Regio quadrangle. These two areas were selected for study because of their recent identification as young topographic highs by Smreker et al. (2010) based on spectral analysis of data acquired by VIRTIS onboard the Venus Express Satellite. By mapping radiating graben-fissure systems in the vicinity of emissivity anomalies, the study may reveal: (a) if radiating graben-fissure systems are found in association with high emissivity anomalies (b) using cross-cutting relationships, determine the relative age of radiating graben-fissure systems and lava flows associated with the high emissivity anomalies (c) if radiating graben-fissure systems associated with high emissivity anomalies are the youngest radiating systems in the surrounding area. As radiating graben-fissure systems are interpreted as the surficial expression of radiating dyke swarms, the study will provide a better understanding of the magmatic and tectonic evolution of the selected study areas and of Venus in general. The second objective is to gain a better understanding of pit crater chains by improving our knowledge of their spatial distributions and associations with other features, such as radiating graben-fissure systems and coronae. Four areas on Venus have been analyzed, including the two areas mapped as part of this project as well as Ganiki Planitia and Ulfrun Regio (Figure 1.2), as these areas have recently been mapped in detail (Studd et al. 2011; Grosfils et al. 2011).

Figure 1.2: Location of study areas on a sinusoidal projection of Venus centred on 0°E. Locations where radiating graben-fissure systems and pit crater chains are mapped are indicated by white boxes. Locations where only pit crater chains are mapped are indicated by stippled regions. (1) Ganiki Planitia, 180°E – 210°E and 25°N – 45°N. (2) Ulfrun Regio, 205°E – 240°E and 0°N – 25°N. (3) Idunn Mons study area (white region) 205°E – 225°E and 35°S – 55°S and Imdr Regio, 205°E – 235°E and 25°S – 55°S (white and stippled region) (4) Mielikki Mons study area (white region) 270°E – 290°E and 15°S – 40°S and Themis Regio (white and stippled region) 270°E – 300°E and 15°S – 40°S. Unmarked white areas are where no Magellan data was collected.

2 Chapter: Background information

2.1 Data

2.1.1 Synthetic aperture radar

As previously mentioned, the synthetic aperture radar (SAR) images utilized in this project were obtained during the Magellan satellite mission, two decades ago. Here, we discuss the characteristics of the data obtained.

Microwaves of a wavelength equal to 12.6 cm were transmitted from the satellite to the surface at an oblique angle (Tanaka 1994). The aperture is considered synthetic as it employs the delay of the returning signal (echo) while in motion resulting, in effect, in obtained information that otherwise would have had to be collected with a much larger receiver. The size of the synthetic aperture (receiver) is dependent on the distance travelled during a given period of time at a given location within the field of view.

Radar images presented here have a resolution of 75 m/pixel and are those acquired during left-looking map cycles. Knowledge of the orientation of the receiver is required as it will affect how the images are interpreted. The intensity (radar bright or dark) of a pixel is determined by the amount of reflectance which is a function of surface roughness and orientation with respect to the transmitter. Radar bright sections are rough surfaces or areas pointing towards the receiver, while radar dark sections are either composed of smooth material or facing away from the receiver.

2.1.2 Visual and infrared thermal imaging spectrometer

Adopted from the Rosetta Mission, the Visual and Infrared Thermal Imaging Spectrometer (VIRTIS) provides an extraordinary opportunity to study the atmosphere and surface composition of Venus (Drossart et al. 2007). Still in orbit as of July 2012

onboard the Venus Express Satellite, VIRTIS has completed mapping of the southern hemisphere of Venus and, in the near future, is scheduled to examine the northern hemisphere as well. It is equipped with two separate devices: VIRTIS-M and VIRTIS-H spectrometers (Drossart et al. 2007). The VIRTIS-M mapping spectrometer is capable of detecting visual (0.25 - 1 μ m) and near-infrared (1-5 μ m) electromagnetic radiation with a spatial resolution of 50 m/pixel (Drossart et al. 2007). VIRTIS-H is a high resolution spectrometer operating in the infrared range between 2-5 μ m (Drossart et al. 2007).

Using principles first tested by the flyby missions Cassini and Galileo, thermal emission (hereafter, emissivity) is measured by the VIRTIS-M spectrometer at specific wavelengths, known as spectral windows, specifically 1.10 μ m, 1.18 μ m and 1.02 μ m (Mueller et al. 2008). Emissivity is the ratio between the radiance measured from the planet's surface and the radiance emitted by a black body at the same temperature. Weathered material, interpreted as the older material on the surface, is characterized by lower emissivity values than unweathered material. Unweathered, high emissivity areas reflect younger lava flows which might have occurred as recently as 250 ka (Smrekar et al. 2010).

In order to distinguish between old and young material, certain elements, and their various oxidation states, are targeted. In particular, the FeO absorption band is at 1 μ m and, as it is an important component in common mafic minerals, it is employed as a proxy for surficial composition and, with the addition of predicted chemical weathering rates, the age of the surface of Venus.

The raw data collected by VIRTIS is enhanced by newly acquired topographic data (also collected by Venus Express), and is corrected for several effects including

instrumental stray light, viewing geometry, cloud opacity, and elevation (Smrekar et al., 2010).

Because VIRTIS measures emissivity, it is important to understand the relation between temperature and the composition of Venus' surface. Smrekar et al. (2010) recognize that following data correction, the emissivity anomalies observed are not true products of surface temperature variations because the measurements were collected over a time span of one and a half years. Any anomaly observed must therefore be due to chemical variations. Mueller et al. (2008) explain that emissivity is one of the variables of the Planck function (used to determine the radiance emitted by a material acting as a black body) which is significantly affected by temperature. Therefore, in order for remote sensing of surficial emissivity to be meaningful, the temperature variable must be well constrained. The temperature of Venus' atmosphere has been measured over several missions including Venera, Pioneer Venus, and Vega descent probes. The temperature is stable because of the atmosphere's substantial greenhouse environment as well as its high heat capacity and limited temperature variation from day to night (Mueller et al. 2008).

The VIRTIS' ability to measure the composition of the atmosphere plays an important role in determining the approximate composition of the surface of Venus since the true oxidation state of the surface remains unknown (Drossart et al. 2007). Knowledge of the atmospheric chemistry is necessary in order to understand chemical weathering and buffering with minerals exposed at the surface (Drossart et al. 2007). Gasses of particular importance, due to their known reactivity with minerals on Earth, include oxygen, carbon dioxide, hydrochloric acid, hydrofluoric acid, and sulphur compounds. Using the relative abundance of carbon dioxide and carbon monoxide in the

lower atmosphere (information also collected by VIRTIS), alongside basic stoichiometry, the reaction rate and total volume of Fe in minerals and the various states can be determined (Drossart et al. 2007).

2.2 Methods

2.2.1 Cross-cutting relationships

Cross-cutting relationships are important observations required for relative dating of graben-fissure systems in relation to other interacting graben-fissure systems as well with lava flows. When more than one radiating system interacts with a lava flow, it (the lava flow) can prove to be useful for determining the relative ages of radiating systems. In Figure 2.1, we outline the relationships observed between graben and lava flows as well as provide interpretations.

2.2.2 Graben assignment and identification of a radiating graben-fissure system

A radiating graben-fissure system is defined by graben that radiate from a central point. The central point may be marked by a volcano-tectonic feature like a volcano, a more complicated feature such as a corona, patera, tholus or mons, or may be inferred based on the orientation of graben. Regardless, graben are assigned to a radiating graben-fissure system based on their orientation with proximal graben (ideally being parallel or subparallel) and the overall pattern that the set of graben exhibit.

2.2.3 Clustering analyses

An average nearest neighbour statistical test is used to determine if the pit crater chains are randomly distributed within each study area. The test, as described by Ebdon (1985), compares an observed average distance between points located nearest one another to an expected distance based on a random distribution. The ratio between the

Figure 2.1: Cross-cutting relationships between graben and lava flows. (A – C) Demonstrating cross-cutting relationships for graben that are younger than lava flows. (D –I) Demonstrating cross-cutting relationships for graben that are older than lava flows. A. Graben sharply cut through the lava flow boundary. The brightness and morphology of the graben are consistent. B. Graben are completely formed (or contained) within the lava flow but their clear, well formed, “sharp” morphology indicates they are younger. C. Graben are trough-like (wide and shallow). Remnants of the lava flow can be detected in the graben where the lava flow boundary is offset. D. Lava flow completely fills a portion of the graben leaving behind one end of the graben exposed. E. Lava flow partially floods the graben leaving behind subtle indications of the negative topography. F. Graben progressively becomes less defined, suggesting partial flooding of graben. G. The lava flow follows the negative topography formed by the graben. H. Graben act as levee for lava flows and results in straight lava flow boundaries. I. Lava flows within the graben.

observed and the expected average distance is known as the nearest neighbour index and indicates whether a distribution is clustered (< 1), random (~ 1) or dispersed (> 1).

Additionally, a two-tailed student's t-test is used to test the significance of the nearest neighbour calculations.

2.2.4 Statistical evaluation of local clusters

The association of pit crater chain clusters with well-defined systems of graben provides a means of assessing the role of extension in the formation of pit crater chains. In cases where we see a regional cluster distinctly associated with a radiating graben-fissure system, we have noted that the pit crater chains are restricted to one or more portions of the radiating system. This represents a more local level of clustering and is a clue to a potential secondary control by lithology, as discussed below. The presence of two levels of clustering is an example of hierarchical clustering which is evaluated using a single linkage standard agglomerative hierarchical clustering method (Everitt et al. 2011). In other words, a second nearest neighbour statistical test is performed for this individual cluster. For this nearest neighbour statistical calculation, the distribution of pit crater chains is compared with a rectangular area that encloses as much of the radiating graben-fissure system as possible but does not extend outside the radiating system (Fig. 3). The rectangle can be oriented in any position depending on the shape of the radiating graben-fissure system and distribution of pit crater chains. Two hypotheses are proposed for results of the single linkage nearest neighbour analyses test conducted under these conditions: (A) If pit crater chains on Venus are primarily controlled by processes related to extension, then we should consistently observe a random distribution of pit crater central point, also known as a focus, are grabens, fissures and fractures (Fig. 2.2). Graben

Figure 2.2: Experimental design and hypotheses regarding the clustering of pit crater chains on regions of well-defined extension. (A) Where pit crater chains are randomly distributed. (B) Where pit crater chains are inhomogeneously distributed. Lines and points represent graben and pit crater chains, respectively. Grey boxes delineate the area used in the calculation of the nearest-neighbour statistical test.

chains within the confines of the extensional system (Figure 2.2 left), or (B) if the formation of pit crater chains is influenced by a secondary variable, then we should observe pit crater chains inhomogeneously distributed within the confines of the extensional system providing that the secondary variable is inhomogeneously distributed itself (Figure 2.2 right).

2.3 Volcano-tectonic features

A wide variety of volcano-tectonic features are present on Venus. Some resemble those found on Earth while others are drastically different. Shield volcanoes and vast plains of shield volcanoes, calderas, lobate lava flows, and pit crater chains are relatively abundant features found on the surface of Venus. Features unique to Venus include chasmata, paterae, tholii, canali and corona. Chasmata are commonly interpreted as evidence of an extensional process or rift zone as they are long, steep-sided negative topographic features consisting of troughs and fractures. Paterae are irregular or complex volcanic calderas and tholii are dome-shaped mountains or hills⁷. Canali are sinuous channels that can be traced for hundreds (to thousands) of kilometers in length and are thought to be streams of low-viscosity lavas or collapsed lava tubes (Waltham et al. 2008). Further details in this chapter will focus on the most relevant volcano-tectonic features discussed in this thesis including radiating graben-fissure systems, corona and pit crater chains.

2.3.1 Radiating graben-fissure systems

Radiating graben-fissure systems are considered to be underlain by laterally propagating dykes fed from a central magma source (Ernst et al. 2001). Radiating from a

⁷ <http://planetarynames.wr.usgs.gov/DescriptorTerms>

are extensional lineaments with flat floors that can have lengths up to 1000's of kilometers and widths of several kilometers. They may be independent structures associated with tectonic extension or related to linear, circumferential or radiating systems underlain by dykes. Fissures and fractures, like graben, are extensional lineaments but do not display a flat floor. Instead, fissures and fractures are lineaments that have v-shaped floors.

These extensional lineaments vary based on morphology, where graben exhibit flat floors, while fissures and fractures do not. Following Studd et al. (2010), we will refer to each type of extensional lineament (graben, fissures and fractures) as a graben, hereafter. The magma source for a radiating graben-fissure systems is considered to be derived from the mantle as diapirs or mantle plumes (Ernst and Desnoyers 2003). As such, the extensional process related to the formation of graben is linked not only to shallow dyke intrusion but also by domical uplift caused by the impinging diapir (Parfitt and Head 1993).

2.3.2 Coronae

Coronae are, on occasion, the central feature of a radiating graben-fissure system. Though not yet recognized on Earth, coronae are annular to semi-annular features common on the surface of Venus (Fig. 2.3). Coronae are characterized by an inner plateau enclosed by circumscribing troughs and ridges, and commonly found in association with rift zones (Stofan et al. 1992). A variety of origins are proposed for coronae including: lithospheric dripping associated with mantle upwelling or downwelling, Rayleigh-Taylor instabilities at the mantle-lithosphere boundary and,

Figure 2.3: An example of a radiating graben-fissure system at 27°S and 273°E, centred on Ts'an Nu Mons located in Themis Regio

Figure 2.4: The Banba Corona located at 210°E and 47°S in Imdr Regio.

finally, the result of interactions between a plume head and depleted mantle layer (Piskorz et al. 2012). In addition to radiating graben-fissure systems, corona are found in association with a variety of volcanic features including lava flows, small cones and shield volcanoes, and can exhibit diameters ranging from tens to a few thousand kilometers (Stofan et al. 1997).

2.3.3 Pit crater chains

Pit craters are bowl-shaped steep-sided circular to elliptical features found on many of our solar system's terrestrial planets and moons: Venus, Mars, Earth, the Moon, Phobos, Eros, Gaspra, Ida, Enceladus and Europa (Mége and Masson 1996; Okubo and Martel 1998; Montesi 2001; Bleamaster and Hansen 2001; Wyrick et al. 2010). These negative shallow topographic depressions can have conical or flat floors, and can be found alone or in a chain in which the alignment of pits can be linear or irregular. Chains can range in length from tens to thousands of kilometers and in diameter from 75 meters to a few kilometers (the minimum discernible size of pit craters on extra-terrestrial bodies is limited by radar resolution) (Bleamaster and Hansen 2001). Along pit crater chains, pits can be isolated and irregularly spaced, contiguous or coalescing, where the pits, following wall collapse, can ultimately merge to form a trough (Fig. 2.4). In many instances, pit crater chains exhibit a combination of the aforementioned styles. On Earth, pit crater chains are found in Hawaii associated with Kilauea volcano on the Big Island, along the East Pacific Rise, in the Dead Sea along the coastlines of Israel and Jordan, and in Iceland (Jaggard 1947; Abelson et al. 2003; Wyrick et al. 2010; Ferrill et al. 2011).

Montesi (2001), Bleamaster and Hansen (2001), and Ernst et al. (2001) document the common association between pit crater chains and graben on Mars and Venus.

Figure 2.5: Examples of pit crater chains and their variability. (I) Isolated pits in Imdr Regio at 207°E 42°S; (II) Contiguous pits in Themis Regio at 280°E 20°S; (III) Coalescing pits in Ganiki Planitia; (IV) A trough with serrated edges in Ulfrun Regio at 214°E 25°N

Pit crater chains have a variety of proposed origins. Most hypotheses can be grouped into three categories: surficial processes, tectonic origin, or magmatic origin. Surficial processes involve the formation of a hollow structure and later collapse by karst dissolution, or compaction by permafrost heating and removal by water, or unconsolidated sediment drainage into underlying voids (Wyrick et al. 2010 and references therein; Ferrill et al. 2011).

Hypotheses pointing to a tectonic origin are related primarily to regional extension, dilatational faulting or fracture widening (Wyrick et al. 2010; Ferrill et al. 2011). Ferrill et al. (2011) examined Icelandic pit crater chains and found they occurred in conjunction with normal fault scarps, extension fractures, dilational faulting and troughs. They were equally distributed between unconsolidated fluvial sediments and older basalts. Pits found solely within the basaltic units were constrained above the aerial extent of local subsurface caves while pits found within the fluvial unit were often bound by graben and thought to form by sediment drainage into underlying fractures and faults (Ferrill et al., 2011). Ferril et al (2011) made two conclusions: (1) that pit crater chains in Iceland were produced by dilational faulting of competent material (basalt) overlain by fluvial sediments, and (2) the geomorphologic patterns seen in Icelandic pit crater chains are similar to those found on Mars.

A magmatic origin considers pit craters as a topographic expression of volcanic activity such as maar explosion, a drop in pressure post dyke emplacement, deflation or stoping (McKenzie et al. 1992; Okubo and Martel, 1998; Mége et al. 2000; Montesi, 2001; Bleamaster and Hansen 2001; Wyrick et al. 2004 Wyrick et al. 2010). Okubo and Martel (1998) explored the mechanisms responsible for Hawaiian pit crater chains

associated with active fissuring and magma flow witnessed by Jaggar (1947). Hawaiian pit crater chains located near Kilauea volcano on the Big Island are thought to form by stoping into a deep seep fracture induced by normal tensile stress (opening mode I fracture) (Fig. 2.5). Pre-existing structural or stratigraphic weaknesses and magma flow exacerbate this formation process.

On Earth, pit crater chains have been found grouped in clusters which indicate formation by a non-random process. Abelson et al. (2003) document clustering of pit crater chains along the Dead Sea pull-apart basin coastlines in Israel and Jordan. They found that pit crater chains are located above concealed faults and in line with exposed faults and rift wall segments. The faults provide easy pathways for ground water influx into salt layers which causes karsting and ultimately forms pit chains.

On Venus, pit crater chains are commonly considered to form by magmatic processes related to dyke swarms (Wyrick et al. 2010).

2.4 Tectono-magmatic setting of the study areas

2.4.1 Imdr Regio

West of Themis Regio and outside the Beta-Atla-Themis (BAT) zone, the Idunn Mons study area is a volcano-dominant topographic rise (Stofan et al. 1995) (Fig. 3.1). The Beta-Atla-Themis (BAT) zone is one of the geologically youngest and volcanically complex zones on Venus. Unlike Ulfrun and Themis Regiones (which are Corona dominated topographic rises), the topographic rise in Imdr Regio is associated with one principal feature, Idunn Mons. Idunn Mons (215°E and 47°S) is the focus of three superimposed radiating graben-fissure systems. Regionally, the study area contains 4 coronae, 1 mons, 1 tholus and 1 patera. The area contains at least 10 radiating graben-

Lava Tube

Dike with Hydrosphere/Cryosphere Interaction

Dike with Exsolved Volatiles

Dike with Plinian-style eruption

Collapsed Magma Chamber

Karst Dissolution

Extension Fractures

Dilational Faulting

Figure 2.6: The proposed origins of pit crater chains from Wyrick et al. (2004). An asterisk indicates a mode of origin not proposed for Venus (A) Collapse of lava tube. (B) Dyke intersects hydrosphere/cryosphere* (C) Dyke exsolves volatiles (D) Plinian style eruption fed by a dyke (E) Collapse of magma chamber (F) Collapse following karst dissolution* (G) collapse following extensional fracture (H) Collapse following dilational faulting.

fissure systems and is equally abundant in extensional and contractional deformation features. Similar to the other study areas, primary lithologies include both regional and local plains units which differ in extent, radar and morphologic properties (Grosfils et al. 2011). Less abundant lithologies include groove belts and tesserae terrain as well as minor rift-related units (Ivanov and Head 2011).

2.4.2 Themis Regio

At the southernmost vertices of the BAT zone, Themis Regio is a corona dominated highland exhibiting significant extensional deformation (Stofan et al. 1995) (Fig. 3.12). Regional extension is associated with the 10,000 km long Parga Chasma rift system that runs north-west through the quadrangle (Martin et al. 2007, Stofan et al. 1995). The area within Themis Regio that is examined in this study contains 2 tholus, 4 mons and 18 coroneae. Similar to Ulfrun Regio, the corona are located within or proximal to the rift system and are aligned along the north-west Parga Chasma trend. In addition to circumferential graben-fissure systems associated with corona, at least 10 radiating graben-fissure systems are present in Themis Regio.

2.4.3 Ganiki Planitia

As the northern-most study area, Ganiki Planitia is positioned south-east of Atalanta Planitia, an area of extensive volcanic flooding, and north-west of the BAT zone (Ivanov and Head 2004; Grosfils et al. 2011) (Fig. 4.4). Lithologically, the V14 quadrangle is primarily host to a variety of volcanically derived regional plains units and, to a lesser extent, tesserae terrain and deformation belts, local plains units, volcanic edifices and corona-related flows, and impact materials. Seventeen major volcanic

edifices are present including eight coronae, five mons, four paterae and one tholus (Grosfils et al. 2011). Only two, possibly three, radiating graben-fissure systems are present, a significant contrast to those parts of the BAT zone, including Ulfrun and Themis Regiones, where they are abundant (Grosfils et al. 2011). In addition to the local extensional lineaments associated with radiating graben-fissure systems, both contractional (wrinkle ridges) and regional extensional deformation (graben, troughs and lineaments) features are represented.

2.4.4 Ulfrun Regio

South-east of Ganiki Planitia is the Ulfrun Regio Quadrangle V-27, an uplifted rift-dominated highland region located within the BAT zone (Stofan et al. 1995) (Fig. 4.3). The Hecate, Devana and Parga Chasma that define the BAT zone link major plume-related volcanic centres (Studd et al. 2011 and references therein). Ulfrun Regio is directly east of Atla Regio and, consequently, the discontinuous Hecate Chasma rift cuts through the quadrangle eastwardly (Hamilton and Stofan 1996). Other volcano-tectonic features in Ulfrun Regio area include 8 coronae, 3 patera, and 4 mons. Structurally, the quadrangle includes abundant extensional features including fissures and fractures. Studd et al. (2011) mapped 66 graben-fissure systems, 38 found in association with corona. These systems range in radii from 10-2000 km (Studd et al. 2011). The extensional lineaments are found with geometries varying from radial, circumferential to linear sets. Radiating graben-fissure systems are thought to be emplaced by laterally propagating dykes fed from a central magmatic centre. Circumferential graben-fissure systems associated with corona are located within or proximal to the Hecate Chasma rift system. The rift system not only includes coronae, but also is associated with graben-fissure

systems linked to the rifting. Similar to Ganiki Planitia, Ulfrun Regio contains a variety of lithologies including local and regional plains units as well as groove belts, and rift zone.

2.5 Map units

Defined by Ivanov and Head (2011), the morphological units on Venus are used as a tool for relative dating of radiating systems. Here, we describe the 13 different units found in the Idunn Mons and Mielikki Mons study areas. The units are presented in order of oldest to youngest as determined by Ivanov and Head (2011) based on global studies and correlations using embayments, superposition and cross-cutting relationships. As explained by Ivanov and Head (2011) it is important to realize that the units are based on morphological qualities and therefore, the map displays the spatial distribution of these morphologically distinct units. Additionally, the mapped units are not directly temporally correlative; different morphologies do not indicate differences in time of emplacement just as similar morphologies are not necessarily contemporaneous.

As previously mentioned, units are defined by their unique morphological traits which may be structural or material in origin. Structural units are those that exhibit some form of extensional or compressional process while material units are defined by features like the presence of small volcanic related features such as shield volcanoes, lobate lava flows and may also be classified based on the texture of the radar image.

Map units based on structure are some of the oldest units found on Venus. Those found in the Mielikki Mons study area include tessera terrain, and densely lineated plains whereas groove belts and rift zones are found in both study areas. Tessera terrain (t) is a structural unit found as topographically high, tectonized belts that include several phases

cf	crater outflow material	rz	rift zones	pr	ridged plains material ridge belts
c	crater material, undivided	rp2	regional plains material, upper unit	mt	mountain belts
pl	lobate plains material	psh	shield plains material	pdl	densely lineated plains material
ps	smooth plains material	rp1	regional plains material, lower unit	t	tessera material
sc	shield clusters material	gb	groove belts		

Figure 2.7: The relative age of map units and accompanying legend based on global geological map of Venus from Ivanov and Head (2011).

(at least two sets) of intersecting structures which may be either compressional or extensional in origin. Densely lineated plains material (pdl), another unit defined by its structural elements, consist of densely packed narrow and relatively short parallel to sub parallel lineaments that are fairly close together. Ridged plains material/ridge belts (pr) are described by Ivanov and Head (2011) as having a morphology similar to lava plains but are host to long ridges. Groove belts are another structural unit which are host to parallel and sub-parallel graben and fractures, and in many cases in this study are directly associated with radiating graben-fissure systems. Rift zones are similar to groove belts but differentiated based on extent and density of lineaments. They are characterized by densely packed (but less than groove belts) extensional lineaments (graben, fissure and fracture) that can extend for hundreds of kilometers and are often directly associated with radiating graben-fissure systems. When named by the international astronomical union, individual rift zones are labeled as chasma.

Map units based on material characteristics are found in both the Mielikki Mons and Idunn Mons study areas. These include shield plains material, regional plains material (upper and lower units), shield clusters, smooth plains and, lobate plains. Shield plains material (psh) encompass smooth plains with clusters of abundant small shield-like volcanic edifices and can sometimes be found deformed by wrinkle ridges. The lower unit of regional plains (rp₁) involves smooth, uniform plains with intermediate-dark to intermediate-bright radar backscatter. The upper unit of regional plains (rp₂) is a less extensive unit consisting of smooth plains and primarily differs from rp₁ by its variation in radar albedo. The shield clusters (sc) differs from shield plains material as it is undeformed and the volcanic edifices themselves are observed as the source of small,

local lobate lava flows. Smooth plains material (ps) consists of a featureless surface, with smooth plains and no deformation with low radar-backscatter. Lobate plains material (pl) is characterized by a morphology of the flow-like features that resembles basaltic lava flows found on Earth. The lobate plains material exhibits a wide-variety of radar backscatter intensities with smooth surfaces and is commonly found in association with rift zones.

3 Chapter: Radiating Graben-Fissure Systems

3.1 Idunn Mons Area

Located largely within Imdr Regio, while partly including the eastern margin of Isabella Regio, the story of Idunn Mons consists both of effusive lava flows and emplacement of radiating graben-fissure systems. Lava flows predate and postdate the many interacting and isolated radiating graben-fissure systems. A total of 12 graben-fissure systems are identified, mapped and analyzed involving 5745 mapped graben-fissure and fracture segments out of a total of 8652 mapped in the area (Figs 3.1 and 3.2). Eleven of the graben-fissure systems are radiating while one linear system (System 12) is located between Idunn Mons and the focal point of System 4 (Fig. 3.3). Here, a detailed description and analysis of each radiating graben-fissure system and its corresponding centre is presented.

3.1.1 Systems 1, 2, 3 and 12: Idunn Mons (215°E, 46°S)

Three radiating graben-fissure systems are found surrounding Idunn Mons. System 1 and 2 are centred on the flanks while System 3 is centred directly on Idunn Mons. Idunn Mons is a topographic high located at the south eastern termination of Olapa Chasma and is directly associated with radiating System 3. System 1 involves 254 graben that are mapped up to 475 km from its inferred centre (Fig. 3.4). Located on the western flank of Idunn Mons, fanning System 1 is present primarily in the northwestern sector surrounding Idunn Mons with some contribution from the northeast and little from the southern sectors. Conversely, System 2 is focused on the eastern flank of Idunn Mons involving 207 graben with a radius of up to 500 km (Fig.

Figure 3.1: Magellan SAR image of the Idunn Mons area. Centres of radiating graben-fissure systems are identified by black dots. The extent of Olapa Chasma is delineated by the region filled by hatched black lines.

Figure 3.2: Mapped graben within the Idunn Mons area overlain on a Magellan SAR image. Black lines are graben unassigned to radiating or linear systems. Graben assigned to radiating or linear systems are grouped by colour and their centres are denoted by labeled black dots. The extent of Olapa Chasma is delineated by the region of black hatched lines.

Figure 3.3: Identical to Figure 3.2 except that unassigned graben are not included. Displayed are graben assigned to radiating or linear graben-fissure systems in the Idunn Mons study area. Systems are distinguished from each other by colour and are overlain on a Magellan SAR image. Centres are denoted by labeled black dots.

3.4). Like System 1, System 2 is a fanning System but less extensive. System 3 is centred directly on Idunn Mons and includes 1102 graben extending a maximum of 1100 km from the volcano (Fig. 3.4). With the exception of a vacant southwestern quadrant, radiating System 3 extends in all directions but dominantly and most extensively towards the northwest, in association with Olapa Chasma.

Systems 1, 2 and 3 heavily cross-cut one another and as a result, produce a disjointed appearance of their associated graben. The cross-cutting relationships indicate the relative age of the radiating Systems (from oldest to youngest): 1, 2 and 3 (Fig. 3.5). Lobate lava flows are abundant in the area and are found pre-dating and post-dating radiating graben-fissure systems (Figs 3.6 and 3.7). Younger lava flows obscure graben and add to the disjointed appearance of the radiating systems.

Linear System 12 consists of 115 graben east of Idunn Mons and are distributed over a length of 330 km (Fig. 3.4). The northeast-southwest orientation of linear System 12 is such that it is not clear whether it is focused on the flanks of Idunn Mons or associated with a centre near system 4. System 12 is cross-cut by both Systems 3 and 4, however, contradictory cross-cutting relationships inhibit the determination of a relative age. In relation to local lobate lava flows, graben are observed cutting through lava flows indicating that System 12 is relatively younger than the lava flows.

3.1.2 Unnamed Mons System 4 (220°E, 47°S)

The radiating graben-fissure System 4 is centred on a mountain that has not been labeled by the International Astronomical Union nomenclature working group⁸ (Figure

⁸ <http://planetarynames.wr.usgs.gov/Page/VENUS/target>

Figure 3.4: The three radiating systems surrounding Idunn Mons (215°E, 46°S): System 1 (red lines), System 2 (yellow lines), System 3 (blue lines), and linear System 12 (orange lines). Olapa Chasma is delineated by the black hatched region. Mapping is overlain on a Magellan SAR image.

Figure 3.5: Cross-cutting relationships between Systems 1, 2 and 3. (A) System 1 (red lines) is cross cut by System 2 (yellow lines) and System 3 (blue lines). (B) System 1 (red lines) is cross-cut by System 3 (blue lines) (C) System 2 (yellow lines) is cross-cut by System 3 (blue lines). These cross-cutting relationships indicate that System 1 is oldest, System 2 is middle-aged and System 3 is youngest.

Figure 3.6: Cross-cutting relationships involving local lobate lava flows (selected examples delineated by purple regions) and Systems 1 (red lines) and 3 (blue lines) overlain on a Magellan SAR image. (A) Lava flows partially fill graben of System 1 and are cut by graben of System 3. (B) Lava flows are cut by graben of Systems 1 and 2. These cross-cutting relationships indicate that lava flows are both older and younger than the radiating systems.

Figure 3.7: Cross-cutting relationships involving lava flows and graben. Lobate flows are observed following the trends of radiating systems. (A) Lava flows flood and obscure graben part of System 2. (B) Lava flows partially flood and obscure graben part of System 1. These relationships suggest that the System 2 dykes and associated lava flows are of similar age range.

Figure 3.8: (1) Radiating graben-fissure System 4 (pink lines), shades of grey are surrounding systems. (2) Radiating graben-fissure System 5 (white lines) centred on the Raskova Patera. System 5 is south of System 4. Line work is overlain on Magellan SAR images.

3.8). System 4 includes 264 graben that extend a maximum of 250 km from the unnamed mons. The area surrounding the central portion of the radiating system is flooded by smooth extensive lava flows that have largely obscured the record of System 4. Though located less than 400 km from Idunn Mons and found interacting with Systems 3 and 12, conclusive cross-cutting relationships are not observed.

3.1.3 Raskova Patera System 5 (222°E, 51°S)

Located 400 km south of the centre of System 4, System 5 is centred on Raskova Patera (Fig. 3.8). Involving 114 graben, the system extends up to 310 km from its centre and into the southern sector of System 4. However, due to a lack of cross-cutting relationships a relative age between these proximal systems cannot be established.

3.1.4 System 6 (210°E, 40°S)

Radiating System 6 is centred on an unnamed mountain that consists of several nested calderas (Fig. 3.9). Located 770 km northwest of Idunn Mons, the system and its focal point sit on the northwestern margin of Olapa Chasma. System 6 contains 280 graben and extends a maximum distance of 500 km from its centre. Graben of System 6 are found interacting with lava flows as well as several nearby radiating systems including 3, 7, 8 and 9, however, due to ambiguous cross-cutting relationships no relative ages are established. Local lobate lava flows are abundant in the immediate area of system 6 and are found completely and partially flooding graben (Fig. 3.9).

3.1.5 System 7 (210°E, 36°S)

Located directly north of System 6, System 7 is a radiating graben-fissure system that includes 150 graben extending a maximum distance of 300 km from its centre (Fig.

Figure 3.9: Radiating graben-fissure System 6 (green lines) and nearby radiating systems are represented by lines of various shades of grey. Boxes delineate the location of images A and B. (A) The cross-cutting relationship between System 6 and lava flows indicating that System 6 is older. (B) Note subdued appearance of System 6 graben which suggests that the selected lava flow is emanating from the graben itself

Figure 3.10: (1) Radiating System 7 (orange lines) and the relation to nearby radiating systems (shades black, grey and white). (2) Radiating graben-fissure Systems 8 (orange lines) and 9 (blue lines). Nearby interacting systems are in shades of black, grey and white. Mapping is overlain on Magellan SAR images.

3.10). The centre of System 7 is inferred as no visible volcano-tectonic feature is present. Dominantly fanning southward, graben of this system are narrow, faint and disjointed. System 7 intersects Systems 6, 8 and 9, however, due ambiguous cross-cutting relationships relative ages cannot be determined.

3.1.6 Systems 8 and 9 (206°E, 36°S and 205°E, 37°S)

Systems 8 and 9 are located on the western boundary of the study area (Fig. 3.10). Unlike Systems 1,2, 3, 4 or 6, neither system is focused on a volcano-tectonic feature. Instead, the area is fairly flat and hosts a small number of shield volcano clusters in addition to faint graben which have been obscured by extensive lava flows. System 8 consists of 218 graben with a maximum radius of 350 km. The graben belonging to this system are fanning from approximately 20°N to 300°W. The northwestern sector of the system is void of graben. System 9 consists of 47 graben that fan from 190°S to 270°W and extend up to 300 km from the inferred centre. Relative ages of Systems 8 and 9 are not clear as cross-cutting relationships do not provide a consistent pattern.

3.1.7 System 10 (206°E, 45°S)

Located at the western margin of the study area, radiating graben-fissure System 10 is isolated from all other systems. It consists of 332 graben and extends up to 150 km from its centre (Fig. 3.11). While the system is not directly focused on a clear tectono-magmatic feature, it is located just over 10 km south of a nested caldera containing at least three craters.

Figure 3.11: Radiating graben-fissure System 10 (orange lines). (2) Radiating graben-fissure System 11 (orange lines). Nearby radiating systems are represented by various shades of grey lines. The white dotted line defines the boundary of the Idunn Mons study area (the centre of System 11 is outside of the study area). Mapping is overlain on Magellan SAR images.

3.1.8 System 11 (227°E, 34°S)

The focal point of radiating graben-fissure System 11 is located north east of the study area. As the system with the largest maximum radius in the Idunn Mons area, spanning up to 1500 km, system 11 incorporates 2662 graben (Fig. 3.11). In many cases, these graben are en echelon and are found in short segments all oriented towards the focal point, a 20 km diameter unnamed caldera. Though the far-reaching southwestern graben part of this System 11 can be found less than a few hundred meters from other radiating systems, none intersect any other systems and therefore a relative age cannot be established.

3.2 Mielikki Mons area

The Mielikki Mons study area is host to 21 radiating and 3 linear graben-fissure systems distributed over an area of approximately $4.6 \cdot 10^6 \text{ km}^2$ (Fig. 3.12). Several radiating graben-fissure systems are centred on a number of volcanic features including mons, coronae, tholii and paterae, while others are not centred on any visible volcano-tectonic feature. In total 18 793 graben are mapped where 8 794 are assigned to either radiating or linear graben-fissure systems (Figs 3.13 and 3.14). In many cases, graben are found nearby and superimposed on local and extensive lava flows. As the more extensive lava flows tend to flood areas of low-lying topography, they partially obscure the record of radiating graben-fissure systems. The graben record is partially exposed by windows of high topography not covered by the lava flows.

3.2.1 System 1: Ts'an Nu Mons (272°E, 27°S)

Radiating system 1 is located in the northwestern portion of the study area. It is centred on Ts'an Nu Mons, a volcano with a diameter of 310 km (Fig. 3.15). The

Figure 3.12: Magellan SAR image of the Mielikki Mons area. Centres of radiating and linear graben-fissure systems are identified by black dots. The extent of Parga Chasma is delineated by the hatched region.

Figure 3.13: Mapped graben within the Mielikki Mons study area. Coloured graben are assigned to radiating systems while black lines are not. The hatched region delineates the extent of Parga Chasma.

Figure 3.14: Identical to Figure 3.2.2 except the unassigned graben are not presented. Displayed are radiating and linear graben-fissure systems in the Mielikki Mons study area. Systems are distinguished from each other by colour and are overlain on a Magellan SAR image. Centres are denoted by labeled black dots and Parga Chasma is delineated by the black hatched region.

radiating system includes 698 graben, distributed over a distance of up to 350 km from its centre. Graben radiate from the Ts'an Nu Mons in all directions, with the exception of the southeast quadrant, which is barren. However, the system is dominated by graben extending towards the northwest and northeast along Parga Chasma. System 1 interacts with several of its neighbours including system 3, 5 and 11. To the northwest, System 3 is a large radiating system with far-reaching graben. Though the graben of the two systems only intersect in a handful of places, the cross-cutting relationships observed are consistent and indicate that System 1 is older (Fig. 3.15). Centred on the Obiemi Corona, System 11 is located 570 km southeast of Ts'an Nu Mons. There are at least 6 independent, consistent intersections between Systems 1 and 11 all indicating that System 1 is older (Fig. 3.15). While there are several points at which Systems 1 and 5 are found intersecting one another, an inconsistent relationship between the two systems prevents a relative age relationship from being established.

3.2.2 System 2: Xmukane Corona and System 15

System 2 is centred both at the westernmost boundary of the study area and on Xmukane Corona (Fig. 3.16). The system includes a minimum of 223 graben as only the portion of the system within the study area was mapped. Graben can be found up to 240 km from the centre and only interacts with radiating system 15. System 15 is a small dominantly fanning set of graben found on the border of Xmukane Corona particularly at the southern portion of the rim. Graben from System 2 are cross-cut in over ten places indicating that graben of System 15 are younger than those of System 2 (Fig. 3.16).

Figure 3.15: Mapping of System 1 (orange lines) and nearby systems represented by lines in shades of black, grey and white. (A) The cross-cutting relationship between system 1 (orange lines) and system 3 (white lines) indicating that System 1 is older. (B) The cross-cutting relationships between system 1 (orange lines) and system 11 (white lines) indicating that System 1 is older. Lines are overlain on Magellan SAR images.

Figure 3.16: (1) Mapping of radiating graben-fissure System 2 (orange lines) and System 15 (blue lines). (A) The cross-cutting relationships between System 2 and System 15 indicating that System 2 is older. Lines are overlain on Magellan SAR images and centres are indicated by labeled black dots.

Figure 3.17: (1) Mapping of radiating graben-fissure Systems 3 (orange lines) and 6 (blue lines). Other nearby systems are represented by lines in shades of black, grey and white. (A and B) Cross-cutting relationships between Systems 3 and 6 indicating that System 6 is older. Lines are overlain on Magellan SAR images.

3.2.3 System 3: Kapenopfu Corona (271°E, 21°S) and System 6 (277°E, 19.5°S)

Radiating graben-fissure System 3 is located at the northwestern corner of the Mielikki Mons study area and centred on Kapenopfu Corona. With a diameter of 200 km, the Kapenopfu Corona hosts one of the largest radiating systems in the study area (Fig. 3.17). A total of 1649 graben are counted and are distributed up to 870 km away from the centre. Though System 3 is located near six other radiating systems (1, 2, 4, 5, 6 and 7), it only intersects systems 1, 5 and 6. As previously demonstrated in Fig. 3.15, System 1 is older than System 3. System 5 is located 1015 km to the southeast of System 3 and is centred on the eastern rim of the Gertjon Corona. Of the 16 instances where Systems 3 and 5 intersect, inconsistent cross-cutting relationships do not yield a relative age. System 6 is located in the northern portion of the study area, approximately 600 km northeast of System 3 and almost 1000 km north of Mielikki Mons. System 6 is a relatively small radiating system that includes 203 mapped graben spanning up to 270 km from the centre (Fig. 3.17). System 6 is intersected by System 3 in a number of places, indicating that system 6 is older than system 3.

3.2.4 System 4: Mielikki Mons (280°E, 27°S) and linear Systems 18 and 23

Located in the centre of the study area, Mielikki Mons is a pancake-shaped topographic high with a diameter of 450 km. The topographic high coincides with the centre of a young area based on VIRTIS emissivity (Smreker et al. 2010). Centred on Mielikki Mons is System 4 which includes 390 mapped graben that extend up to 400 km away (Fig. 3.18). Linear Systems 18 and 23 frame the eastern and western flanks of Mielikki Mons, respectively. System 18 includes 83 graben with a maximum length of

Figure 3.18: Radiating graben-fissure System 4 (orange lines), linear Systems 23 (blue lines) and 18 (green lines). Other systems are represented by lines of various shades of grey and selected lava flows are delineated by purple regions. Mapping is overlain on Magellan SAR images.

275 km. System 23 is smaller in comparison to System 18, containing only 25 graben and extending up to 100 km long (Fig. 3.18).

System 4 intersects several local lobate lava flows, linear Systems 23 and 18, as well as radiating Systems 3 and 25. Local lobate lava flows are found following the edge of graben as well as completely filling other sections, indicating that the lava flows are younger (Fig. 3.18). Furthermore, in several other cases, the graben have been obscured by extensive lava flows indicating that effusive volcanism occurred after the emplacement of System 4. Cross-cutting relationships involving radiating Systems 3 and 25 and linear Systems 18 and 23 all prove to be inconclusive with respect to the relative age of System 4 due to a lack of contrast.

3.2.5 System 5 (278°E, 29°S)

Though not centred on a volcano-tectonic feature, System 5 is located on the rim of Gertjon Corona, which is part of Parga Chasma. System 5 is located approximately 350 km to the southwest of Mielikki Mons and includes 371 graben that up to 360 km from the centre (Fig. 3.19). Graben part of System 5 are fanning towards the northeast and are not found southwest of the centre.

System 5 intersects the northern portion of System 3, however, the lack of a clear cross-cutting relationships prevents the determination of a relative age. Local lava flows are found abundantly through System 5, particularly in its northeastern section. Cross-cutting relationships indicate that these lava flows are older than System 5 (Fig. 3.19).

3.2.6 System 7: Yunya-Mana Mons (286°E, 17°S)

System 7 is the largest radiating graben-fissure system and is located at the northeast corner of the study area. It is centred on Yunya-Mana Mons, which has a

Figure 3.19: (1) Radiating graben-fissure System 5 (orange lines) and other systems are represented in lines of various shades of grey. Selected lava flows are delineated by purple regions. (A) Cross-cutting relationship between System 5 and a lava flow emanating from Mielikki Mons indicating that System 5 is younger. Mapping is overlain on Magellan SAR images.

Figure 3.20: (1) Radiating graben-fissure System 7 (orange lines) and selected lava flows delineated by purple regions. Other, nearby radiating graben-fissure systems are represented by lines of various shades of grey. (A) Showing the relationship between a graben part of System 7 and local lava flows. I, II and IV display partially filled graben where the lava flows follow the trend of the graben and appear to be sourced from underlying dykes. Mapping is overlain on Magellan SAR images.

diameter of 500 km. The radiating system is located at the edge of the study area, and only the portion located within the study area was mapped. In this portion of the radiating pattern 880 graben were mapped (Fig. 3.20). Though System 7 is the most extensive system in the Mielikki Mons area, with graben extending up to 1120 km from Yunya-Mana Mons, it is an isolated system that does not intersect other radiating systems. Large lobate lava flows are abundant in the area and are clearly cross-cut by graben. Smaller local lava flows are found emanating from the graben themselves (Fig. 3.20).

3.2.7 System 8: Angerona Tholus (287°E, 29°S)

System 8 is an isolated radiating system located on the mid-eastern margin of the study area. The system is focused on Angerona Tholus, which has a diameter of 200 km. It includes 283 graben that are mapped up to 200 km from the centre (Fig. 3.21). Lava flows are abundant in the area, many of which are older than the radiating system itself (Fig. 3.21)

3.2.8 System 9 (285°E, 31°S)

System 9 is a very small radiating system that incorporates 44 graben extending in all directions (Fig. 3.22). The graben themselves are found no further than 40 km from the centre. Graben from System 9 are found cross-cutting system 10 as well as an undefined linear system to the north. According to the cross-cutting relationships radiating System 9 is younger than system 10 (Fig. 3.22).

3.2.9 System 10 (282°E, 32°S)

Radiating System 10 is located 275 km west of system 9. There are 458 graben mapped in the system extending 330 km from its centre (Fig. 3.23). Most of System 10

Figure 3.21: (1) Radiating graben-fissure System 8 (orange lines), selected lava flows are delineated by purple regions and other nearby systems represented by grey lines. (A) Cross-cutting relationships between System 8 and local lobate lava flows indicating that System 8 is younger.

Figure 3.22: (1) Radiating graben-fissure System 9 (orange lines) and nearby systems represented by lines of shades of grey. (A) The cross-cutting relationship between System 9 and System 10 (white lines) indicating that System 9 is younger. Mapping is overlain on Magellan SAR images.

Figure 3.23: (1) Radiating graben-fissure System 10 (orange lines) and surrounding systems represented by lines in various shades of grey. (A) Cross-cutting relationship between System 10 and System 20 (grey lines) indicating that System 10 is younger. Mapping is overlain on Magellan SAR images.

has been obscured by extensive lava flows, leaving only the northeastern quadrant of the suite exposed.

System 10 intersects Systems 9 (Fig. 3.22) and System 20 (Fig. 3.23). Cross-cutting relationships in both cases are conclusive and indicate that System 10 is older than System 9 and younger than System 20.

3.2.10 System 11: Obiemi Corona (276°E, 31°S) and linear System 21

Obiemi Corona is yet another corona along the Parga Chasma rift. It has a diameter of 300 km and is located just over 600 km southeast of Ts'an Nu Mons. Host to radiating system 11, the corona is irregularly shaped. System 11 involves 934 graben and is distributed up to 550 km in radius (Fig. 3.24). Graben have been overprinted by younger extensive lava flows and deformed by the emplacement of younger coronae. The majority of the graben from System 11 are found within the Parga Chasma rift system.

Interactions with other radiating systems are limited to System 1, which is associated with Ts'an Nu Mons, and System 21, a small linear system on the southern rim of the Obiemi Corona. Based on cross-cutting relationships (Fig. 3.24), System 11 is younger than System 1 and older than System 21.

Linear system 21 runs for approximately 200 km along southwestern flank of Obiemi Corona (Fig. 3.24). It includes 51 graben and have clearly cross-cut the lava flows which likely emanated from Obiemi Corona.

3.2.11 System 12: Santa Corona (288°E, 34°S)

Like System 10, System 12 is an isolated radiating system. It incorporates 416 graben, extending up to 180 km from the centre (Figs 3.25-1A and -1B). The system is centred on Santa Corona (200 km diameter), which is located near the south eastern

Figure 3.24: (1) Radiating graben-fissure System 11 (orange lines) and linear System 21 (blue lines). Other nearby radiating systems are represented by lines in shades of black, grey and white. Boxes A, B, and C, correspond to the approximate areas for: (A) The cross-cutting relationships between System 11 and 1 (black lines) indicating that System 11 is younger. (B) The cross cutting-relationships between System 11 and 21 indicating that system 21 is younger. (C) The cross-cutting relationships between System 11 and System 17 (white lines) indicating that System 17 is younger. Mapping is overlain on Magellan SAR images.

Figure 3.25: (1-A) Radiating graben-fissure System 12 (orange lines) and nearby radiating systems represented by grey lines. (2-A). Radiating graben-fissure System 13 (orange lines) and nearby radiating systems represented by grey lines. (1, 2-B) Uninterpreted Magellan images. Mapping is overlain on Magellan SAR images.

border of the study area. Santa Corona is part of the northwest-southeast oriented Parga Chasma trend and appears to be the source of several lobate lava flows located on the far northeast extent of the radiating system.

3.2.12 System 13: Mertseger Mons (270°E, 38°S)

System 13 is located in the southwestern corner of the study area. It includes at least 351 graben, as only graben within the study area are mapped, then the accounted for (Fig. 3.25-2A and -2B). Centred on Mertseger Mons, which is a large volcano-tectonic feature with a diameter of 450 km, graben are found extending up to 500 km from the centre dominantly towards the south east along an exposed area spared of volcanic flooding. In contrast, regions towards the north and east have been extensively flooded.

3.2.13 System 14: Shulamite Corona (285°E, 38°S)

Like System 12, System 14 is an isolated radiating system. It is centred on Shulamite Corona which has a diameter of 275 km and is located in the southeastern corner of the study area and at the southern end of the Parga Chasma trend. Radiating System 14 includes 203 graben that are found up to 310 km from the centre (Fig. 3.26).

3.2.14 System 16 (285°E, 33°S)

The asymmetrical radiating graben-fissure system includes 191 graben and is located just off the eastern edge of the Parga Chasma rift system (Fig. 3.26). Graben are observed a maximum of 250 km from the inferred centre with the longest portion extending north towards System 9. While System 16 does intersect System 9, a relative age cannot be determined because of ambiguous cross-cutting relationships.

Figure 3.26: (1) Radiating graben-fissure System 14 (orange lines). (2) Radiating graben-fissure System 16 (orange lines) and nearby systems represented by lines in shades of grey. (3) Radiating graben-fissure System 17 (orange lines) and nearby systems represented by lines in shades of grey. Mapping is overlain on Magellan SAR images.

3.2.15 System 17: Rigatona Corona (280° E, 33° S)

The Rigatona Corona is located along the Parga Chasma trend southeast of Obiemi Corona. On the southeastern margin of Rigatona Corona is the centre of radiating system 17 which host 389 graben measured up to 365 km from the centre (Fig. 3.26). Though radiating graben-fissure System 17 is located within the Paraga Chasma, it only intersects System 11 and based on cross-cutting relationships described in Section 3.2.10, System 17 is younger than System 11 (Fig. 3.24).

3.2.16 System 19 (288° E, 32° S)

System 19 is the second smallest radiating graben-fissure system in the Mielikki Mons study area (Figure 3.27). The isolated system includes 43 graben which are found a maximum of 65 km from the inferred centre.

3.2.17 System 20: Anjea Corona (283° E, 29° S)

The 261 graben of System 20, centred on Anjea Corona, radiate in an asymmetric form, dominantly towards the southeast (Figure 3.27). In the southeastern direction, graben are measured up to 330 km from the centre, while graben extending in other directions are found at maximum distances of less than 100 km from the centre.

Radiating System 20 interacts with systems 7 and 10; however, the only cross-cutting relationships with system 10 are conclusive, indicating that system 20 is younger.

3.2.18 System 22: Unnamed Patera (280° E, 37° S)

Isolated system 22, focused on an unnamed Patera located just outside of the Parga Chasma trend, is 450 km south of System 17 (Rigatona Corona) and 435 km northwest of System 14 (Shulamite Corona). System 22 includes 210 graben radiating primarily towards the north and south with a maximum radius of 200 km (Fig. 3.28).

Figure 3.27: (1) Radiating graben-fissure System 19 (orange lines). (2) Radiating graben-fissure System 20 (orange lines) and other nearby system represented by grey lines. Mapping is overlain on Magellan SAR images.

3.2.19 System 25: (278° E, 24° S)

System 25 is located approximately 475 km northwest of System 4 (Mielikki Mons) and includes 381 graben that can be found up to 440 km from the inferred centre (Fig. 3.28). Located in an area of regional plains 1 map unit, the system is not centred around a visible volcano-tectonic feature. System 25 intersects System 3 and System 4. In each case, the cross-cutting relationships are ambiguous and as a result, no relative age for Systems 3 and 4 with respect to System 25 can be determined.

Figure 3.28: (1) Radiating graben-fissure System 22 (orange lines). (2) Radiating System 25 (orange lines) and other nearby systems are represented by various shades of grey lines. Mapping is overlain on Magellan SAR images.

4 Chapter: Pit crater chains

4.1 Regional associations and distributions of pit crater chains

The Idunn Mons study area, Themis Regio, Ulfrun Regio and Ganiki Planitia display various degrees of pit crater chain abundance. The characteristics of pit crater chains including their average length, morphology and structural associations are summarized in Table 4.1. The associations between map units defined by Grosfils et al. (2011) and pit crater chains are examined for those in Ganiki Planitia, which are presented in Figure 4.1.5. In order to assess whether the pit chain clustering observed is statistically significant, an average nearest neighbour statistical test is conducted for each area independently. Table 4.2 summarizes the results and shows that pit crater chains are clustered with 99.9% confidence.

Pit crater chains in the Idunn Mons area are found clustered with an average nearest neighbor index of 0.46 comprising the lowest density of pit crater chains in any given area (of this thesis) with $5.5 \cdot 10^{-6}$ pit crater chains per square kilometer (Fig. 4.1). The 42 pit crater chains have varied morphologies: isolated (16), contiguous (11), coalescing (8), trough-shaped (3) and other morphologies (4). Fourteen (33%) of pit crater chains are superimposed on graben. Nearly all (12 of 14) pit crater chains located along graben are associated with the graben-fissure System 3 which is centred on Idunn Mons. In fact, the graben-fissure systems radiating from Idunn Mons host the majority of pit crater chains (24 or 57%). The remaining 2 pit crater chains found along graben are not associated with any radiating system. Similar to the other study areas, although pit crater chains are not always directly found superimposed on graben, they are most often found aligned parallel or sub-parallel to graben.

Though clustering is present in Themis Regio, it is weak and not visually apparent as reflected in a higher value (0.6) for the nearest neighbour index compared to the other areas in this study (Fig 4.2). With 63 pit crater chains in total, the study area hosts the highest density of pit crater chains at $1.1 \cdot 10^{-5}$ pit crater chains per square kilometer. The average pit crater chain has a length of 8.2 km and contains 7 pits. Seven radiating graben-fissure systems and 2 corona are host to pit crater chains involving 32 (51%) of pit crater chains in the area. Of this set, approximately half are located directly along graben and half are found aligned parallel or sub-parallel to graben.

In Ulfrun Regio a total of 156 pit crater chains are found clustered with an average nearest neighbor index of 0.4 and a density of $1.43 \cdot 10^{-5}$ pit crater chains per square kilometer (Fig 4.3). The average pit crater chain is 6.5 km long and contains 5 pits, most often with a coalescing or contiguous pit style. Mapping in this area completed by Studd et al. (2011) reveals 66 radiating graben-fissure systems. Sixteen of these mapped graben-fissure systems host 74 pit crater chains, 52% of all pit crater chains found in Ulfrun Regio. A total of 73 pit crater chains are found independent of radiating systems or corona, 48% of all pit crater chains mapped in Ulfrun Regio. Twenty-nine of these pit crater chains are found along graben and 45 are found as independent structures. In all, 70% of pit crater chains are either located directly along or parallel to graben, and half of all pit crater chains are located directly along graben.

Pit crater chains in Ganiki Planitia are clustered with an average nearest neighbour index of 0.42 and a density of $1.43 \cdot 10^{-5}$ pit crater chains per square kilometer (Fig. 4.4). These pit crater chains commonly exhibit a distinct coalescing or contiguous morphology accounting for 56% or 53 pit chains out of a total of 93. The remaining 44% of pit chains

either exhibit spacing between individual pits (25%) or some combination of isolated, coalescing or contiguous pits (19%). Superimposition of pit crater chains on graben is uncommon, occurring only 17 times (19%). In these cases, 2 are found along circumscribing graben which are part of Qakma Corona, 1 is found proximal to the southeastern radiating graben-fissure system but along an unrelated graben, the remaining 14 are located northwest of the central radiating graben-fissure system, centred on Xtoh Mons, in association with local graben. Though the majority (81%) of pit crater chains are not located directly along an extensional graben, many pit crater chains are found aligned parallel or sub-parallel to regional or local extensional trends.

The diverse assembly of map units in Ganiki Planitia provide an opportunity to study the distribution of pit crater chains in different geological circumstances. When analyzed relative to material units mapped by Grosfils et al. (2011), pit crater chains are found in many different units including tesserae, regional and local plains units as well as local volcanic edifice flows and corona rims (Fig. 4.5). The only units that do not host a pit crater chain are impact-related. The primary host map units are regional plains-2 (pr2), shield plains (ps) and lineated plains (pl). The most extensive unit, pr2, occupies many of the lower elevations, covers 40.6% of Ganiki Planitia, and is interpreted as a relatively thin, low viscosity volcanic deposit. Both the shield plains and lineated plains are less extensive, covering 8.4% and 5.1% of Ganiki Planitia, respectively (Davey et al. 2012). Figure 4.5 does not provide evidence of map unit control in the distribution of pit crater chains in Ganiki Planitia.

Table 4.1: Characteristics of pit crater chains in Ganiki Planitia, Themis Regio, Ulfrun Regio and the Idunn Mons study area.

	Ganiki Planitia	Ulfrun Regio	Themis Regio	Idunn Mons Area
Topographic rise as defined by Stofan et al. (1995)	N/A	Adjacent to a rift dominated region (Atla Regio)	Corona Dominated	Volcano Dominated
Total number of pit crater chains	93	156	63	42
Maximum pit count	12	41	51	12
Average pit count	3.6	4.6	6.3	4.7
Maximum pit chain length (km)	17.8	46	57.8	46.1
Average pit chain length (km)	3.25	6.6	8.3	3.5
Association with radiating graben-fissure system	6 (6.5%)	73 (46.8 %)	25 (39%)	24 (57.1%)
Association with circumscribing graben on corona	12 (12.85%)	9 (5.8%)	7 (12%)	0
Association with independent structure (neither a radiating graben-fissure system or corona)	12 (12.85%)	29 (18.6%)	9 (14%)	2 (4.8%)
Not in association with any visible structure	63 (67.8%)	45 (28.8%)	22 (39%)	16 (38.1%)

Table 4.2 The average nearest neighbor's statistical test and student's t-test.

	Ganiki Planitia	Ulfrun Regio	Themis Regio	Idunn Mons Area
<i>Known Values</i>				
Number of pit crater chains	93	156	63	42
Area, km ²	$6.49 \cdot 10^6$	$1.09 \cdot 10^7$	$5.71 \cdot 10^6$	$7.59 \cdot 10^6$
<i>Calculated Values</i>				
Density (pit crater chains/km ²)	$1.43 \cdot 10^{-5}$	$1.43 \cdot 10^{-5}$	$1.10 \cdot 10^{-5}$	$5.53 \cdot 10^{-6}$
Observed average distance, km ¹	55.5	52.9	93.7	98.5
Expected average distance, km	132.1	132.2	150.5	212.6
Standard error	7.2	5.5	9.9	17.2
<i>Results</i>				
Nearest Neighbour Index, R	0.42	0.40	0.6	0.46
z-score	-10.7	-14.3	-2.7	-6.7
<i>Standards used for a two- tailed student's t- test</i>				
p-value	0.001	0.001	0.001	0.001
Confidence Interval %	99.9	99.9	99.9	99.9
Critical value for t-test	-3.29	-3.29	-3.29	-3.29
Critical value for R	0.82	0.88	0.79	0.74

Figure 4.1: Distribution of pit crater chains in the Idunn Mons area. Radiating graben-fissure Systems 1, 2 and 3 are centred on Idunn Mons. Boxes delineate the three clusters found in association with radiating graben-fissure systems emanating from Idunn Mons.

Figure 4.2: Distribution of pit crater chains in Themis Regio. Radiating graben-fissure systems in shades of grey are associated with pit crater chains. Radiating graben-fissure systems in colour are discussed in the following section.

Figure 4.3: Distribution of pit crater chains in Ulfrun Regio. Radiating graben-fissure systems present are associated with pit crater chains. Box 1 delineates the area discussed in section 4.2.3.1. Box 2 delineates the area discussed in section 4.2.3.2. Box 3 delineates the area discussed in section 4.2.3.3.

Figure 4.4: Distribution of pit crater chains in Ganiki Planitia. Black lines are radiating graben-fissure systems. Box 1 delineates the extent of Qakma Corona discussed in section 4.2.4.1 Box 2 delineates the area discussed in section 4.2.4.2. Box 3 delineates the area discussed in section 4.2.4.3.

Figure 4.5: The number of pit crater chains in their host map units in Ganiki Planitia. Percentages above each map unit denote the total area of Ganiki Planitia covered by each unit. Map units: regional plains-2 (pr2), shield plains (ps), lineated plains (pl), volcano edifice flows (fe), Lahevhev lineated plains (pLl), tessera (t), regional plains-1 (pr1) and Lahevhev hummocky plains (pLh). The normalized values were reduced by a factor of 10 for easier comparison to original data.

4.2 Local associations and distributions of pit crater chains

Here, the characteristics and distributions of individual clusters are examined in detail. In general, clusters are focused associated with local or regional extensional events such as tectono-magmatic features, including radiating graben-fissure systems or corona. Like in the regional analyses of pit crater chains in chapter 4.1, the distribution of pit crater chains within an individual cluster is assessed using the nearest neighbor statistical test. The motivation for conducting nearest neighbor analyses of individual clusters focused on radiating graben-fissure systems is to gain an understanding of the degree of influence that extension has in forming pit crater chains. If extension is the limiting and primary mechanism, then we would expect to see pit crater chains randomly distributed within every radiating system. If pit crater chains are clustered, this would indicate that another variable plays at least an equally important role in the formation of pit crater chains. Table 4.3 summarizes the results and shows that pit crater chains within individual clusters may exhibit a random or clustered distribution. The term hierarchical clustering is applied when the distribution of pit crater chains within a regionally-identified cluster is also clustered itself.

4.2.1 Idunn Mons Area

The 24 pit crater chains found in association with radiating graben-fissure System 3, centred on Idunn Mons, are clustered into three individual groups. Each cluster differs in regards to their map unit associations and densities (Fig. 4.6). Cluster 1 includes 15 pit crater chains all of which are located within Parga Chasma. As the densest cluster surrounding Idunn Mons, it is hosted within rift zone and shield plains material. Located approximately 500 km east of cluster 1, cluster 2 includes 5 pit crater chains hosted

Table 4.3 The average nearest neighbours statistical test for selected clusters in Themis Regio, Ulfrun Regio, Ganiki Planitia and Idunn Mons area

	Themis Regio			Ulfrun Regio			Ganiki Planitia		Idunn Mons
	Ts'an Nu Mons	Shulamite Corona	Obiemi Corona	Ozza Mons	Perchata Corona	Qakma Corona	Area B		
Number of pit crater chains	11	5	7	18	19	16	57	25	
Area, km2	37,630	92,980	98,500	1,120,000	58,000	16,500	347,000	630,000	
Calculated Values									
Density	$2.92 \cdot 10^{-4}$	$5.38 \cdot 10^{-5}$	$7.11 \cdot 10^{-5}$	$1.61 \cdot 10^{-5}$	$3.28 \cdot 10^{-4}$	$9.70 \cdot 10^{-4}$	$1.64 \cdot 10^{-4}$	$3.97 \cdot 10^{-5}$	
Observed Average Distance, km	13.27	102.24	84.09	52.14	16.15	11.17	21.22	32.60	
Expected average distance, km	29.24	68.18	59.31	124.72	27.63	16.06	39.01	79.37	
Standard error	4.61	15.94	11.72	15.37	3.31	2.10	2.70	8.30	
Results									
Nearest Neighbour Index, R	0.45	1.50	1.42	0.42	0.58	0.70	0.54	0.41	
z score	-3.47	2.14	2.11	-4.72	-3.46	-2.33	-6.59	-5.64	
Standards Used for a two tailed significance test									
p-value	0.001	0.001	0.001	0.001	0.001	0.05	0.001	0.001	
Confidence Interval %	99.90	99.90	99.90	99.90	99.9	95	99.9	99.9	
Critical value for t-test	-3.29	-3.29	-3.29	-3.29	-3.291	-1.96	-3.291	-3.291	
Critical value for R	0.52	1.76	1.65	0.66	0.605	0.736	0.783	0.678	
Conclusions									
	Reject H ₀ Clustered	Accept H ₀ Random	Accept H ₀ Random	Reject H ₀ Clustered	Reject H ₀ Clustered	Reject H ₀ Clustered	Reject H ₀ Clustered	Reject H ₀ Clustered

Figure 4.6: The three pit crater chain clusters surrounding Idunn Mons. (A) Pit crater chains and radiating graben-fissure systems overlain on a Magellan SAR image. (B) Pit crater chains and radiating graben-fissures systems overlain on geological map (Ivanov and Head, 2011)

within shield plains material. In contrast to cluster 1, only 2 of the pit chains are superimposed on graben associated with radiating System 3. The remaining three pit crater chains are located outside of the extent of the radiating systems but share a similar orientation. Cluster 3 includes 5 pit crater chains hosted in lobate plains and groove belts. All but one pit crater chain in this cluster are aligned with graben that form part of radiating System 3.

4.2.2 Themis Regio

4.2.2.1 Ts'an Nu Mons (272°E, 27°S)

The cluster focused on Ts'an Nu Mons is of interest because of its hierarchical clustering (clustering recognized from the regional scale and now at a local scale). Host to 10 pit crater chains and radiating graben-fissure System 1 (Fig. 4.7A), Ts'an Nu Mons is located in the northern area of Themis Regio within Olapa Chasma. Half of the pit crater chains are superimposed on graben of the radiating system and half are independent but are aligned parallel or sub-parallel to graben (Fig. 4.8). Of the pit crater chains associated with graben, 3 are contiguous, and 1 consists of spaced pits. Pit crater chains found independent of graben include 1 trough, 3 that are contiguous, and 1 that is coalescing,

While all pit crater chains are hosted in the rift zone map unit (Fig. 4.7B), the pit crater chains of Ts'an Nu Mons are primarily constrained to the northeastern quadrant of the radiating system. As an example of hierarchical clustering, the pit crater chains focused on Ts'an Nus Mons yield a nearest neighbor index of 0.45 (Table 4.3).

○ Pit crater chains — Graben (white lines on map)

Mapping by Ivanov and Head (2011)

pl Lobate plains TZ Rift zone

—●— Extensional lineaments

➞ Lobate flows and interpreted flow direction

Figure 4.7: Pit crater chains in the vicinity of Ts'an Nu Mons located at -27°S and 273°E . (A) The distribution of pit crater chains (white dots) associated with the radiating graben-fissure system (grey lines) emanating from Ts'an Nu Mons overlain on Magellan SAR image. Box 1 delineates the area examined in Figure 4.2.3. (B) The distribution of pit crater chains overlain on map units of Ts'an Nu Mons mapped by Ivanov and Head (2011).

Figure 4.8: Pit crater chain clusters in the vicinity of Ts'an Nu Mons located at 27°S and 273°E (A) Box 1 in Figure 4.7 delineating the areas corresponding to Boxes 1 and 2 of this figure. (1) Pit crater chains with contiguous and spaced morphologies parallel to graben. (2) Pit crater chains with spaced and contiguous morphologies along and parallel to graben.

Figure 4.9: Pit crater chains in the vicinity of Obiemi Corona located at 31° S and 276°E. (A) The distribution of pit crater chains associated with the radiating graben-fissure system (white dots, grey lines) emanating from Ts'an Nu Mons (System 11) and linear System 21 just south of the corona (black dots, black lines) are overlain on Magellan SAR image. Box 1 delineates the area examined in Figure 4.2.7. (B) The distribution of pit crater chains overlain on map units of Ts'an Nu Mons mapped by Ivanov and Head (2011).

4.2.2.2 Obiemi Corona (276°E, 31°S) and linear System 21

Obiemi corona hosts a cluster of 10 randomly distributed pit crater chains (Fig. 4.9A). Seven pit crater chains are associated with the radiating graben-fissure System 11, centred on Obiemi Corona, while 3 are found in association with a linear System 21 located on the southwestern margin of the corona (Section 3.2.10). Four pit chains are located along graben in association with radiating graben-fissure System 11, of which, 3 are troughs and 1 is contiguous (Fig 4.10). Pit crater chains that are found aligned either parallel or subparallel to System 11 graben display spaced, contiguous and trough varieties of pit crater chains. The 3 pit crater chains associated with linear System 21 display both trough and spaced morphologies. The pit crater chains with a spaced morphology is superimposed on a graben whereas the other two pit crater chains are independent (but oriented parallel) to structure.

Pit crater chains are hosted in rift zone (6), shield cluster (3) and shield plains (1) map units (Fig 4.9B). In this case the pit crater chains are distributed randomly throughout the area but are primarily hosted in the southern region of Obiemi Corona.

4.2.2.3 Shulamite Corona (285°E, 38°S)

Located at the southern margin of Themis Regio, Shulamite corona hosts a randomly distributed cluster of 5 pit crater chains with a nearest neighbor index of 1.42 (Table 4.3). With the exception of one, most pit crater chains display a coalescing morphology and are either oriented parallel or subparallel to graben that are part of radiating System 14. In this example, all pit crater chains are hosted within the rift zone map unit (Fig. 4.11).

Figure 4.10: Pit crater chain clusters in the vicinity of Obiemi Corona located at 31° S and 276° E.
 (1) The area delineated in Figure 4.2.4, showing radiating System 11 (grey lines) emanating from the centre of Obiemi Corona and linear System 21 (black lines) (A) Pit crater chains associated with linear System 21. (B) Pit crater chains associated with System 11.

Figure 4.11: Pit crater chain clusters in the vicinity of Shulamite Corona located at 39° S and 284° E. (A) Pit crater chains (white dots) and associated radiating graben-fissure System 14 (grey lines) overlain on Magellan SAR image. Box 1 delineates the area examined in Figure 4.2.9. (B) Pit crater chains (white dots) overlain on map from Ivanov and Head (2011).

4.2.3 Ulfrun Regio

4.2.3.1 Unnamed Corona at 25°N and 213°E

Located on the northern boundary of Ulfrun Regio is an unnamed corona with a circumscribing graben along its rim (Fig. 4.12A). The corona has been heavily overprinted by a younger smooth lava flow leaving only the topographically higher areas exposed and for this reason, an average nearest neighbor statistical test was not conducted. In this example, 9 pit crater chains are positioned along, and are aligned parallel and subparallel to the graben circumscribing the corona rim. It is these exposed regions, namely densely lineated plains, where we see circumscribing graben and associated pit crater chains. Five of the 9 pit crater chains have evolved into troughs and the remaining 4 exhibit contiguous, spaced and coalescing morphologies (Fig. 4.13). In one particular area near the boundary between the flooded area and local topographic high (densely lineated plains), pits are found clustered and lacking alignment (Fig. 4.12B).

4.2.3.2 Perchata Corona

A total of 19 pit crater chains are found in association with a radiating graben-fissure system centred on Perchata Chasma, previously mapped by Studd et al. (2011) (Fig. 4.14). With a density of $3.28 \cdot 10^{-4}$ pit crater chains per square kilometer and an average nearest neighbor index of 0.58, pit crater chains are clustered and confined to the southwestern quadrant of the radiating system. Of the 19 pit crater chains in this example, 7 are parallel to a graben but not clearly bounded by one. The pit chains tend to be short,

○ pit crater chains — graben (white lines on map)

Mapping by Ivanov and Head (2011)

pl lobate plains material **rz** rift zone **rp** regional plains 1, lower unit **psh** shield plains material

Figure 4.12: Pit crater chains found in association with a corona in the northern area of Ulfrun Regio located at 25°N and 213°E corresponding to Box 1 Figure 4.3. (A) Circumferential graben and pit crater chains (white lines and dots) overlain on Magellan SAR image. (B) Pit crater chains overlain on geological map produced by Ivanov and Head (2011).

Figure 4.13: Pit crater chains found in association with a corona in the northern area of Ulfrun Regio located at 25°N and 213°E overlain on Magellan SAR images. (1) corresponding to Box 1 Figure 4.12. (A) Coalescing and contiguous styles of pit crater chains on the southwestern rim of the corona (B) A cluster of pits that are not aligned (C) Trough, spaced and contiguous pit crater chains on the eastern rim of the corona.

Figure 4.14: Pit crater chains in the vicinity of Perchata Corona, Ulfrun Regio located at 20°N 232°E corresponding to Box 2 Figure 4.3 (A) Radiating graben-fissure system and pit crater chains (white lines and dots) overlain on Magellan SAR image (B) Pit crater chains overlain on geological map of Venus by Ivanov and Head (2011).

Figure 4.15: Radiating graben-fissure System centred on Perchata Corona and pit crater chains (white lines and dots) overlain on Magellan SAR image located at 20°N 232°E (1) Corresponding to Box 1 Figure 4.14. (A) Coalescing and contiguous pit crater chains. (B) Trough and coalescing pit crater chains.

comprised of two to three wide, flat-bottomed pits (Fig. 4.15). Two pit crater chains are classified as troughs but display serrated edges.

4.2.3.3 Ozza Mons and System 58

Similar to the Obiemi Corona example located in Themis Regio, Pit crater chains are clustered in an area dominated by two extensional events, radiating graben-fissure System 47, which emanates from Ozza Mons and an older fanning system to the southeast, labeled System 58 by Studd et al. (2011) (Fig. 4.16). Both radiating systems are host to clusters of pit crater chains. The average nearest neighbor index for those associated with Ozza Mons and its radiating system is 0.42. System 47, centred on Ozza Mons, is the largest radiating graben-fissure system in Ulfrun Regio based on extent, having a maximum radius of 1985 km and including 1508 graben. Small and less extensive, System 58 has a maximum radius of 805 km and includes 947 graben. While the radiating systems are not similar in size or extent, they are both host to clusters of pit crater chains.

Based on cross cutting relationships between graben as well as lava flows, System 58 was emplaced first, followed by a regional flooding event which essentially overprinted the central portion of System 58's radiating pattern (Studd et al, 2011). Sometime following the flooding event 47 was emplaced and pit crater chains formed. Fig. 4.17 demonstrates the relationship between pit crater chains and System 47. In the southern smaller cluster, though pit crater chains are located closest to graben of System 47 they are aligned with graben from System 58.

Figure 4.16: Pit crater chains and radiating graben-fissure systems in the vicinity of Ozza Mons, Ulfrun Regio located at 4.5° N 201° E corresponding to Box 3 of Figure 4.3. Radiating graben-fissure System 47 (white lines) emanates from the centre of Ozza Mons (delineated by Box 1). Pit crater chains associated with System 47 are marked by white dots. The interacting radiating graben-fissure System 58 and associated pit crater chains are marked by black symbols (lines and dots).

Figure 4.17: Pit crater chains and radiating graben-fissure systems in the vicinity of Ozza Mons, Ulfrun Regio located at 4.5° N 201° E corresponding to box 2 of Figure 4.16. (1) Large pit crater chains (white dots) on the caldera margin of Ozza Mons and associated radiating graben-fissure System 47 (white). (2) Pit crater chains (black dots) associated with System 58 (black lines) located in an area dominated by radiating System 47 (white lines). The black dotted line indicates the boundary of a lava flow that obscured (and is younger than) System 58.

Figure 4.18: Radiating graben-fissure System 15 as mapped by Studd et al (2011). (A) System 15 (white lines) overlain on Magellan SAR images. (B) System 15 overlain on geological map of Ivanov and Head (2011).

4.2.3.4 Radiating graben-fissure system unoccupied by pit crater chains

The relation between radiating graben-fissure systems and pit crater chains is important but it is also significant that radiating graben-fissure systems can exist without the formation of a single pit crater chain. Fig. 4.18, shows a radiating graben-fissure system mapped by Studd et al. (2011) that does not host pit crater chains. Though void of pit chains, still present are shield plains, rift zone and densely lineated plains map units which are common hosts of pit crater chains in other areas.

4.2.4 Ganiki Planitia

4.2.4.1 Qakma Corona

Covering an area of 20,046 km², Qakma Corona hosts a cluster of 12 pit crater chains (Fig. 4.19). With an average nearest neighbor index of 0.7, it is the least clustered example presented in section 4.2 and the only example of a cluster focused on a volcano-tectonic feature in Ganiki Planitia. Pit crater chains are found in shield plains and densely lineated plains material that circumscribe the corona. In some cases they occur along graben, but in other cases they are independent of graben (Fig. 4.20).

4.2.4.2 Xtoh Mons

A cluster of 29 pit crater chains is distributed over an area of 78,400 km² which is located between the periphery of a radiating graben-fissure system focused on Xtoh Mons and a zone of multiple generations of regional extension (Fig. 4.21). Pit crater chains are found aligned parallel to regional extensional lineaments where approximately half are located directly along a graben and others are located parallel to sub parallel to nearby

Figure 4.19: Pit crater chains in the vicinity of the Qakma Corona corresponding to Box 2 of Figure 4.4 Qakma corona is located at 36°N and 207°E. (A) Graben and pit crater chains (white lines and dots) overlain on Magellan SAR image. (B) Pit crater chains overlain on geological map of Venus of Ivanov and Head (2011).

Figure 4.20: Pit crater chains in the vicinity of the Qakma Corona is located at 36°N and 207°E overlain on Magellan SAR images. (1) Graben and pit crater chains (white lines and dots) in the area corresponding to Box 1 of Figure 4.19. (A) Pit crater chains circumscribing Qakma Corona with a contiguous and spaced morphology. (B) Pit crater chains circumscribing Qakma Corona with contiguous and trough morphologies.

Figure 4.21: Pit crater chains north of Xtoh Mons corresponding to Box 3 of Figure 4.4 Xtoh Mons is located at 39°N and 194°E. (A) Graben and pit crater chains (white lines and dots) overlain on Magellan SAR image. Box 1 delineates the area shown in Figure 4.19. (B) Pit crater chains overlain on geological map of Venus of Ivanov and Head (2011).

Figure 4.22. Pit crater chains north of Xtoh Mons located at 39°N and 194°E overlain on Magellan SAR images. (1) Graben and pit crater chains (white lines and dots) in the area corresponding to Box 1 of Figure 4.2.18. (A) Pit crater chains along graben with trough, coalescing and contiguous morphologies. (B) Pit crater chains parallel and sub-parallel to graben with coalescing and contiguous morphologies.

graben (Fig. 4.22). Shield plains, regional plains 2, ridged plains and tessera all host the pit crater chains.

4.2.4.3 Association with regional structures

The southernmost cluster in Ganiki Planitia spans 760,858 km² and includes 26 pit crater chains with an average nearest neighbor index of 0.54 (Figure 4.23). The area is cross cut by 6 independent sets of extensional graben, recognized based on their distinct orientations. Set 1, oriented NW-SE, is the most extensive. Pit crater chains are found aligned parallel or sub-parallel to sets 1 and 3; none are found directly on extensional graben in this particular area (Figure 4.22 and 4.23). This example shows that, in a complex area, pit crater chains can have a preferred orientation, parallel to certain extensional sets and unrelated to other sets (Figure 4.23).

Graben sets — 1 — 2 — 3 — 4 — 5 — 6

ps	smooth plains material	rp	regional plains 1, lower unit	gb	groove belt
rz	rift zone	psh	shield plains material	pr	ridged plains
rp	regional plains 2, upper unit	pdl	densely lineated plains	T	Tessera

Figure 4.23: The six graben sets and their spatial relation to pit crater chains corresponding to Figure 4.4 Box 3 spanning 30°N to 25.5°N and 185°E and 194°E. (A) The 6 extensional sets 1 (red), 2 (orange), 3 (yellow), 4 (green), 5 (blue), and 6 (violet) and pit crater chains (white dots) overlain on Magellan SAR image. (B) Pit crater chains (white dots) overlain on geological map of Ivanov and Head (2011).

Figure 4.24: The six extensional lineament sets 1 (red), 2 (orange), 3 (yellow), 4 (green), 5 (blue), and 6 (violet) and their spatial relation to pit crater chains overlain on Magellan SAR images corresponding to Figure 4.23 Box 1. (A) Pit crater chains with contiguous morphology along set 1. (B) Pit crater chains with spaced morphologies

Figure 4.25: Structures corresponding to those presented in Figure 4.23. (A) The orientation of pit crater chains. (B) The orientation of the 6 graben sets (C) Orientation of graben sets 2 to 6 zoomed in from C. The letter “n” refers to the percentage of graben found in a specific set out of a possible total of 148 graben.

5 Chapter: Discussion

5.1 Radiating graben-fissure systems

5.1.1 Idunn Mons study area

5.1.1.1 Synthesis of chronology and regional trends of radiating graben-fissure systems

Here, a synthesis of the chronology and regional characteristics of graben-fissure systems in the Idunn Mons study area is discussed. The majority of the systems in the Idunn Mons study area are distributed along a diagonal trend from the northwestern corner to the southeastern corner (Fig. 3.1). The Idunn Mons volcano is located at the midpoint of the trend, and includes 11 radiating systems, 1 linear system as well as Olapa Chasma. Systems 10 and 11 are the only two systems in the study area that are not located within the diagonal trend. It is not clear whether this configuration of radiating systems is a genuine regional trend or a geometric artifact observed because of examining a small, focused study area. Continued mapping in the areas surrounding Idunn Mons will help to address this uncertainty.

Fig. 3.3 displays all the radiating systems in the Idunn Mons study area. Though it is evident that a majority of systems interact (with the exception of system 10 and 11), they do not necessarily reveal clear cross-cutting relations such that unambiguous age relationships can be established. Fig. 5.1 displays relative ages of the radiating systems based on cross-cutting relationships.

Systems dated using cross-cutting relationships include 1, 2, 3, and 12. Radiating systems 1, 2 and 3 display the most discernible cross-cutting relationships as these three systems are found consistently interacting with each other. Linear System 12 only

Figure 5.1: The relative ages of radiating systems located in the Idunn Mons study area. (A) The relative ages for each radiating system is based on cross-cutting relationships between graben established in section 3.1. (B) The relation ages for each radiating system with respect to cross-cutting relationships between radiating systems and map units of Ivanov and Head (2011) established in this section. The vertical dotted line represents the timing of Olapa Chasma. The horizontal dashed line connected to System 12 indicates an unknown maximum age.

interacts with System 3. This interaction indicates that linear System 12 is older than System 3 but because linear System 12 does not intersect with System 1 or 2, a relative lower constraint on age cannot be determined.

Systems 5, 6, 7, 8, 9, 10 and 11 are not represented in Figure 5.1 A for two reasons; (1) the systems are isolated from surrounding systems or (2) the interactions that are observed are not consistent enough to establish a relative chronology.

5.1.1.2 Radiating graben-fissure systems in relation to surface geology

A second approach as a method of determining the relative ages of radiating systems is by integrating surface geology into the timeline. Mapped by Ivanov and Head (2011), the global geological map of Venus is used to analyze the relative ages of radiating systems with respect to stratigraphy (Fig. 5.2). Relative ages of graben-fissure systems with respect to map units are presented in Figure 5.1B.

The most common and consistent stratigraphic relationships between radiating systems and surface geology involve the map units: lobate plains material (pl), groove belts (gb), regional plains 1 (rp₁) and shield plains (psh). Other, less extensive map units found in the area include rift zone (rf), regional plains 2 (rp₂), ridged plains and densely lineated plains (pdl); stratigraphic relationships between these map units and radiating graben-fissure systems are not as consistent or obvious because of their relatively low abundance. Crater material is also found distributed throughout the area but is not useful to stratigraphic analyses as these impact events are random and unrelated to intrusive volcanism. A full description of each map unit can be found in section 2.5.

In many instances radiating systems are found in association with rift zone and groove belt map units. As discussed by Ernst et al. (2003), because rift zone and groove

Figure 5.2. The surface geology of Idunn Mons (Ivanov and Head, 2011). Radiating centres are labeled and indicated by black dots.

belt units are defined by the presence of structures like graben and fractures, the association with radiating graben-fissure systems is inevitable. Four different systems, including 2, 3, 4 and 10, are found in association with groove belts while only System 3 is part of a rift zone. Groove belt units are found at markedly different positions in the stratigraphy. Based on contacts between neighbouring units, it is apparent that Systems 4 (Fig. 5.3) and 10 are part of groove belts older than the regional plains 1 and shield plains unit. In contrast, Systems 2 and 3 are clearly carving through this regional plains 1, indicating that groove belts associated with Systems 2 and 3 are younger than the regional plains 1 unit (Fig. 5.4).

Lobate plains materials (pl) are found in association with System 1, 2, 3, and 6, and in most cases lobate plains are sourced from the magmatic events that produced the radiating systems (Fig. 5.4 and 5.5). In other words, lobate plains are consistently some of the youngest units in the area but can be found to be contemporaneous with radiating graben-fissure systems or older.

Regional plains 1 and shield plains material were formed both before and after the radiating systems. Systems 1, 2, 3, 5, 6, and 12 are younger than these units, while Systems 4, 7, 8, 9, 10, and 11 are older.

When amalgamated, the relative ages determined by comparing radiating systems amongst themselves and by associations with stratigraphy, result in a more complete chronology of volcanic activity (Fig. 5.1B). Systems 4, 7, 8, 9, 10, and 11 are determined to be the oldest systems in the area as they are partially filled by extensive lava flows associated with the regional plains 1 unit and, to a lesser extent, are overprinted by shield plains material (e.g. Fig 5.3). System 5 is younger than the regional plains 1 unit but is

Figure 5.3: Radiating System 4 in relation to local surface geology. (A) Radiating System 4 (red lines) overlain on geological map produced by Ivanov and Head (2011). The white box delineates the area focused in images B and C. (B) Radiating system 4 (red lines) overlain on Magellan SAR image. White dashed lines delineate a selected boundary between the groove belt (pink region in image A) and the shield plains material (sea foam green region in image A). (C) Uninterpreted Magellan SAR image.

Figure 5.4: Radiating System 3 in relation to surface geology. (A) Radiating System 3 (white lines) overlain on surface geology map (Ivanov and Head 2011). (B) Radiating System 3 in relation to synchronous groove belts (gb) and younger lobate plains (pl). (C) Radiating System 3 in relation to older shield plains (psh) and younger lobate plains (pl). (D) Radiating System 3 in relation to older regional plains 1 (rp₁) and younger lobate plains (pl).

Figure 5.5: Radiating system 6 in relation to local surface geology in the Idunn Mons study area. (A) Radiating system 6 (white lines) overlain on the geological map produced by Ivanov and Head (2011). The black box delineates the area focused in images B and C. **(B)** Radiating system 6 (white lines) overlain on Magellan SAR image. White dashed delineate the boundary between shield plains (sea foam green in image A) and regional plains 1 (cyan in image A). **(C)** Uninterpreted Magellan SAR image. Note that the graben are obscured by regional plains 1 just east of the contact outlined in image B.

Figure 5.6: Radiating graben-fissure System 5 in relation to local surface geology. (A) Radiating graben-fissure System 5 (red lines) overlain on the geological map of Venus (Ivanov and Head 2011). The white box delineates the area focused in images B and C. (B) Graben from radiating System 5 and a selected, approximate lava flow boundary (white dashed line) overlain on Magellan SAR image. (C) Uninterpreted Magellan SAR image.

partially filled by regional plains 2 (Fig 5.6), a unit that is generally older than regional plains 1 and younger than lobate plains and rift zones (Ivanov and Head, 2011). Radiating System 6 clearly cross-cuts regional plains units and, as demonstrated earlier, is younger than System 7. A minimum age for System 6 cannot be determined because it is not cross-cut by any other radiating systems. Systems 12, 1, 2 and 3 are the youngest systems in the study area and are focused on Idunn Mons. Clearly cutting through regional plains 1, Systems 12, 1, 2, and 3 are contemporaneous with lobate lava flows emanating from the volcanic centre (Idunn Mons).

In terms of the distribution of radiating systems based on relative age, no regional trends in distribution are observed. It is clear that amongst the radiating systems dated, those focused on Idunn Mons are young (Fig. 5.4).

5.1.2 Mielikki Mons study area

5.1.2.1 Synthesis of chronology and regional trends of radiating graben-fissure systems

Here, a synthesis of the relative chronology and regional trends of graben-fissure systems in the Mielikki Mons study area is presented. In similarity to the Idunn Mons study area, half of the systems are observed either proximal to, or part of an area of rifting. From Fig. 3.14, it is apparent that though the systems are extensive, not all systems intersect others thereby limiting the scope of a relative chronology based on cross-cutting relationships. In the case of Mielikki Mons study area, many of the systems are found in association with Parga Chasma. The Parga Chasma extends from the southwestern margin to the central-west edge of the study area and includes several

corona and large volcanoes. While the remaining area is not devoid of volcanic activity, the proximity and concentration of radiating systems is much higher near the rift zone.

Four independent groups of radiating systems are identified based on available cross-cutting relationships (Fig. 5.7). While these groups do not interact with one another, their timing with respect to Parga Chasma is determinable with the exception of Group 4. Group 1 involves a total of 6 radiating systems including 1, 3, 6, 11, 17 and 21. All but system 6 are directly associated with Parga Chasma. System 6 is located off the rift zone and heavily overprinted by the systems that are found in association with the rift zone indicating that System 6 is older. Group 2 involves system 2 radiating systems, 2 and 15. System 2, located at the western boundary of the study area is centred on Xmukane Corona and is part of the rift system. System 15 is a younger, small, fanning system that is located within Parga Chasma. Group 3 includes systems 5, 14 and 22. These are grouped together as they are clearly associated with Parga Chasma, but lack unambiguous cross-cutting relationships with other systems. Lastly, Group 4 involves a clear succession of radiating systems involving Systems 20, 10, and 9. The oldest system (20) in Group 4 is located farthest from the rift zone. The middle-aged system and oldest system (9 and 10) are located just north of System 20 and the Parga Chasma rift zone

Figure 5.7: Relative ages of systems located in the Mielikki Mons study area. (A) Relative ages based on cross-cutting relationships. (B) Relative age of radiating system 4 with respect to map units by Ivanov and Head (2011) and proximal graben-fissure systems. Dotted horizontal lines separate unrelated groups while the vertical dashed line represents the time when Parga Chasma developed.

5.1.2.2 Radiating graben-fissure systems in relation to surface geology

The relative ages of radiating systems in the Mielikki Mons area in comparison to surface geology are discussed here. As in Section 5.1.1.2, which examined the relationships of systems located in the Idunn Mons study area with respect to surface geology, the global geological map of Venus is utilized (Ivanov and Head, 2011).

Mapped units traversed by the radiating systems include shield plains (psh), regional plains 1 (rp₁), smooth plains (ps), shield clusters (sc), lobate plains (pl), rift zones (rz) and groove belts (gb). While a handful of these map units are found in consistent stratigraphic relationships with radiating systems, others are not. It is important to note that the stratigraphic however, cannot be fully correlated as the timing of formation of the Parga Chasma cannot be constrained and relationships available are limited to visible surface contacts. As a result, though it is clear that the lobate plains map units are younger, the stratigraphic position of less abundant units in relation to radiating systems is not as well constrained. Rift zone and groove belt map units are often defined by the radiating systems themselves. Lobate plains are often found partially flooding radiating systems indicating that they are younger or contemporaneous with the magmatic activity responsible for the formation of the radiating systems. Map units such as shield clusters and smooth plains are not well constrained as they are local materials and likely occur at multiple occasions during the evolution of the study area. Though the contacts between regional plains 1 and radiating systems are scarce, the few examples indicate that most radiating systems are younger.

Figure 5.8: The surface geology of Mielikki Mons (Ivanov and Head, 2011). Radiating centres are labeled and indicated by black dots.

5.1.3 Idunn Mons and Mielikki Mons and the VIRTIS emissivity anomaly

Smrekar et al. (2010) identified the Idunn Mons and Mielikki Mons study areas as hosts to high emissivity anomalies detected from data acquired by VIRTIS. The high emissivity anomalies are associated with lava flows centred on top of, or, on the flanks of volcanic rises. The anomalies are interpreted as the youngest volcanic activity within their respective areas (Smrekar et al. 2010). This study provides an independent assessment of the volcanic and magmatic activity in the Idunn Mons and Mielikki Mons study areas using radiating graben-fissure systems and cross-cutting relationships between intersecting systems and surface geology.

Idunn Mons is the volcano at the centre of a topographic rise and host to a notable emissivity anomaly located in Imdr Regio (Fig 5.10). As presented in Section 3.1, three radiating graben-fissure systems, one of which is associated with a small rift system (Olapa Chasma), are focused on Idunn Mons. Cross-cutting relationships presented in Section 3.1.1 are interpreted to be contemporaneous with the lava flows associated with the high emissivity anomalies. In the immediate area surrounding these radiating systems, 8 radiating graben-fissure systems are located and found to be older than the three radiating graben-fissure systems associated with the high emissivity anomaly.

In Themis Regio, one radiating graben-fissure system is centred on Mielikki Mons, the volcano at the focus of the second emissivity anomaly identified by Smrekar et al. (2010) (Fig 5.11). As in the case of the anomaly focused on Idunn Mons, the high emissivity anomaly focused on Mielikki Mons is associated with widespread lobate lava flows. While lava flows are found surrounding the volcano, only those on the eastern flank of Mielikki Mons are identified as high emissivity anomalies. In contrast to the

Idunn Mons study area, cross-cutting relationships between intersecting radiating graben-fissure systems do not yield a relative age. However, cross-cutting relationships between graben from System 7 and the high emissivity related lava flows indicate that the lava flows are older (Fig 5.12). As presented in Section 3.2.6, not only is radiating graben-fissure System 7 the largest system in the study area (focused on Yunya-Mana Mons), but is it also host to local and extensive lobate lava flows (Fig 5.9). Lava flows found in association with Yunya-Mana Mons are not identified by Smrekar et al. (2010) as high emissivity material. It is important to note that VIRTIS data are not yet wholly available to the scientific community. As such, the only VIRTIS data available to analyze are what have been published in scientific journals. Therefore, it is possible that Yanya-Mana Mons is host to an emissivity anomaly, but, has not been discussed or highlighted by present research. However, if these lava flows have not been identified by VIRTIS it suggests either a problem with the model or interpretation of the data. Perhaps high

Figure 5.9: On the left, VIRTIS emissivity anomalies (outlined) on Magellan image, with superimposed radiating graben-fissure systems (lines in shades of black, white and grey, the hatched area delineates Olapa Chasma). On the right, the VIRTIS emissivity anomaly uninterpreted (right). Base map from Smrekar et al. (2010).

Figure 5.10: Top: Radiating and linear graben-fissure systems (lines of black, grey and white) overlain on VIRTIS emissivity map from Smrekar et al. (2010). Box A delineates the area examined in Figure 5.12. Bottom: Uninterpreted VIRTIS emissivity map.

Figure 5.11: Cross-cutting relationships between far-reaching graben from System 7 (orange lines) and selected lava flows (purple regions) associated with high emissivity anomalies. Mapping is overlain on Magellan SAR images.

emissivity anomalies are not an indication of young lava flows but an indication of primary chemistry?

5.2 Pit crater chains

Confirmed by nearest neighbour pattern analyses and student's t-test, we find pit crater chains clustered in Ganiki Planitia, Ulfrun Regio, Themis Regio and Imdr Regio. Often focused on regional extensional graben, radiating graben-fissure systems, and corona, clustering in each area varies by intensity and density. The intensity is measured by the nearest neighbour index where strong clustering (0.4) is observed in Ganiki Planitia, Ulfrun Regio and Imdr Regio and comparatively weaker clustering (0.6) is observed in Themis Regio. Regions of high cluster density are observed in Ganiki Planitia and Ulfrun Regio whereas lower cluster densities are observed in Themis Regio and the Idunn Mons area. Details of the observed clustering, particularly regarding structural and or lithological preferences, provide insight into the origin of pit crater chains on Venus.

Examples from Ulfrun Regio, Themis Regio and the Idunn Mons area demonstrate a robust association between pit crater chains and extensional features. The extensional features are predominately part of graben-fissure systems as defined by Ernst et al. (2001). As graben-fissure systems are thought to be underlain by dykes radiating from a central magmatic body, these data provide firm support for the models in which pit crater chains on Venus are theorized to form in association with dyke injection (Okubo and Martel 1998) in which modes of origin may be akin to those observed in Hawaii (Fig. 2.6).

Ganiki Planitia, on the other hand, hosts pit crater chains in somewhat different settings. One cluster is associated with the circumferential graben-fissure system defining the rim of Qakma Corona, another is located in the presence of regional extensional features not part of any observed radiating graben-fissure system. In this latter example, pit crater chains do not overlie individual extensional graben but are offset from and aligned parallel or sub-parallel to them. A number of reasons may account for this offset including: (1) the associated extensional graben are too small to be detected by the SAR resolution; or (2) as in the Dead Sea case (Abelson et al., 2003), the extensional graben may be concealed. It is not clear whether the extensional system preference is due to degree of dilation or another regional strain-related variable. However, the origin of pit crater chains in the latter example may be similar to those found in Iceland (as discussed above).

It is significant that not all radiating graben-fissure systems host pit crater chains, which indicates that another factor besides extension associated with dyke injection control the distribution of pit crater chains (Fig. 4.18). The radiating systems of Perchata Corona and Ts'an Nu Mons have associated pit crater chain distributions which are clustered in only part of the radiating systems. In both cases, pit crater chains are located near the focal point of the radiating systems, but only in particular sectors (south west sector, and northern sectors, respectively). This localized distribution suggests an additional control on pit chain distribution, possibly lithology. However, the map units do not correlate spatially to the distribution of pit crater chain clusters (Fig. 4.5). On the other hand, the map units used here and elsewhere on Venus are mapped based on qualitative and quantitative surface aspects recognizable at the resolution of Magellan

images. Quantitative data used for interpretation of map units include elevation, radar backscatter, slope, surface emissivity and surface reflectivity (Grosfils et al. 2011). Qualitative aspects involve assessing geomorphological traits (lobate flows, for instance) and identifying common features within an area such as wrinkle ridges or shield volcanoes. It can, therefore, be hypothesized that the distribution of pit crater chains may be reflecting a lithological difference not captured by these mapped units. In the pit crater chains associated with the Dead Sea on Earth, buried salt layers were easily dissolved and collapsed to form pit chains that occurred above these localized areas of salt dissolution whose distribution does not correlate with any surface features (Abelson et al. 2003). Though lithologically different from the Dead Sea, clustering of pit crater chains on Venus may be due to a lithological control such as degree of welding or induration, unit thickness and any other factors that may control competency. However, these physical properties may be difficult to recognize as vulnerable layers may be buried, like in the case of the Dead Sea, or exposed at the surface but not interpretable using the available Magellan images.

6 Chapter: Conclusions

Detailed maps of radiating graben-fissure systems, covering an area of 8,891,279.5 km² have been produced for two areas of Venus focused on the VIRTIS emissivity anomalies identified by Smrekar et al. (2011) including Idunn Mons and Mielikki Mons. Often found in relation to graben-fissure systems, pit crater chains are mapped in 4 areas covering 30 690 000 km² including the Idunn Mons study area, Themis Regio, Ganiki Planitia, and Ulfrun Regio, in an effort to better understand these poorly documented surficial structures.

The Idunn Mons study area includes 8585 graben, 5790 of which are assigned to radiating or linear graben-fissure systems covering 4 249 567.5 km². In total, 1 linear and 11 radiating graben-fissure systems are mapped. Four radiating systems are found centred on various volcano-tectonic features including patera and mons. The remaining 6 radiating systems are not focused on any volcano-tectonic feature.

The radiating graben-fissure systems in the Idunn Mons study area are generally aligned in a northwest-southeast trend, however, no regional temporal conclusions are possible due to limited cross-cutting relationships. Three radiating graben-fissure systems are found centred on the VIRTIS emissivity anomaly identified by Smrekar et al. (2010). Using the cross-cutting relationships between radiating systems that are present, in addition to examining and comparing with the surficial geology mapped by Ivanov and Head (2011), we can establish that radiating graben-fissure systems focused on Idunn Mons are the youngest in the area.

The Mielikki Mons study area includes 18 126 graben, where 8703 graben are associated with radiating or linear graben-fissure systems. In total, 4 linear and 20

radiating systems are mapped and identified over an area of 4 641 712 km². Radiating systems are focused on a variety of volcano-tectonic features including 4 mons, 7 corona, 1 tholus and 1 patera. The remaining 6 radiating systems are not focused on a volcano-tectonic feature.

Using cross-cutting relationships between interacting graben, a relative chronology of radiating systems in the Mielikki Mons study area is established. The relative chronology of four independent groups, involving 14 systems, is determined and placed on a timeline relative to Parga Chasma. In summary, 2 systems are older than Parga Chasma, 7 systems are contemporaneous with Parga Chasma and 2 are younger than Parga Chasma and 3 systems cannot be relatively dated with respect to the rift zone. Spatially and temporally, no regional progression in the ages of graben-fissure systems is apparent. Radiating graben-fissure System 4, centred on Mielikki Mons and the VIRTIS emissivity anomaly is contemporaneous with Parga Chasma. Based on cross-cutting relationships between System 7 and the lava flows associated with the anomaly, it is possible to conclude that System 4 and its associated lava flows are not the youngest volcanic activity in the Mielikki Mons study area.

Based on these analyses of pit crater chain distribution and associations, clustering and hierarchical clustering of pit crater chains in the four areas of Venus examined. These observations indicate that pit crater chains are associated with graben formed by two extensional processes: (a) extension involving local volcano-tectonic features such as radiating graben-fissure systems and corona, and (b) regional tensile stresses. Pit crater chains associated with graben-fissure systems are found either along graben, parallel or sub-parallel to graben. In Ganiki Planitia, pit crater chains are oriented

parallel or sub-parallel to regional extensional graben. These associations suggest that, although extension is necessary for formation, pit crater chains are not limited to one particular type of extension on Venus. Although structural control appears to be the dominant factor, based on observation of hierarchical clustering, it is hypothesized that pit crater chain formation may also be influenced by a secondary, lithology-related variable such as degree of welding or unit thickness, as these characteristics may dictate how tensile stress is expressed within a particular lithological unit.

Appendix A: The nearest neighbour statistical test procedure and calculations

Because a combination of ArcGIS tools and basic statistics was utilized to calculate the average nearest-neighbour statistical test a summary of the procedure and an example calculation of Ganiki Planitia is provided.

Hypotheses:

H₀: The pit crater chains are distributed randomly throughout the area.

H_a: The pit crater chains clustered throughout the area.

Ganiki Planitia example calculation

Given values:

Total number of pit crater chains: 93

Area of Ganiki Planitia: 6491040.463 km²

1. Calculate the density (ρ) of pit crater chains in the total area (km²) examined for pit crater chains.

$$\rho = \frac{\text{number of pit crater chains}}{\text{area (km}^2\text{)}}$$

$$\rho = \frac{93}{6491040.46 \text{ km}^2}$$

$$\rho = 1.45 \cdot 10^{-5} \frac{\text{pit crater chain}}{\text{km}^2}$$

2. Calculate the expected nearest neighbour distance ($\bar{d}_{\text{ran}}$) for a random distribution.

$$\bar{d}_{\text{ran}} = \frac{1}{2\sqrt{\rho}}$$

$$\bar{d}_{\text{ran}} = \frac{1}{2\sqrt{1.45 \cdot 10^{-5}}}$$

3. Calculate the average nearest neighbor distance ($\bar{d}_{\text{obs}}$). Using ArcGIS 10 in arc toolbox, analysis tools, under proximity select generate near table. The shapefile used for both the input and near feature is the pit crater chain point shapefile. Leave the remaining options empty. Open the table generated and right click on the column header labeled NEAR_DIST. From the drop down menu select statistics. Another window will open with the desired information (mean).

The average nearest neighbor distance calculated for Ganiki Planitia using this method is 55.46 Km.

4. Calculate the nearest neighbor index (R)

$$R = \frac{\bar{d}_{obs}}{\bar{d}_{ran}}$$

$$R = \frac{55.46 \text{ km}}{131.39 \text{ km}}$$

$$R = 0.42$$

Since $R < 1$, we can say that the pit crater chains in Ganiki Planitia are clustered.

5. Compare the calculated R to a critical values chart made specifically for the nearest-neighbour index (two-tailed).

For the case of Ganiki Planitia, the critical value of R for a sample size of 93 and a significance value 0.001 is 0.824. Therefore, we can say with 99.9% confidence that the pit crater chains are clustered.

6. Apply a student's t-test to determine the nearest-neighbour analysis as a means of determining the probability that the observed distribution is by chance.
 - a. Calculate the standard error of the mean. n is the number of points.

$$SE_{\bar{d}} = \frac{0.26136}{\sqrt{n\rho}}$$

$$SE_{\bar{d}} = \frac{0.26136}{\sqrt{93 \cdot (1.44 \cdot 10^{-5})}}$$

$$SE_{\bar{d}} = 7.16$$

- b. Calculate the z score

$$z \text{ score} = \frac{\bar{d}_{obs} - \bar{d}_{ran}}{SE_{\bar{d}}}$$

$$z \text{ score} = \frac{55.46 - 131.39}{7.16}$$

$$z \text{ score} = -10.703$$

7. Compare the calculated z score to a critical values table of the standard normal deviate for a two-tailed test with a p-value of 0.001. The distribution is clustered and the null hypothesis is rejected if the z score is less than the critical value. The value -3.291 is the critical value of a standard normal deviate of a 0.001 significance level for a two-tailed distribution (Ebdon, 1985).

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